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Comprehension in Proficient Readers: The Nature of Individual Variation

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Abstract

Individual-difference research on reading comprehension is challenging because reader characteristics are as correlated with each other as they are with comprehension. This study was conducted to determine which abilities are central to explaining comprehension and which are secondary to other abilities. A battery of psycholinguistic and cognitive tests was administered to community college and university students. Seven constructs were identified: word decoding, working-memory capacity (WMC), general reasoning, verbal fluency, perceptual speed, inhibition, and language experience. Only general reasoning and language experience had direct effects; these two variables accounted for as much variance in comprehension as did the complete set. Direct effects of WMC and decoding were found only when general reasoning and language experience were deleted from the models. The authors question the need to include WMC in our theories of variability in adult reading comprehension and highlight the need to understand precisely how vocabulary facilitates comprehension.

Reading is the primary means of knowledge acquisition in many domains; thus, the ability to construct accurate and comprehensive representations of texts has significant implications for academic performance, occupational success, and physical well-being. Reading is a complex skill, involving both domain-general and language-specific abilities. Variation in reading skill among individuals is considerable, even among university students. Understanding this variation is important for both practical and theoretical reasons. With respect to practice, it can help in the identification of individuals who struggle to comprehend texts and in the design of effective reading instruction. With respect to theory, individual-difference research is an important means of specifying the cognitive and linguistic processes that underlie reading. For example, contemporary theories of working memory (WM) and its role in language processing, both written and spoken, have their foundation in studies showing that reading span, a task that involves processing sentences while holding a set of words in memory, is linked to language processing as assessed by comprehension tests, eye-tracking, reading time, and event-related potentials (ERPs).

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Although individual-difference research is critical to our understanding of variation in language processing, it can be difficult to conduct. A significant obstacle is that performance across a variety of tasks tends to correlate (cf. Deary, 2000). Researchers develop tasks that are intended to assess participants' performance on a specific linguistic or cognitive process, such as working-memory capacity (WMC) or word-identification skill. The problem is that no task is "process pure;" they all involve multiple component processes. A particular task may be affected by one process more than another, but it is never an assessment of a single one. To the extent that processes overlap across tasks, performance on them will be correlated. Indeed, research on individual differences in reading comprehension shows that performance on individual-difference tasks correlate with each other as much as they do with reading comprehension itself. These correlations make it difficult to determine whether a particular individual characteristic (e.g., WMC) is uniquely predictive of language processing skill or if it correlates only because of its relation to some other individual-difference variable. As we discuss in the following sections, several individual-difference measures, such as WMC and word decoding, have dominated research on language processing and comprehension, even though there is scant evidence that these measures are uniquely predictive of performance. This raises significant concerns about theoretical interpretations of this research.

Our goals in the current study were (1) to understand how reader characteristics are related to each other and to text comprehension, with a particular focus on determining the extent to which WMC, vocabulary, and word knowledge are uniquely predictive of comprehension, and (2) to examine how these relations change depending on which reader characteristics are included in the analysis. We used a structural equation modeling framework in a group of proficient adult readers to determine which reader characteristics are central in predicting comprehension and which are related by means of shared variance with other characteristics. Few large-scale studies of comprehension in proficient adult readers have been conducted even though several theories about the nature of individual variation in reading ability have been developed based on empirical findings in this population (e.g., Ericsson & Kintsch, 1995; Gernsbacher, 1990; Just & Carpenter, 1992; MacDonald & Christiansen, 2002). In the sections below, we review the literature on three classes of variables: domain-general cognitive abilities, language-specific abilities, and background knowledge/reading experience. We focus our review on large-scale multiple-regression and SEM studies of proficient adult readers whenever possible.

Domain-General Cognitive Abilities

No single cognitive ability has received as much empirical and theoretical attention as WMC. Many researchers have argued that the WM system is integral to maintaining activated representations and computing semantic and syntactic relations among them. Moreover, they have argued that individuals vary in the amount of information that they can maintain in memory as they perform computations to complete a complex cognitive task. These claims are supported by hundreds of studies showing a positive correlation between complex span tasks, such as reading span, and tests of verbal ability such as the verbal SAT and the Nelson-Denny Reading Test. Daneman and Merikle (1996) conducted a meta-analysis of the relation between complex span tasks and verbal ability and reported correlations across studies that ranged from .20 to .52. Studies in which WMC has been assessed as a latent variable have also found a significant relation between WMC and comprehension (Engle, Tuholski, Laughlin, & Conway, 1999; McVay & Kane, 2012).

Several explanations of the correlation between complex span and comprehension have been developed in the context of sentence-processing research to explain why some readers have greater difficulty processing sentences with complex syntactic structures than do other readers. These explanations are all grounded in the assumption that difficulty in processing sentences has consequences for comprehension overall. Explanations for the correlation between span and language processing generally fall into two classes: (1) those in which the relation between span and processing is a direct one in that limitations in the ability to simultaneously maintain and process information affect the types of relations that readers are able to construct during comprehension and (2) those in which the relation between span and processing is indirect in that the correlation reflects shared variance between span tasks and other variables, in particular, language experience.

A direct relation between complex span and comprehension is predicted in two models: the Capacity Theory of Comprehension (Just & Carpenter, 1992) and the Separate-Sentence-Interpretation-Resource Theory (SSIR) (Waters and Caplan, 1996). According to Capacity theory, WM consists of a finite pool of cognitive resources that supports both storage and processing of information. The total amount of activation that is available in WM varies across individuals. When the amount of activation that is needed for storage and processing exceeds the total activation that is available, one or both functions are impaired and information is lost. Thus, individuals who are low span have insufficient resources to execute necessary comprehension processes when storage and processing demands are high as, for example, when readers encounter syntactically difficult sentences (Just & Carpenter, 1992; King & Just, 1991). The SSIR Theory differs from Capacity Theory with respect to predictions about the role of WMC in sentence processing, but not with respect to predictions about text comprehension. According to this view, WMC is modular with a dedicated module devoted to syntactic parsing and a second module that is devoted to post-parsing processes involved in the integration and elaboration of ideas in comprehension. Individuals show little variation in the capacity of the first module, but vary substantially in the capacity of the second. Thus, SSIR Theory is similar to Capacity Theory in attributing individual differences at the discourse level to a limited-capacity system.

In contrast, an indirect relation between WM span and comprehension is predicted in a connectionist-based framework proposed by MacDonald and Christiansen (2002) and the Long-Term Working-Memory (LTWM) Theory proposed by Ericsson and Kintsch (1995). According to the connectionist-based framework, the capacity of a system arises from its architecture (e.g., the number of processing units, how activation passes through the weights) and the system's experience (e.g., how often it has processed similar input in the past). Thus, capacity is not a separate pool of resources; it is a property of the processing system. The relation between complex span and comprehension arises from variation in two factors. First, individuals vary with respect to basic sensory/perceptual abilities, primarily the ability to represent and process phonological information. The ability to discriminate phonemes quickly and represent them accurately in short-term memory is important in grapheme-to-phoneme mapping during reading and for performing well on verbal span tasks. Second, individuals vary in reading experience, giving rise to individual differences in practice with linguistic stimuli. Poor comprehenders read less frequently than do good ones; thus, they are less likely to encounter low-frequency linguistic stimuli (e.g., uncommon syntactic structures). Consequently, variation in the processing of low frequency input is due to differences in practice (Long & Prat, 2008; Wells, Christiansen, Race, Acheson, & MacDonald, 2009). The LTWM Theory also emphasizes the role of experience in explaining the relation between complex span and comprehension. According to the theory, skilled readers develop mechanisms for encoding and retrieving information from long-term memory that meet the demands of the task. Thus, individuals who read frequently are skilled at encoding linguistic input into structures that can be quickly and easily retrieved when needed.

Although WM span has been used in hundreds of studies to predict language processing in proficient adult readers, only a handful of them have examined whether or not span is uniquely predictive of comprehension when other linguistic and cognitive variables are considered. Does span have a direct relation on comprehension as predicted by the Capacity and SSIR Theories or is the relation indirect as predicted by the connectionist-based and LTWM Theories? In one study, Hannon (2012) found that WMC had a significant effect on comprehension using an SEM approach. She assessed high-level skills (e.g., knowledge access, knowledge integration) and low-level skills (e.g., lexical decision, phonological decision). The model, the Cognitive Components and Resource Model of Reading Comprehension (CC-R), was restricted such that low-level skills (e.g., word decoding) directly predicted both reading speed and reading comprehension; reading speed directly predicted reading comprehension; WMC, text-based processing, and knowledge access directly predicted knowledge integration; and knowledge integration directly predicted reading comprehension. A variant of the model, the CC-R2, allowed WMC to have a direct effect on reading comprehension and was found to be the best fitting one. Hannon concluded that high-level and low-level skills are dissociable and that high-level skills have a greater impact on comprehension than do low-level ones. A critical drawback of the study in assessing the role of WMC in comprehension, however, is that latent variables in the model were not allowed to covary although many of the measures were significantly correlated. Thus, WMC may have had a direct effect only because shared variance was not assessed.

In contrast, two large studies have found no unique effect of complex span on comprehension. Macaruso and Shankweiler (2010) used multiple regression to examine the unique contributions of several variables to comprehension. They found significant effects of listening comprehension and word decoding. Importantly, they found no unique effect of WMC. Britton and colleagues also found no unique effect of WMC in a study using SEM (Britton, Stimson, Stennett, & Gülgöz, 1998). They assessed reading comprehension, metacognitive ability, inference ability, domain knowledge, and WM span. The model was constrained such that metacognitive ability predicted inference ability; inference ability predicted both domain knowledge and WM span; and domain knowledge predicted comprehension. All of the paths were significant and positive. An alternative model allowing for a direct effect of WM span on comprehension did not result in a better fit and span had no significant effect on comprehension. In a recent meta-analysis of comprehension

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performance in struggling adult readers, Tighe and Schatschneider (2016) found no support for an effect of WMC when linguistic variables, such as word decoding and oral vocabulary, were included in the studies under review.

In summary, we have a huge literature in psycholinguistics that has focused on the role of WMC in language processing, based on the assumption that WMC has a unique and direct effect on comprehension. However, only one major study has found such an effect (Hannon, 2012). Given the hundreds of studies that include WM span measures in investigations of language processing in proficient adults, the lack of large-scale studies that support WMC as a unique predictor of comprehension is striking. A major question to be addressed in this study is whether WM span has a direct effect on comprehension when it is allowed to covary with other variables.

A second cognitive variable, inhibition/suppression, has received modest attention in research on language processing in proficient adult readers. Readers appear to differ in the extent to which they can suppress or inhibit activated, but context-irrelevant, information. Suppression plays a prominent role in Gernsbacher's (1990) Structure Building Framework. According to the framework, readers begin the process of constructing a text representation by establishing a foundation based on initial input. They add incoming information to the structure when it is meaningfully related. When information is unrelated, readers shift to initiate a new substructure. Two processes play an important role in creating text structures: enhancement and suppression. Enhancement increases the activation of memory traces when their content is relevant to the developing text representation; suppression dampens activation when their content is unrelated. According to the framework, good and poor comprehenders are similar in their ability to enhance relevant information, but differ significantly in their ability to suppress activated, but irrelevant, information (Gernsbacher, 1993, 1997; Gernsbacher, Robertson, Palladino, & Werner, 2004; Gernsbacher, Varner, & Faust, 1990).

Unfortunately, large-scale studies of comprehension in proficient adult readers have not included measures of suppression/inhibition ability. This is surprising given that several researchers have suggested that the ability to inhibit task-irrelevant information is an important component of the WM system (Conway & Engle, 1994; Engle, Conway, Tuholski, & Shisler, 1995; Engle, Kane, & Tuholski, 1999; Engle, Tuholski, Laughlin, & Conway, 1999; Kane, Bleckley, Conway, & Engle, 2001; Kane & Engle, 2000; Rosen & Engle, 1997). Thus, the relation between performance on complex span tasks and comprehension may be secondary to the relation between span and suppression ability.

Two cognitive variables that have been important in studies of language processing in children—processing speed and general reasoning—have been largely ignored in studies of proficient adult reading. Processing speed is believed to be important because reading is a sequential and speed-dependent activity; words are received one at a time and must be integrated into a sentence representation before the verbal trace of preceding words begins to decay. Numerous studies in children have found that performance on speed-of-processing tasks, such as pattern comparison and letter comparison, are uniquely predictive of comprehension (Borella, Carretti, & Pelegrina, 2010; Borella & Ribaupierre, 2014; Joshi &

Aaron, 2000; Peter, Matsushita, & Raskind, 2011; Swanson, 1996; Swanson, Howard, & Saez, 2006; Tiu, Thompson, Lewis, 2003). Processing speed has also been investigated in older adults (Caplan, DeDe, Waters, Michaud, & Tripodis, 2011; Payne & Stine-Morrow, 2014). For example, Payne and Stine-Morrow (2014) found that individual variation in processing speed was predictive of sentence wrap-up effects. However, investigations of proficient adult readers are absent from the literature.

Similarly, measures of general reasoning, such as IQ, are common in large-scale studies of reading in children and low-literacy adults (Swanson et al. 2006; Tiu et al., 2003), but are seldom included in comprehension studies of proficient adult readers. This is unfortunate because the purpose of including such measures is to identify the cognitive variables that influence a complex task separate from the overall influence of intelligence. If a construct such as WMC fails to influence comprehension when general reasoning is included as a variable, then the theoretical importance the construct is undermined.

In summary, few large-scale studies have examined the unique influence of different domain-general cognitive variables on comprehension in proficient adults. A handful of large studies have included measures of WMC, but they have produced contradictory results. In addition, measures of inhibition/suppression, processing speed, and general reasoning have seldom been examined concurrently with WMC. In the current study, we include latent variables of all these constructs. We allow the variables to covary and examine their direct and indirect effects.

Language-Specific Abilities

In order to understand a text, a reader must map orthographic representations to phonological ones, use these representations to access word meanings, and integrate these meanings with preceding information. The dominant theory of reading comprehension in children is the Simple View of Reading (Gough & Turner, 1986). According to this view, reading comprehension is the product of linguistic comprehension—all of the skills and capacities that are necessary to understand discourse in its oral form—and word decoding. Word decoding is a limiting factor in reading comprehension because the product of word decoding and linguistic comprehension will be relatively low whenever word decoding is poor. Most studies of the Simple View of Reading have focused on reading comprehension in children and have found considerable support for the view (Adams, 1990; Snow, Burns, & Griffin, 1998). Decoding skill is also important in predicting comprehension in struggling adult readers (for a review, see Tighe & Schatschneider, 2016), although the effects of decoding seem to be smaller in low-literacy adults than in children.

Word decoding skill plays a somewhat less prominent role in Perfetti's (2007) Lexical Quality Hypothesis, a framework for understanding the role of lexical ability in comprehension that emphasizes the rich and detailed representations of words that skilled readers know (Taylor & Perfetti, 2016). He argues that comprehension skill requires high-quality lexical representations, that is, representations that consist of detailed orthographic-to-phonological mappings and rich semantic meanings. Readers who have poor quality representations are slow at identifying words, have a poor understanding of the words that they read, and may activate incorrect word meanings.

The relative contributions of word knowledge (e.g., vocabulary) and word decoding (e.g., word-identification speed) have been studied extensively in children and both characteristics are strongly predictive of comprehension (Gough & Tunmer, 1986; Hoover & Gough, 1990; Joshi, 2005; Perfetti & Hogaboam, 1978; Perfetti, 1985; Verhoeven & Van Leeuwe, 2008). The role of word-decoding skill in proficient adult readers is less clear than it is in children; fewer studies have included measures of both decoding and word knowledge. Those that have done so report mixed results with respect to the significance of word decoding in proficient readers. We briefly describe a few studies that are representative of those that have included both word-decoding and word knowledge in large samples of proficient adult readers.

Macaruso and Shankweiler (2010) used multiple regression to assess reading comprehension, listening comprehension, word decoding, receptive vocabulary, WMC, and general reasoning in community college students. With all predictors included, the model accounted for 48% of the variance in reading comprehension. Word decoding and listening comprehension alone accounted for 34% of the variance; listening comprehension uniquely contributed 13%. Although word decoding was a significant predictor, it only accounted for 6% of unique variance. Similarly, Landi (2010) found a relatively small effect of word decoding ability on reading comprehension. She used hierarchical regression analyses with measures of word knowledge and experience, spelling, and general reasoning. Regardless of order of entry, vocabulary accounted for the largest portion of variance, ranging from 39% – 45%. Word decoding was a significant predictor, but accounted for only a small portion of the variance, ranging from 0.3% – 0.8%.

Braze, Tabor, Shankweiler, and Mencl (2007) found no unique effect of word decoding on comprehension in a group of adolescents and young adults when vocabulary was included as a predictor. They assessed listening comprehension, word decoding, vocabulary, and general reasoning. When reading comprehension was regressed on listening comprehension and word decoding with age as a covariate, both measures uniquely and significantly predicted reading comprehension. However, when vocabulary was added to the analysis, listening comprehension and word decoding no longer made individually identifiable contributions. Braze et al. concluded that their results challenged the Simple View of Reading, suggesting that decoding and listening comprehension was secondary to vocabulary in adolescents and young adults.

Very few studies have used an SEM framework to examine reading comprehension in adults and even fewer have included measures of both word decoding and word knowledge. Cromley, Snyder-Hogan, and Luciw-Dubas (2010) assessed reading comprehension as a function of variation in domain knowledge, inference ability, reading strategy use, vocabulary, and word decoding. Domain knowledge was the most important predictor of comprehension, with significant direct and indirect effects. Vocabulary also had direct and indirect effects, whereas strategy use had only indirect effects. In contrast, they found no significant effect of word decoding on comprehension. Braze, Katz, Magnuson, Mencl, Tabor, Van Dyke, Gong, Johns, and Shankweiler (2016) examined comprehension in a group of adolescent readers and community college students. They assessed listening comprehension, word decoding, and vocabulary. They found that the listening comprehension and vocabulary measures loaded on a single factor. In the SEM, this factor covaried with word decoding and both it and word decoding had direct effects on comprehension. This result was in conflict with the earlier study by Braze and his colleagues in which decoding had no unique effect on comprehension (Braze et al., 2007).

In summary, studies that have examined the unique effects of word decoding and word knowledge in proficient readers have generally found that word knowledge accounts for significant variation in comprehension (Braze et al., 2007; Braze et al., 2016; Bell & Perfetti, 1994; Cromley et al., 2010; Landi, 2010). A few studies have found unique effects of word decoding on comprehension, although the effects have been relatively small or limited to particular genres of text (Bell & Perfetti, 1994; Braze et al., 2016; Landi, 2010; Macaruso & Shankweiler, 2010).

Domain Knowledge/Print Exposure

Individuals enjoy reading to different extents and engage in a wide variety of reading practices. Research has established a positive correlation between print exposure, the frequency with which individuals read, and comprehension in both children and adults (Cunningham & Stanovich, 1990, 1991; Stanovich & Cunningham, 1992; Stanovich & West, 1989; West & Stanovich, 1991; West, Stanovich, & Mitchell, 1993). Print exposure is likely to influence comprehension in at least two ways. First, individuals who read often are more likely to learn about rare words and low frequency syntactic structures than are individuals who read less, primarily because these stimuli appear more often in print than they do in speech (Carroll, Davies, & Richman, 1971; Hayes & Ahrens, 1988). Second, individuals who read often are likely to acquire more world knowledge than individuals who read less often as reading is an important means of knowledge acquisition in many domains.

Just as readers vary in their reading practices, they vary in their knowledge about the domain in which they are reading. High-knowledge readers access a rich, interconnected network of concepts and ideas when they read a text in their domain of expertise (Chi, Feltovich, & Glasser, 1981; Chiesi, Spilich, & Voss, 1979; Means & Voss, 1985). Moreover, they employ more effective reading strategies than do less knowledgeable readers (Afflerbach, 1986; Lundeberg, 1987) and are faster and more efficient at retrieving information from their knowledge domain (Ericsson & Smith, 1991). The comprehension advantage associated with background knowledge has been well documented in both recall (Alba, Alexander, Hasher, & Caniglia, 1981; Bransford & Johnson, 1972; Schneider, Körkel, & Weinert, 1990; Spilich, Vesonder, Chiesi, & Voss, 1979; Sulin & Dooling, 1974; Summers, Horton, & Diehl, 1985) and recognition (Long, Johns, & Jonathan, 2012; Long & Prat, 2002; Long, Prat, Johns, Morris, & Jonathan, 2008). Two of the studies that we described in the previous section included domain knowledge among other reader characteristics to examine its unique effect on comprehension: Cromley, et al. (2010) and Britton et al. (1998). Both studies found that domain knowledge was the most significant of their predictors, with both reliable direct and indirect effects.

In summary, few large-scale studies have included print exposure and domain knowledge as predictors of reading comprehension in proficient adult readers. This is unfortunate given two studies reporting that domain knowledge was more important than other predictors in accounting for variance in reading comprehension (Britton et al., 1998; Cromley et al., 2010).

The Current Study

The two aims of this study were to understand how reader characteristics are related to each other and to text comprehension and to examine how these relations change depending on which reader characteristics are included in the analysis. We used structural equation modeling to identify the unique predictors of reading comprehension in a large group of community college and university students. SEM has important advantages over other techniques for analyzing correlational data. First, variables in SEM can be both predictors and outcomes simultaneously. Thus, it goes beyond techniques that identify unique sets of predictors, such as multiple regression, by specifying the relations among the predictor variables. Mediation of one variable by another can be identified, providing information about the primary or secondary role of a particular variable in explaining the outcome. Second, predictors can be measured as latent variables in SEM, derived from shared variance among a set of measures that is intended to assess a theoretical construct. This allows the construct to be identified separately from the measurement error that is associated with individual tasks. Finally, SEM estimates the error that is associated with measuring a construct of interest separately from unexplained variance in the outcome variable. Thus, it can be used to analyze dependencies among psychological constructs without measurement error.

The list of language-specific and domain-general abilities that could be investigated is long. Given the constraints of any single study, decisions must be made about which abilities to investigate. Our decisions were guided by three criteria. First, we selected abilities that have played the largest role in theories of reading comprehension in adult readers: word decoding, vocabulary, and WMC. Second, we included a set of variables that have been involved in debates about the extent to which the Simple View of Reading (Gough & Turner, 1986) should be augmented with additional abilities. These variables include processing speed (Joshi & Aaron, 2000; Tiu, Thompson, & Lewis, 2003), verbal fluency (Adolf, Catts, & Little, 2006; Silverman, Speece, Harring, & Ritchey, 2013), and general reasoning (Tiu et al., 2003; Van Dyke, Johns, & Kukona, 2014). Third, we selected several variables that have been linked specifically to variation in comprehension among proficient adults; these variables include inhibition/suppression (Gernsbacher, 1990), print exposure (Cunningham & Stanovich, 1990, 1991; Stanovich & Cunningham, 1992; Stanovich & West, 1989; West & Stanovich, 1991; West, Stanovich, & Mitchell, 1993), and domain knowledge (Long, Johns, & Jonathan, 2012; Long & Prat, 2002; Long, Prat, Johns, Morris, & Jonathan, 2008). In selecting the abilities that we included in this study, we chose those that we believed had the greatest likelihood of direct, rather than indirect, effects. Many high-level abilities have been linked to adult reading comprehension, such as meta-cognitive ability, comprehension monitoring, and inference ability. Given limitations on the number of abilities that can be investigated in any single study, we thought in best to focus on abilities that have been closely linked to intelligence, WMC, general reasoning, perceptual speed, and inhibition/suppression. In addition, we chose not to include oral measures in this study. The difference in performance between oral and written tasks diminishes greatly across development and tends not to be significant in proficient readers (Braze et al., 2016; Gernsbacher, 1990).

Performance on the battery of psycholinguistic and cognitive tests was factor-analyzed to determine its underlying structure and to confirm that the measures in our study assessed the theoretical constructs of interest. We hypothesized 9 factors: WMC, general reasoning, perceptual speed, inhibition/suppression, word decoding, vocabulary, verbal fluency, print exposure, and background knowledge. We constructed an SEM in which the predictors were latent variables corresponding to the constructs that were identified in the factor analysis. Comprehension was also a latent variable and each predictor was allowed a unique regression path to it. In addition, all predictors were allowed to covary. Paths were removed from the model following a backward-building procedure.

Once we had the full model constructed, we examined its stability as a function of the latent variables that were included in it. The paths in a SEM can vary in significance depending on the inclusion or exclusion of variables, just as the significance of a predictor variable can change in a regression analysis depending on what other predictors are included. We conducted two types of analyses. In one type, we compared the amount of explained variance in a large model (Models 1, 2, 3, and 4) to a model in which only those latent variables with direct paths were included (Models 1-Reduced, 2-Reduced, 3-Reduced and 4-Reduced). Our goal in these analyses was to determine how much explanatory power was lost when variables with indirect effects were eliminated. In the second type of analysis, we examined the pattern of direct and indirect effects on comprehension when we deleted a latent variable that had a significant direct path to comprehension in the full model (Model 1). Our goal in these analyses was to reconcile discrepancies in the previous literature. Together, these analyses allowed us to determine the stability of our direct effects and information about why previous studies have obtained mixed results about the predictive power of variables such as WMC and word decoding.

Method

Participants

Participants were 357 young adults (243 female, 26 declined to respond) ranging in age from 17 – 29 ($M = 18.48$, $SD = 0.87$) who were paid $10/hr. to attend ~16 hours of testing across 11 sessions. Participants were University of California, Davis undergraduates (58% of participants) and local community college students. All participants were fluent English speakers, with normal or corrected-to-normal vision, and none reported neurological or cognitive impairments.

Materials and Procedure

Participants received a battery of tests to assess the constructs that we discussed in the introduction: WMC, suppression/inhibition, processing speed, general reasoning, word decoding, vocabulary, print exposure, verbal fluency, and background knowledge. One goal in selecting measures was to identify those that were standardized or had good reliability in previous studies. A second goal was to choose measures that were likely to give us a factor structure in which separate latent variables could be identified for the constructs of interest. One source of measures was the Ekstrom Battery of Factor-Referenced Tests (Ekstrom, French, Harman & Dermen, 1976). The Kit consists of 72 tests; each test loads strongly on one of 23 factors. We selected 12 tests from the Kit; these tests loaded on 4 factors: vocabulary, verbal fluency, general reasoning, and processing speed.

We anticipated a significant dropout rate given that tasks were administered across a large number of sessions. Thus, we randomized the order of tasks so that data would be missing at random if participants failed to complete one or more sessions. This was important because missing data can be estimated in a SEM only if the data are missing at random. A random order of tasks was generated for each participant and then adjusted such that the most difficult and time-consuming tasks (e.g., Raven's matrices, span tasks) were administered in different sessions. The tasks were administered to participants individually and each session was ~1.5 to 2 hours long. Participants received breaks between tasks.

Comprehension Measures

Participants read 10 full-length texts in a dual-Purkinje eye-tracker. The texts were selected to represent a range of genres: literature ("The Oval Portrait" by Edgar Allen Poe; "Harrison Bergeron" by Kurt Vonnegut, Jr.; 1288 and 2228 words, respectively), contemporary fiction ("The Secret Life of Walter Mitty" by James Thurber; "I am Bigfoot" by Ron Carlson;2110 and 725 words, respectively), procedural ("What you can do to Minimize Online Risks," from *Consumer Reports*; 912 words), biography ("The Bass, the River, and Sheila Mant" by W.D. Wetherell; 2720 words), and expositions about science and history ("Four Score and Seven Lattes Ago: How a coffee shortage killed the Confederacy" by David A. Norris; "Professors: Email diminishes formality, respect students display towards teachers" by Dyanna Quizon; "One-hit Wonder" from the Science section of the *New York Times*; "Cell phone or pheromone? New props for the mating game" by Natalie Angier; 693, 574, 777, and 1227 words, respectively). The focus in this study was on the comprehension data; thus, the eye-tracking data were not included in the analyses.

A comprehension test (Investigator-Generated Test) was developed for each text to assess participants' memory for explicit information and their understanding of main ideas and themes. The test consisted of 10 multiple-choice questions (4-response options) for each text. Main ideas were identified by having a group of 25 pilot participants identify the 10 most important ideas in each text. We then chose five of the text ideas with the highest rate of identification. All of these ideas were selected by more than half of the participants (M = 19). The investigators wrote an additional five questions for each text that were intended to assess inferences that were important in comprehending the texts. Completion of the test was untimed. Participants also received the comprehension section of the Nelson-Denny Reading Test, Forms F (Brown, Bennett, & Hanna, 1980) and G (Brown, Fischo, & Hanna, 1993). Participants read short passages and answered a total of 36 and 38 questions (Forms F and G, respectively). Participants were given 20 minutes to complete the test.

Individual-Difference Measures

Working-Memory Capacity—Four WM span tasks were included: (1) Reading Span (Just & Carpenter, 1980; Unsworth, Heitz, Schrock, & Engle, 2005) – Participants read a series of sentences and made a sense/nonsense judgment to each one (e.g., *On warm sunny afternoons, I like to walk in the park; Most people agree that Monday is the worst stick of the week*). After each judgment, they received a single word that was unrelated to the previous sentence and were asked to remember it. The sentences were presented in 15 sets, varying in size from two to seven sentences. Set size was presented randomly. At the end of each set, participants recalled the target words in order of presentation. They received 60 target words across all trials; (2) Alphabet Span (Craik, 1986) – Participants received 25 lists of words, one word at a time (e.g., jam, dog, eel, book). Each list was preceded by a fixation cross for 1000 ms and each item was presented for 1000 ms. The number of words in a set varied from two to six. At the end of each set, participants were asked to recall the words in alphabetical order; (3) Minus Span (Salthouse, 1988) – Participants received 35 sets of random numbers, one number at a time. The size of the set varied from two to eight. Participants were asked to subtract 2 from each number in the set and then to recall the differences in numerical order. Participants received 175 numbers across all trials; (4) Visual Number Span (from the Ekstrom Battery) – Participants received digits in 24 sets of varying lengths from 4 to 13 at a rate of one digit per second. At the end of a set, participants recalled the digits in the reverse order of presentation.

Suppression/Inhibition Ability—A set of tasks was selected to assess participants' ability to respond to a target while inhibiting a pre-potent response[1]: (1) Go/No–Go (https://www.sacklerinstitute.org/cornell/assays_and_tools/) – Participants received letters one at a time on the computer screen, each for 1500 ms. They were asked to press the 'z' key (go) in response to any letter except the letter X. When the letter X appeared, participants were told not to respond (no-go). Participants received a set of practice trials and then 300 test trials, 240 of which were 'go' trials. All responses were recorded; (2) Stroop Interference – Participants received 105 letter strings one at a time on a computer screen. The strings consisted of a series of X's or the name of a color (e.g., red). All of the letter strings were presented in colored font and participants were asked to name the color of the font. Included were compatible and incompatible word trials. Compatible trials consisted of words in a font that matched the meanings of the words (e.g., the word "red" in red font). Incompatible trials consisted of words in a font that did not match the meanings of the words (e.g., the word "red" in green font). Accuracy and onset latencies were recorded for each letter string.

General Reasoning—A set of general reasoning tasks was selected to assess readers' ability to solve novel problems. We included a standardized test, Raven's Advanced Progressive Matrices (Raven, 1962), and tests from the Ekstrom Battery that loaded on a general reasoning factor. Participants received the first two sets of Raven's Matrices. There were a total of 48 matrix problems in which participants had to choose the missing element that completed each pattern. The tests from the Ekstrom Battery included (1) Arithmetic

[1]The Eriksen-Flaker Task was included as one of our inhibition/suppression task; however, a programming error led to significant loss of data and the task was dropped from the study

Aptitude – the test consisted of arithmetic word problems, two sections of 15 items each. Participants had 10 minutes to complete each section; (2) Mathematic Aptitude – the test consisted of multiple-choice word problems that required the use of arithmetic and algebraic operations, two sections of 15 items each. Participants had 10 minutes to complete each section; (3) Necessary Arithmetic Operations – the test consisted of arithmetic word problems. Participants had to determine which numerical operations were required to solve each problem, but were not required to perform the computations. There were two sections; each had 15 items. Participants had five minutes to complete each section.

Perceptual Speed Tasks—A set of tasks was selected to assess the speed with which participants could perform perceptual processes. These included: (1) Letter Comparison (Salthouse & Babcock, 1991) – The task consisted of pairs of letter strings (e.g., MVX—MXV; QFLJEO— QFLJEO). The strings were three, six, or nine letters in length. String length was presented in random order. Participants were asked to indicate whether the letter strings in each pair were the same or different. There were two lists of 21 pairs and each list had a 30 second time limit; (2) Pattern Comparison (Salthouse & Babcock, 1991) – The task consisted of patterns that were presented in pairs. Each pattern contained three, six, or nine line segments. Participants were asked to indicate whether the patterns in each pair were the same or different. There were two lists of 15 pairs and each list had a 30 second time limit; (3) Finding As (Ekstrom Battery) – Participants received a list of words that were arranged in columns. Each column contained 41 words. Participants were asked to scan the list and to mark five words in each column that contained the letter “a”. There were 25 columns to be scanned in a total of two minutes; (4) Number Comparison (Ekstrom Battery) – Participants inspected pairs of multi-digit numbers and indicated whether or not the numbers in each pair were the same. There were 48 pairs of numbers in a list and participants had 90 seconds to complete the list. Participants completed two lists; (4) Identical Pictures (Ekstrom Battery) – Participants were shown six numbered geometrical figures in a row. They were asked to use the first item as their standard and to determine which of the remaining five were identical to the first. There were 48 rows in a list and two lists. Each list had a time limit of 90 seconds.

Word Decoding Tasks and Phonological Awareness—Our primary interest was in the decoding tasks, but we included two phonological awareness tasks given how important phonological awareness has been in the study of reading comprehension in children. The decoding tasks included (1) Phonological Decision, sometimes called the pseudohomophone choice task (Bell & Perfetti, 1994; Landi, 2010; Olson, Kliegl, Davidson, & Foltz, 1985) – Participants received two letter strings side-by-side on a computer screen, both of which were non-words. One of the letter strings sounded like a real word if pronounced aloud (e.g., *HOWLKE* vs. *HOWSE*). Participants indicated, as quickly as possible, which of the two letter strings sounded like a real word. Accuracy and reaction times were recorded for each of 75 trials. Thus, only the latency data were analyzed; (2) Non-word Naming (Bell & Perfetti, 1994) – Participants received pronounceable letter strings that were presented in the center of a computer screen (e.g., *phlambust*). They pronounced the string aloud as quickly and as clearly as possible. A voice key was used to record responses and voice onset times for each of 100 trials; (3) Orthographic Decision task (Bell & Perfetti, 1994; Olson et al., 1985). Participants received two letter strings side-by-side on a computer screen, one of which was a correctly spelled word. The other was a non-word, although it sounded like a word if pronounced aloud (e.g., *DEAL* vs. *DEEL*). Participants indicated, as quickly as possible, which of the two strings was a correctly spelled word. Accuracy and reaction times were recorded for each of 75 trials.

One phonological awareness task was administered[2]: Phoneme Transposition (Olson, Wise, Conners, Rack, & Fulker, 1989) – Participants heard words one at a time. They were asked to remove the first phoneme from the word, move it to the end, and add a long “a” sound (e.g., “*lock”* would become “*ocklay*”). Accuracy was recorded for each of 45 trials.

Vocabulary—We administered the vocabulary section of the Nelson-Denny Reading Test, Form F (Brown et al., 1980) and Form G (Brown et al., 1993). Form F consists of 100 items; each item is a sentence with the final word missing. Participants are asked to complete the sentence with an appropriate word from among five response options. Form G consists of 80 items, structured in the same fashion. Participants had 15 minutes to complete each test. All scores were converted to scale scores to ensure the forms were equivalent. We also administered the Extended Range Vocabulary and Advanced Vocabulary sections of the Ekstrom Battery. Both are multiple-choice tests of participants’ knowledge about synonyms. The Extended Range test consists of two sections of 24 items each and participants had four minutes to complete each section. The Advanced Vocabulary test consists of two sections of 18 items each and participants had four minutes to complete each section.

Verbal Fluency—The verbal fluency tasks were selected from the Ekstrom Battery to assess the speed with which participants were able to generate words in specific categories. These included (1) Word Beginnings – Participants were asked to write as many words as possible beginning with a target letter (e.g., “Write as many words as you can that begin with C”). They were given two different prompts and allowed to work for three minutes on each prompt; (2) Word Endings – Participants were asked to write as many words as possible ending with a specific letter (e.g., “Write as many words as you can that end in T”). They were given two different prompts and allowed to work for three minutes on each prompt; (3) Word Beginnings and Endings – Participants were asked to write as many words as possible beginning with one target letter and ending with another target letter (e.g., “Write as many words as you can that begin with S and end with N”). They were given two different prompts and allowed to work for three minutes on each prompt.

Background Knowledge and Print Exposure—Most measures of background knowledge are constructed to assess the depth of an individual’s expertise in a single domain. The texts that were used in this study, however, spanned multiple genres and knowledge domains. Thus, we decided to include measures that would assess knowledge generally. Unfortunately, our choices were limited by the absence of general knowledge measures in previous reading research. Thus, we examined the literature on cultural literacy and selected a test from a popular book on the topic: Test-Prep your IQ with the Essentials

[2]A second phonological awareness task, phoneme-deletion, was also administered. A error in task administration made the data unusable.

of Cultural Literacy (Zahler & Zahler, 2003). Questions on the test assessed knowledge about American History, Geography, Myth and Religion, Science, and Art.

Several of the texts that we used in the study were about topics in science; thus, we also constructed a “Scientist Knowledge Test” that was modeled after the Author Recognition Test (Stanovich & West, 1989). Participants were asked to distinguish the names of scientists from foils. Fifty scientists were drawn from a list of those who had received a Nobel Prize in science. Fifty foils were created by drawing names from the National Academy of Sciences, at random. The foils were scientists, but we did not expect them to have the same name-recognition as the Nobel Prize winners. Similar measures have been constructed by Long and colleagues to assess knowledge in science-fiction domains (Long & Prat, 2002; Long et al., 2006). Participants were told to respond only if they were sure that the name belonged to a scientist in order to discourage guessing. Two measures of reading frequency were included: (1) the Author Recognition Test (Stanovich & West, 1989) – Participants were asked to distinguish real author names from foils. Fifty authors (80% fiction, 20% non-fiction) were drawn from a list of those who had appeared on the *New York Times* Best Seller List for at least one month during the preceding 12 months. Fifty foils were created by drawing names from the editorial boards of experimental psychology journals. Participants were told to respond to the name only if they were sure that the name was an author in order to discourage guessing; (2) The Reading Habits Questionnaire (Scales & Rhee, 2001) – Participants completed a questionnaire consisting of 37 items that assessed how often participants read, what genres that they prefer to read, their self-perceived level of reading skill, their behavior while reading (e.g., “How often do you look up the definition of a word that you don’t know?”). We included participants’ responses to the item “How often do you read?” (5-point scale from “Never” to “Very Often”) as a measure of reading frequency.

Results

Two-hundred and seventy-four participants (77%) completed all sessions. Almost all of the remaining participants completed at least half of the sessions. The analyses below confirmed that the data were missing at random (i.e., there was no systematic pattern to the data that were missing). For those tasks in which we collected latency data, outliers were identified by computing a mean and SD for each participant. Outliers were defined as latencies that were three SDs above or below the participant’s mean and were deleted from the data set. Accuracy on the reaction time tasks was very high, ranging from 92% to 97% across tasks. Accuracy on these tasks did not correlate with performance on any other task; thus, only the reaction-time data were analyzed further. Descriptive statistics and correlations among the variables are reported in Tables 1 and 2, respectively. Accuracy data is reported in proportions to facilitate comparison across tasks. It is important to note that many of the measures were significantly correlated with each other and with one or both of the comprehension tests.

Factor Analysis

All measures except the comprehension ones were factor analyzed using a principal components analysis (PCA) method of extraction, with orthogonal rotation (Varimax). The purpose of the factor analysis was to identify the individual-difference measures that corresponded to the theoretical constructs that were described in the introduction and to reduce the number of constructs to a set that would be manageable in the SEMs. In our initial analysis, we identified nine factors. The measures loaded onto our hypothesized factors with three exceptions: the Go/No-Go measure loaded with the word-decoding measures, the phoneme transposition measure failed to load highly on any factor, and the pattern comparison task did not load with other measures of perceptual speed. We then dropped these measures from the dataset and reanalyzed the data.

The component matrix for the remaining measures is reported in Table 3. The Kaiser-Meyer-Olkin measure verified the sampling adequacy of the analysis, KMO = 0.825. Bartlett's test of sphericity, χ^2 (325) = 1791.110, $p < .001$, indicated that correlations among variables were appropriate for PCA. Seven components were extracted, accounting for 61.73% of variance in the data. The factor loadings generally corresponded to hypothesized relations among the variables in our battery of tests. All span tasks loaded on a factor that we labeled WMC. Raven's Matrices and the general reasoning tasks from the Ekstrom Battery loaded onto a factor that we labeled reasoning. All perceptual speed tests, except pattern comparison (see above), loaded onto a factor that we labeled perceptual speed. The phonological awareness measures were dropped for the reasons described above and all of the word decoding measures loaded on a single factor that we called decoding. The measures of verbal fluency from the Ekstrom Kit loaded on a factor that we called fluency. Stroop Interference loaded onto its own factor. As we mentioned above, the Go/No-Go Task was dropped because it loaded with the decoding measures. As a consequence, Stroop Interference was entered into the SEM as a single measure instead of a latent variable. We labeled this variable inhibition. We had anticipated separate factors for measures of vocabulary, background knowledge, and print exposure; however, all of these measures loaded on a single factor. The factor appears to assess knowledge about words and the world that correlates with general language experience. We labeled this factor language experience.

Structural Equation Model

Full Model (Model 1)—We constructed a model with the seven predictor variables that we identified in the factor analysis. Comprehension was a latent variable consisting of the Nelson- Denny and Investigator-Generated Tests. The factor loadings are shown in Figure 1. Paths were removed from the model following a backward-building procedure. Each predictor was allowed a unique regression path to comprehension. All predictors were allowed to covary. The final model, Model 1, appears in Figure 2. Model testing statistics for the procedure appear in the supplementary materials, Tables 4–7. The tables include change in model misfit, measurement-model factor loadings, factor variances and unique variances, and standardized covariance path weights. The model was an adequate fit to the data (N = 346 with 134 patterns of missing data; $\chi^2(333) = 542.882$, $p < 0.001$; CFI = 0.913; TLI = 0.901; RMSEA = 0.043; 90% confidence interval [0.036 – 0.049]). The data were missing at random in all models; thus, missing data were estimated in the analyses.

The latent variables accounted for 76.68% of variance in comprehension. Only two of the variables had direct effects: language experience ($\beta = 8.44$, $SE = 0.002$, $p < 0.001$) and reasoning ($\beta = 3.43$, $SE = 0.001$, $p = 0.001$). Higher reasoning and greater language experience were associated with better comprehension. All other variables had indirect effects on comprehension via their covariance with reasoning and/or language experience. As we predicted, the covariances were substantial and in the expected directions. Faster decoding was associated with greater language experience, faster perceptual speed, and greater fluency. Decoding covaried positively with inhibition, indicating that slower decoding was associated with more Stroop interference when participants had to suppress a word meaning to name an incongruent font color. Higher WMC was associated with greater language experience, higher reasoning, faster perceptual speed, and greater fluency. Language experience was positively associated with reasoning, perceptual speed, and fluency. Language experience covaried negatively with inhibition, such that greater language experience was associated with less Stroop interference. Higher reasoning was associated with faster perceptual speed and greater fluency. Perceptual speed also covaried positively with fluency such that faster speed was associated with greater fluency. Perceptual speed covaried negatively with inhibition, such that faster speed was associated with less inhibition.

Models of Path Stability and Alternative Sets of Latent Variables

An important goal in this study was to examine how changes in the dataset affect direct and indirect relations between predictors and comprehension. This goal is critical for two reasons: (1) to ensure that the direct paths in the model are robust to changes in the particular set of predictor variables that were included in the study and (2) to understand how explained variance shifts from one latent variable to another when measures are deleted from the models. We addressed this goal in two types of analyses. In one type (model-reduced analyses), we examined how the direct paths changed as we deleted the latent variables that had indirect effects. This enabled us to determine the extent to which the indirect effects contributed to the amount of variance explained by the variables with direct effects and to determine whether the direct effects remained stable in the absence of other variables. In the second type of analysis, we examined the pattern of direct and indirect effects on comprehension when a latent variable with a direct path to it (language experience, reasoning, or both) was removed from the model. This analysis allowed us to examine the importance of those variables with indirect effects and provided potential explanations for why previous studies have reported inconsistent results with respect to relations among decoding, vocabulary, WMC, and comprehension.

Stability of the Direct Paths in Model 1 (Model 1-Reduced)—Model 1-Reduced was constructed to test random path coefficients against fixed path coefficients by including only those factors from Model 1 that had a direct effect on comprehension: language experience and reasoning. The covariance paths among individual-difference variables were included as per their relations in Model 1. Their path weights were allowed to vary at random in each model. Latent variables that indirectly affected comprehension were removed systematically from the data set according to the number and weights of their covariance paths. As each latent variable was removed, the regression paths were backward-built until only the significant paths remained. In all iterations, the only direct paths were from reasoning and language experience to comprehension. As the regression weights were allowed to vary at random in the models, we ran each model again and fixed the regression weights for reasoning and language experience to those that we had obtained in Model 1. The change in model misfit between the random- and fixed-coefficient models was tested to determine the stability of the paths. The results revealed that the paths remained stable with no increase in model misfit across the model-reduction process; thus, we report only the fixed regression paths. Model testing statistics appear in the supplementary materials, Tables 5–8. The tables include measurement-model factor loadings, factor variances and unique variances, standardized covariance path weights, and change in model misfit. The final model, with only reasoning and language experience, is depicted in Figure 3, Panel A. The paths accounted for 76.01% of the variance in comprehension. The model was an good fit to the data (N = 345, with 76 patterns of missing data; $\chi^2(64) = 114.482$, $p < 0.001$; CFI = 0.967; TLI = 0.960; RMSEA = 0.048; 90% confidence interval [0.033 – 0.062]).

SEM Model without Language Experience: Model 2—Model 2 was constructed to determine how variance in comprehension was apportioned by removing language experience from the model. This allowed us to determine the significance of decoding in the absence of covariation with knowledge about words. The SEM was backward-built following the same procedure as in Model 1. The final model appears in Figure 4. Model testing statistics for the procedure appear in the supplementary materials, Tables 9–12. The tables include change in model misfit, measurement-model factor loadings, factor variances and unique variances, and standardized covariance path weights. The covariance paths among the remaining latent variables generally replicated those found in Model 1. In the absence of language experience, decoding had a direct effect on comprehension ($\beta = -4.81$, $SE = 0.06$, $p < 0.001$). The path between reasoning and comprehension remained significant ($\beta = 5.28$, $SE = 0.002$, $p < 0.001$). The latent variables accounted for 52.82% of the variance. The model fit the data adequately (N = 330, with 99 patterns of missing data; $\chi^2(178)$ = 295.049, $p < 0.001$; CFI - 0.913; TLI = 0.897; RMSEA = 0.045; 90% confidence interval [0.035 – 0.054]).

Stability of the Direct Paths in Model 2 (Model 2-Reduced)—Model 2-Reduced was constructed to test random path coefficients against fixed path coefficients by reducing the factors from Model 2 to those that had direct effects on comprehension, as we did in Model 1- Reduced. The change in model misfit between the random- and fixed-coefficient models was tested to determine the stability of the paths. The paths remained stable with no increase in model misfit across the factor-reduction process. Model testing statistics appear in the supplementary materials, Tables 10–13. The tables include measurement-model factor loadings, factor variances and unique variances, standardized covariance path weights, and changes in model misfit. Decoding and reasoning did not covary and both significantly predicted comprehension, accounting for 50.86% of the variance. The final model, depicted in Figure 3, Panel B, was a good fit to the data (N = 327, with 66 patterns of missing data; $\chi^2(27) = 48.293$, $p = 0.007$; CFI = 0.968; TLI = 0.958; RMSEA = 0.049; 90% confidence interval [0.025 – 0.071]).

SEM Model without Reasoning: Model 3—In Model 3, Reasoning was removed from the data set. The final model appears in Figure 5. Model testing statistics for the procedure are located in the supplementary materials, Tables 14–17. The tables include change in model misfit, measurement-model factor loadings, factor variances and unique variances, and standardized covariance path weights. The covariance paths among the remaining latent variables generally replicated those in Model 1. In the absence of reasoning, WMC (β = 2.85, *SE* = 0.001, $p = 0.004$) and language experience (β = 8.81, *SE* = 0.002, $p < 0.001$) had direct effects on comprehension, accounting for 73.77% of the variance. The model was an adequate fit to the data (N = 346, with 132 patterns of missing data; $\chi^2(239) = 390.634$, $p < 0.001$; CFI = 0.917; TLI = 0.904; RMSEA = 0.043; 90% confidence interval [0.035 – 0.050]).

Stability of the Direct Paths in Model 3: Model 3-Reduced—Model 3-Reduced was constructed to test random path coefficients against fixed path coefficients by reducing the factors from Model 3 to those with direct effects on comprehension. The change in model misfit between the random- and fixed-coefficient models was tested to determine the stability of the paths. Model testing statistics appear in the supplementary materials, Tables 15–18. The tables include measurement-model factor loadings, factor variances and unique variances, standardized covariance path weights, and changes in model misfit. The paths remained stable with no increase in model misfit across the factor-reduction process. Language experience and WMC covaried positively and significantly predicted 74.51% of the variance in comprehension. The final model, shown in Figure 3, Panel C, was good fit to the data (N = 345, with 80 patterns of missing data; $\chi^2(64) = 126.315$, $p < 0.001$; CFI = 0.950; TLI = 0.940; RMSEA = 0.053, 90% confidence interval [0.039 – 0.067]).

SEM Model without Language Experience and Reasoning Model 4—In Model 4, both language experience and reasoning were removed from the data set. The final model appears in Figure 6. Model testing statistics for the procedure appear in the supplementary materials, Tables 19–22. The tables include changes in model misfit, measurement-model factor loadings, factor variances and unique variances, and standardized covariance path weights. The covariance paths among the remaining latent variables generally replicated those in Model 1. In the absence of language experience and reasoning, decoding had a significant effect on comprehension (β = −4.39, *SE* = 0.07, $p < 0.001$), replicating the pattern that we found in Model 2, and WMC had a direct effect (β = 4.02, *SE* = 0.001, $p < 0.001$), as we observed in Model 3. The latent variables together accounted for 44.30% of the variance. The model was a barely adequate fit to the data (N = 329, with 84 patterns of missing data; $\chi^2(111) = 199.140$, $p < 0.001$; CFI = 0.888; TLI = 0.863; RMSEA = 0.049; 90% confidence interval [0.038 – 0.060]).

Stability of the Direct Paths in Model 4: Model 4-Reduced—Model 4-Reduced was built to test random path coefficients against fixed path coefficients by reducing the factors in Model 4 to those that had direct effects on comprehension. The change in model misfit between the random- and fixed-coefficient models was tested to determine the stability of the paths. The paths remained stable with no increase in model misfit across the model-reduction process. Model testing statistics appear in the supplementary materials, Tables 20–23. The tables include measurement-model factor loadings, factor variances and unique variances, standardized covariance path weights, and changes in model misfit. In the final model, shown in Figure 3, Panel D, decoding and WMC did not covary and accounted for 43.23% of the variance in Comprehension. The model was a poor fit to the data (N = 326, with 49 patterns of missing data; $\chi^2(27) = 90.357$, $p < 0.001$; CFI = 0.847; TLI = 0.796; RMSEA = 0.085; 90% confidence interval [0.066 – 0.104]).

SEM model with only Language Experience and Decoding: Model 5—Our final model was constructed to examine the relations among vocabulary, decoding, and comprehension. Braze et al. (2007) conducted regression analyses of comprehension in young adults (16–24 years old) and found no effect of decoding on comprehension when vocabulary was included in the analyses. In contrast, Braze et al. (2016) used SEM to investigate the relations in a sample of adolescent and community college readers and found a direct effect of both decoding and vocabulary on comprehension. We conducted the same analysis in our sample of community college and university students.

The model was constructed using the procedures described above. The measurement model is shown in Figure 7, Panel A, and the final model is shown in Figure 7, Panel B. Model testing statistics for the procedure appear in the supplementary materials, Tables 24–27. The model was a good fit to the data (N = 331 with 59 patterns of missing data; $\chi^2(18) = 46.497$, $p < 0.001$; CFI = 0.96; TLI = 0.937; RMSEA = 0.069; 90% confidence interval [0.045 – 0.094]). The latent variables accounted for 71.74% of variance in comprehension. Only vocabulary had a direct effect ($\beta = 8.04$, $SE = 0.002$, $p < 0.001$). Faster decoding was predictive of higher vocabulary and higher vocabulary was predictive of better comprehension.

Discussion

Previous research has identified numerous variables that are predictive of comprehension in proficient readers. Most of this research has been relatively small in scale, examining only a few variables at a time. This is problematic because researchers often operate under the assumption that the variables they study are uniquely predictive of comprehension. This assumption can lead to the development of theories that overstate the contribution of a variable to comprehension, as we believe has been the case with WMC. We addressed this gap in the literature by examining direct and indirect influences of language-specific abilities (e.g., word decoding, vocabulary) and domain-general ones (e.g., WMC, general reasoning) on reading comprehension. We also examined how these relations change depending on the set of measures included in the analysis. We used an SEM framework that allowed us to assess the influence of latent variables on comprehension in light of their covariance with other variables. Our results have implications for evaluating theories about the roles of lexical abilities and WMC in comprehension, for understanding inconsistent outcomes in previous research, and for selecting measures of individual differences in future studies of variation in adult comprehension.

We selected tasks for the study from among those that have been used in previous studies of comprehension in proficient readers. In addition, we included some tasks that have received substantial attention in empirical studies of cognition in children and older adults, but have received much less attention in the literature on adult reading comprehension, such as general reasoning and perceptual speed. As expected, these measures were correlated with each other as strongly as they were with comprehension. Our factor analyses revealed a pattern of loadings that generally corresponded to the set of constructs that we discussed in the introduction. Importantly, we found that decoding measures loaded on a factor separate from our vocabulary measures, allowing us to assess the unique contribution of decoding to comprehension in proficient readers. In addition, our WMC measures loaded on a factor separate from other domain-general abilities, such as general reasoning and perceptual speed, allowing us to examine predictions about the direct and indirect effects of WMC on comprehension. Not all of our measures loaded as expected, however. We failed to find separate factors for vocabulary, print exposure, and background knowledge. Although we had hypothesized separate factors, we were not surprised to find that these measures loaded on a single one. Our vocabulary measures were normed for a university population and print exposure is the primary means by which an advanced vocabulary is acquired. In addition, our measures of background knowledge—Cultural Literacy and Scientist Recognition—assessed general world knowledge more than they assessed knowledge about domain-specific topics that were relevant to our texts. General world knowledge, like vocabulary, is enhanced by substantial print exposure.

The focus of our SEM analyses was to identify those latent variables that were directly predictive of comprehension. The seven individual-difference variables in Model 1 accounted for 77% of the variance in comprehension. Of the seven variables, only two had significant direct paths: language experience and reasoning. Comprehension scores increased as performance on language experience and reasoning tasks increased. The direct paths were stable and did not depend on the presence of other latent variables in the model. When we systematically deleted measures from the dataset, we found that the paths from language experience and reasoning remained significant. The fact that language experience and reasoning directly predicted comprehension is not surprising; we included vocabulary in the study because it is so strongly predictive of comprehension in both children and adults and we included general reasoning because all complex cognitive tasks correlate with reasoning measures, such as IQ, to a significant extent. The surprise in this study is that only language experience and reasoning had direct effects. Given the substantial literature identifying other variables, such as WMC and decoding, as significant contributors to comprehension, we had expected direct paths from these variables as well. Indeed, language experience and reasoning alone accounted for as much variance in comprehension (76%) as did the full set of measures (77%).

The pattern of direct and indirect effects in Model 1 has important implications for evaluating theories about the role of WMC in comprehension. As we described in the introduction, a direct path from WMC to comprehension is predicted by the Capacity Theory and the SSIR Theory, whereas the connectionist-based framework and the LTWM theory predict an indirect path via shared variance between measures of WMC and language experience. In Model 1, we found that WMC affected comprehension indirectly via shared variance with other latent variables, in particular, language experience, reasoning, and fluency. The indirect effect is consistent with previous research using an SEM framework by Britton and colleagues (1998), but inconsistent with findings by Hannon (2006).

Subsequent analyses were informative about the nature of the relations among WMC language experience and comprehension. In Model 3 and Model 3-Reduced, measures of general reasoning were deleted from the dataset. In the absence of a reasoning variable, the path from WMC to comprehension was significant (Model 3). The path was stable in that removing additional latent variables from the dataset did not affect model fit. Language experience and WMC alone accounted for approximately the same amount of variance that was explained in the full model (74%). The indirect relation between WMC and comprehension and the strong covariance between WMC and language experience is consistent with the connectionist-based framework and LTWM theory. Interestingly, however, eliminating language experience measures from the dataset (Model 2) did not result in a significant path from WMC to comprehension as might be expected given predictions from these accounts. Instead, WMC had a significant direct path only when measures related to reasoning were eliminated from the dataset (Model 3). Thus, the covariance between WMC and reasoning appears to be more important in explaining the correlation between WM span and comprehension than is the covariance between WMC and language experience, a finding that is somewhat problematic for these latter two models. A more parsimonious account of our data is that WMC is mostly secondary to reasoning, even though it has indirect paths through both reasoning and language experience. Individuals perform well on span tasks because they are high on reasoning and they perform well on comprehension tests because they are high on reasoning and language experience. This account goes somewhat further than the connectionist-based and LTWM in diminishing the theoretical importance of WMC in explaining individual variation in adult reading comprehension.

Our failure to find a direct effect of WMC on comprehension is significant given that WMC is among the most studied individual-difference variables in proficient adult readers. Much of this research, however, has been conducted using on-line measures of processing rather than off-line comprehension measures, as we did in this study. This raises an important question: does WMC have a direct effect on on-line processing measures such as reading time, eye fixations, and ERPs? A recent study by Van Dyke and colleagues suggest that the answer to this question may be no (Van Dyke, Johns, & Kukona, 2014). They analyzed reading times and recall as a function of several variables, including IQ, WMC, and vocabulary. Importantly, they showed that WMC had no effect on reading time in an analysis accounting for shared variance between WMC and IQ. Although Van Dyke et al. found no unique effect of WMC on reading times, aspects of their design prevented them from entering all variables in a single model and their sample size was relatively small. Thus, an important goal of future research should be to examine the direct and indirect effects of WMC on on-line measures when general reasoning is included in the models. The results of such studies may lead to a change in the emphasis placed on WMC in research on on-line language processing. This change may be warranted even if WMC is found to have a significant direct effect on on-line measures. It is reasonable to ask whether WMC should be the focus of so much individual-difference research when it has no ultimate effect on comprehension. Rather, it may be more worthwhile to understand how low-capacity readers compensate such that their overall comprehension is unaffected. At minimum, researchers who use span measures to predict on-line processing should acknowledge that evidence for a direct effect of WMC on comprehension is scant and should interpret their results accordingly.

Our results highlight the importance of understanding why WM span measures are correlated with general reasoning tasks (Shipstead, Redick, Hicks, & Engle). Several studies have examined the relation between WMC and measures of fluid intelligence, such as Raven's Matrices and concluded that attentional control plays a significant role in the correlation (Engle & Kane, 2004), but is probably not solely responsible for it (Harrison, Shipstead, & Engle, 2014; Shipstead, Harrison, & Engle, 2015; Unsworth & Spillers, 2010). The strong correlation between WMC and fluid intelligence makes it important to find situations in which the measures dissociate. Our results suggest that reading comprehension is one of these situations and that it may be fruitful to conduct studies to exploit this dissociation by manipulating text properties that differentially strengthen the relations among comprehension, WMC, and general reasoning.

The pattern of direct and indirect effects also has implications for evaluating the role of decoding in comprehension among proficient readers and for explaining why word decoding effects have been small or non-significant in studies that have included measures of both decoding and vocabulary (Bell & Perfetti, 1994; Braze et al., 2007; Cromley et al., 2010; Landi, 2010; Macaruso & Shankweiler, 2010). When measures of language experience were deleted from our dataset (Models 2 and 4), the decrease in explained variance was substantial, from 77% in the full model (Model 1) to 53% in Model 2 and 44% in Model 4. In Model 5, we examined the influence of decoding and vocabulary alone, similar to the analyses conducted by Braze et al. (2016) in their study of adolescent and community college participants. We found that only vocabulary had a direct effect; moreover, the amount of variance explained by vocabulary alone was 72% compared to the 76% that was explained by language experience and reasoning (Model 1-Reduced). This finding goes well beyond previous research in highlighting the importance of word knowledge in explaining adult reading comprehension and is likely to explain why reading comprehension in older adults is relatively unimpaired even when they exhibit significant deficits in general cognitive ability. Our finding is also consistent with Braze et al.'s suggestion that the influence of decoding on comprehension probably diminishes with reading expertise (see also, Protopapas, Mouzaki, Sideridis, Kotosolakou, & Simos, 2013). Thus, the Simple View of Reading in which decoding plays a large role is most appropriate as a model of comprehension in children; the direct influence of decoding on comprehension declines significantly in adolescent readers and disappears in the most proficient adult readers. Although proficient readers differ in their decoding abilities, slow decoding impairs comprehension primarily because it is associated with limitations in vocabulary.

The significance of language experience (and more specifically, vocabulary) in this study suggests that more research should be directed at understanding precisely how knowledge about words affects comprehension. Obviously, comprehension will be impaired to the extent that a text contains words that a reader does not know. Among proficient readers, however, the influence of word knowledge is likely to be more subtle and more interesting (Adolf, Frishkoff, Dandy, & Perfetti, 2016; Adelman, Brown, & Quesada, 2006; Durso & Shore, 1991). Knowledge about words is not all-or-none and proficient readers are likely to have at least some knowledge about most of the words that they encounter. Subtle variations in word meanings, however, can have significant consequences for comprehension. Thus, it is important to understand how the depth of a reader's vocabulary affects comprehension. One possibility is that knowledge about words facilitates a reader's ability to make predictions about upcoming words. Recent advances in computational psycholinguistics have contributed to the development of metrics (e.g., surprisal, entropy) that quantify the likelihood that words will appear in very specific contexts. High vocabulary readers are likely to have more knowledge than low vocabulary ones about how words are used across contexts and may be better at predicting subsequent words (Kuperman & Van Dyke, 2011, 2013). This knowledge may be important in processing incoming words even if the words themselves are not predictable in context. Boudewyn, Long, and Swaab (2015) examined the processing of nouns (e.g., cake) that were plausible in context, but had low cloze probabilities in their specific contexts. They found that semantic features of the word that were relevant to the context (e.g., sweet) were activated before the word was received, even when that word could not be predicted. The ability to predict context-relevant features of subsequent words would mean that high vocabulary readers could integrate incoming words much faster than other readers.

The results of our study must be interpreted in light of several limitations. One limitation involves the large number of parameters that were estimated in our full model. This raises a concern about whether some paths in our model would have been significant with more power. This concern is partially addressed in our Model-Reduced analyses, in which we deleted measures from our data set, decreasing the number of latent variables. Removing these variables from the model reduced the number of parameters to be estimated, but did not reduce the number of participants. Importantly, these analyses did not yield an increase in the number of significant paths that we detected. A second limitation is that we were unable to create a latent variable for inhibition/suppression ability. We lost one measure of inhibition due to a programming error and another loaded with decoding measures in our factor analyses. Our remaining measure, Stroop Interference, covaried with our latent variables in the manner that we hypothesized, but the direct path to comprehension was not significant. This result may change if inhibition is assessed as a latent construct from multiple measures. Finally, the outcome of an SEM is strongly dependent on the inter-correlations among variables; thus, outcomes can change when variables are added or deleted. We demonstrated this when we conducted analyses in which we eliminated measures of language experience and general reasoning. Our full model contained the variables that we hypothesized were most likely to be predictive of comprehension, but numerous other abilities are likely to play a role. Further research will be necessary to determine whether our pattern of findings hold when other language and cognitive abilities are assessed.

Conclusions

The results of the current study have both practical and theoretical significance. Practically, our results offer information about the identification of struggling readers and the design of effective remediation. Our results showed that language experience, as assessed by vocabulary tests, is a robust means of identifying poor comprehenders. Importantly, research has shown that vocabulary knowledge is particularly amenable to training (Coyne, McCoach, & Sharon, 2007; Roberts, Torgesen, Boardman, & Scammacca, 2008; Scammacca, Roberts, Vaugh, & Stuebing, 2015). Further research should be directed in understanding how readers learn and use subtle distinctions of word meanings as they develop their mental representations of texts. Theoretically, our results contribute to understanding the complex correlations among individual-difference variables and reading comprehension. We have shown that proficient adult readers vary substantially in their decoding ability, but the variance in decoding is secondary to language experience in predicting individual differences in reading comprehension. In addition, our results raise significant concerns about the unique role of WMC in comprehension, suggesting that its contribution is secondary to general reasoning ability.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Appendix

Table 4

Change in misfit for the full model (Model 1) as measured by χ^2 during backward-building.

Path Removed	df	χ^2	Δ df	Δ χ^2	*p* of Δ χ^2
None	323	528.629	-	-	-
WMC ↔ Inhibition	324	528.654	1	0.025	0.8744
Fluency ↔ Inhibition	325	529.826	1	1.172	0.2790
Decoding ↔ Reasoning	326	531.733	1	1.907	0.1673
Reasoning ↔ Inhibition	327	533.066	1	1.333	0.2483
Decoding ↔ WMC	328	535.291	1	2.225	0.1358
Inhibition → Comprehension	329	535.298	1	0.007	0.9333
Perceptual Speed → Comprehension	330	535.446	1	0.148	0.7004
Fluency → Comprehension	331	538.120	1	2.674	0.1020
Decoding → Comprehension	332	540.466	1	2.346	0.1256
WMC → Comprehension	333	542.882	1	2.416	0.1201

Notes: ↔ indicates a covariance path

→ indicates a regression path.

Table 5

Measurement-model factor loadings for the full model (Model 1) and the model with only Language Experience and General Reasoning (Model 1-Reduced).

Model	Factor	Variable	Estimate	Standard Error	Loading (z-score)
1	Decoding	Orthographic Decision	1.00	n/a	n/a
		Phonological Decision	9.06	1.52	5.94
		Non-word Naming	1.49	0.42	3.54
	WMC	Reading Span	1.00	n/a	n/a
		Alphabet Span	1.53	0.20	7.69
		Minus Span	2.38	0.34	6.94

Model	Factor	Variable	Estimate	Standard Error	Loading (z-score)
		Visual Number Span	0.12	0.02	4.96
	Language Experience	Author Recognition Test	1.00	n/a	n/a
		Reading Questionnaire	0.10	0.02	6.23
		Cultural Intelligence	3.04	0.27	11.05
		Scientist Recognition Test	0.79	0.11	7.52
		Extended Range Vocabulary	1.73	0.15	11.78
		Advanced Vocabulary	1.11	0.11	10.37
		Nelson-Denny Vocabulary	5.00	0.42	11.89
	Reasoning	Raven’s Progressive Matrices	1.00	n/a	n/a
		Arithmetic Aptitude Test	1.24	0.13	9.85
		Mathematic Aptitude Test	0.98	0.10	9.86
		Necessary Arithmetic Operations	1.05	0.11	9.41
	Perceptual Speed	Letter Comparison	1.00	n/a	n/a
		Finding As	2.30	0.43	5.37
		Number Comparison	0.71	0.15	4.79
		Identical Pictures	1.12	0.27	4.21
	Fluency	Word Beginnings	1.00	n/a	n/a
		Word Endings	0.88	0.11	8.33
		Word Beginnings & Endings	0.75	0.09	8.09
	Comprehension	Investigator-Generated	1.00	n/a	n/a
		Nelson-Denny	1.46	0.16	9.21
1-Reduced	Language Experience	Author Recognition Test	1.00	n/a	n/a
		Reading Questionnaire	0.11	0.02	6.74
		Cultural Intelligence	3.02	0.23	13.17
		Scientist Recognition Test	0.79	0.10	8.07
		Extended Range Vocabulary	1.72	0.12	14.52
		Advanced Vocabulary	1.10	0.09	12.14
		Nelson-Denny Vocabulary	4.93	0.33	14.71
	Reasoning	Raven’s Progressive Matrices	1.00	n/a	n/a
		Arithmetic Aptitude Test	1.29	0.13	9.89
		Mathematic Aptitude Test	1.03	0.10	9.96
		Necessary Arithmetic Operations	1.08	0.11	9.37
	Comprehension	Investigator-Generated	1.00	n/a	n/a
		Nelson-Denny	1.46	0.15	9.76

Table 6

Measurement-model factor variances and unique variances for the full model (Model 1) and the model with only Language Experience and General Reasoning (Model 1-Reduced).

Model	Factor	Factor Variance	Factor Variance (Std. Error)	Variable	Unique Variance	Unique Variance (Std. Error)
1	Decoding	0.01	0.002	Orthographic Decision	0.01	0.002
				Phonological Decision	0.49	0.12
				Non-word Naming	0.21	0.02
	WMC	30.79	5.87	Reading Span	35.00	4.53
				Alphabet Span	102.32	11.98
				Minus Span	394.64	41.03
				Visual Number Span	2.61	0.24
	Language Experience	11.68	1.95	Author Recognition Test	15.27	1.42
				Reading Questionnaire	0.79	0.06
				Cultural Intelligence	71.31	7.44
				Scientist Recognition Test	22.28	1.96
				Extended Range Vocabulary	14.51	1.68
				Advanced Vocabulary	12.82	1.27
				Nelson-Denny Vocabulary	102.28	12.95
	Reasoning	14.84	2.83	Raven’s Progressive Matrices	23.89	2.29
				Arithmetic Aptitude Test	11.38	1.45
				Mathematic Aptitude Test	6.69	0.90
				Necessary Arithmetic Operations	12.12	1.36
	Perceptual Speed	22.05	6.93	Letter Comparison	83.08	8.35
				Finding As	155.45	23.33
				Number Comparison	25.04	2.97
				Identical Pictures	147.38	14.57
	Fluency	32.31	5.34	Word Beginnings	28.38	3.97
				Word Endings	39.36	4.44
				Word Beginnings & Endings	28.92	3.16
	Inhibition Comprehension	−0.001	<0.001	Stroop Interference	0.01	0.001
				Investigator-Generated	0.003	0.001
				Nelson-Denny	0.01	0.002
1-Reduced	Language Experience	12.15	1.64	Author Recognition Test	15.11	1.40
				Reading Questionnaire	0.78	0.06
				Cultural Intelligence	71.21	7.49
				Scientist Recognition Test	22.26	1.96
				Extended Range Vocabulary	14.38	1.69
				Advanced Vocabulary	12.71	1.27
				Nelson-Denny Vocabulary	105.82	13.23
	Reasoning	13.89	2.66	Raven’s Progressive Matrices	24.86	2.34

Model	Factor	Factor Variance	Factor Variance (Std. Error)	Variable	Unique Variance	Unique Variance (Std. Error)
				Arithmetic Aptitude Test	11.09	1.47
				Mathematic Aptitude Test	6.17	0.91
				Necessary Arithmetic Operations	12.50	1.40
	Comprehension	0.001	<0.001	Investigator-Generated	0.003	0.001
				Nelson-Denny	0.014	0.002

Table 7

Co-variance path weights for the full model (Model 1) and the model with only Language Experience and General Reasoning (Model 1-Reduced).

Model	Factor	Co-varying with	Covariance (Estimate)	Covariance (Std. Error)	Covariance (z-score)	Covariance (*p*-value for z-score)
1	Decoding	WMC	-	-	-	-
		Language Experience	−0.10	0.02	−4.06	< 0.001
		Reasoning	-	-	-	-
		Perceptual Speed	−0.15	0.06	−2.77	0.006
		Fluency	−0.26	0.05	−4.84	< 0.001
	Inhibition WMC	Inhibition	0.002	0.001	2.63	0.009
		Language Experience	7.65	1.67	4.57	< 0.001
		Reasoning	12.57	2.25	5.59	< 0.001
		Perceptual Speed	5.67	2.57	2.20	0.027
		Fluency	14.01	2.90	4.83	< 0.001
		Inhibition	-	-	-	-
	Language Experience	Reasoning	5.80	1.11	5.24	< 0.001
		Perceptual Speed	3.14	1.48	2.13	0.033
		Fluency	10.68	1.80	5.94	< 0.001
		Inhibition	−0.04	0.02	−2.16	0.031
	Reasoning	Perceptual Speed	6.61	1.93	3.42	0.001
		Fluency	8.42	1.85	4.54	< 0.001
		Inhibition	-	-	-	-
	Perceptual Speed	Fluency	11.23	2.99	3.76	< 0.001
		Inhibition	−0.09	0.04	−2.18	0.029
	Fluency	Inhibition	-	-	-	-
1-Reduced	Language Experience	Reasoning	5.98	1.06	5.66	< 0.001

Table 8

Change in misfit for the model with only Language Experience and Reasoning (Model 1-Reduced) as latent variables were deleted from the dataset (measured by χ^2 during backward-building).

	β allowed to vary at random			β fixed to weight in Model 1					
Variable Removed	**df**	χ^2	**% R**	**df**	χ^2	**% R**	**Δ df**	**Δ χ^2**	***p* of Δ χ^2**
None	333	542.882	76.68	-	-	-	-	-	-
Inhibition	309	495.657	76.51	311	495.731	76.29	2	0.074	0.9637
Decoding	240	398.179	76.56	242	398.314	76.32	2	0.135	0.9347
WMC	162	263.777	76.19	164	263.848	75.99	2	0.071	0.9651
Perceptual Speed	99	156.281	76.10	101	156.349	75.90	2	0.068	0.9666
Fluency	62	114.411	76.13	64	114.482	76.01	2	0.071	0.9651

Table 9

Change in misfit for the model without Language Experience (Model 2) as measured by χ^2 during backward-building.

Path Removed	**df**	χ^2	**Δ df**	**Δ χ^2**	***p* of Δ χ^2**
None	169	283.680	-	-	-
WMC ↔ Inhibition	170	283.700	1	0.020	0.8875
Fluency ↔ Inhibition	171	284.518	1	0.818	0.3658
Reasoning ↔ Inhibition	172	286.320	1	1.802	0.1795
Decoding ↔ Reasoning	173	287.849	1	1.529	0.2163
Decoding ↔ WMC	174	289.953	1	2.104	0.1469
Fluency → Comprehension	175	289.988	1	0.035	0.8516
Perceptual Speed → Comprehension	176	290.372	1	0.384	0.5355
Inhibition → Comprehension	177	291.375	1	1.003	0.3166
WMC → Comprehension	178	295.049	1	3.674	0.0553

Notes: ↔ indicates a covariance path

→ indicates a regression path

Table 10

Measurement-model factor loadings for the model without Language Experience (Model 2) and the reduced model with only Decoding and Reasoning (Model 2-Reduced).

Model	**Factor**	**Variable**	**Estimate**	**Standard Error**	**Loading (z-score)**
2	Decoding	Orthographic Decision	1.00	n/a	n/a
		Phonological Decision	9.50	1.44	6.58
		Non-word Naming	1.51	0.42	3.58
	WMC	Reading Span	1.00	n/a	n/a
		Alphabet Span	1.54	0.20	7.61
		Minus Span	2.49	0.36	6.94

Model	Factor	Variable	Estimate	Standard Error	Loading (z-score)
		Visual Number Span	0.13	0.02	5.17
	Reasoning	Raven's Progressive Matrices	1.00	n/a	n/a
		Arithmetic Aptitude Test	1.23	0.12	9.90
		Mathematic Aptitude Test	0.97	0.10	9.90
		Necessary Arithmetic Operations	1.04	0.11	9.46
	Perceptual	Letter Comparison	1.00	n/a	n/a
	Speed	Finding As	2.29	0.43	5.33
		Number Comparison	0.67	0.13	4.99
		Identical Pictures	1.12	0.26	4.29
	Fluency	Word Beginnings	1.00	n/a	n/a
		Word Endings	0.93	0.11	8.24
		Word Beginnings & Endings	0.76	0.10	7.84
	Comprehension	Investigator-Generated	1.00	n/a	n/a
		Nelson-Denny	2.02	0.30	6.75
2-Reduced	Decoding	Orthographic Decision	1.00	n/a	n/a
		Phonological Decision	9.74	1.73	5.63
		Non-word Naming	1.58	0.43	3.68
	Reasoning	Raven's Progressive Matrices	1.00	n/a	n/a
		Arithmetic Aptitude Test	1.28	0.12	10.30
		Mathematic Aptitude Test	1.03	0.10	10.43
		Necessary Arithmetic Operations	1.07	0.11	9.81
	Comprehension	Investigator-Generated	1.00	n/a	n/a
		Nelson-Denny	2.14	0.25	8.63

Table 11

Measurement-model factor variances and unique variances for the model without Language Experience (Model 2) and the model with only Decoding and Reasoning (Model 2-Reduced).

Model	Factor	Factor Variance	Factor Variance (Std. Error)	Variable	Unique Variance	Unique Variance (Std. Error)
2	Decoding	0.01	0.002	Orthographic Decision	0.01	0.002
				Phonological Decision	0.46	0.11
				Non-word Naming	0.21	0.02
	WMC	29.54	5.77	Reading Span	36.13	4.55
				Alphabet Span	104.45	12.10
				Minus Span	386.60	40.95
				Visual Number Span	2.56	0.24
	Reasoning	15.04	2.85	Raven's Progressive Matrices	23.70	2.28
				Arithmetic Aptitude Test	11.40	1.45
				Mathematic Aptitude Test	6.78	0.90

Model	Factor	Factor Variance	Factor Variance (Std. Error)	Variable	Unique Variance	Unique Variance (Std. Error)
				Necessary Arithmetic Operations	12.18	1.36
	Perceptual Speed	23.14	7.06	Letter Comparison	82.00	8.31
				Finding As	151.05	23.40
				Number Comparison	26.09	2.83
				Identical Pictures	146.20	14.56
	Fluency	31.19	5.35	Word Beginnings	29.50	4.12
				Word Endings	37.33	4.46
				Word Beginnings & Endings	29.11	3.22
	Comprehension	0.002	<0.001	Investigator-Generated	0.005	0.001
				Nelson-Denny	0.01	0.002
	Inhibition	-		Stroop Interference	0.01	0.001
2-Reduced	Decoding	0.01	0.002	Orthographic Decision	0.01	0.002
				Phonological Decision	0.44	0.15
				Non-word Naming	0.21	0.02
	Reasoning	13.96	2.53	Raven’s Progressive Matrices	24.61	2.33
				Arithmetic Aptitude Test	11.03	1.48
				Mathematic Aptitude Test	6.14	0.91
				Necessary Arithmetic Operations	12.73	1.41
	Comprehension	0.002	<0.001	Investigator-Generated	0.005	0.001
				Nelson-Denny	0.01	0.002

Table 12

Co-variance path weights for the model without Language Experience (Model 2).

Model	Factor	Co-varying with	Covariance (Estimate)	Covariance (Std. Error)	Covariance (z-score)	Covariance (*p*-value for z-score)
2	Decoding	WMC	-	-	-	-
		Reasoning	-	-	-	-
		Perceptual Speed	−0.15	0.05	−2.81	0.005
		Fluency	−0.26	0.05	−4.90	<0.001
		Inhibition	0.002	0.001	2.93	0.003
	WMC	Reasoning	12.54	2.25	5.58	<0.001
		Perceptual Speed	5.78	2.59	2.23	0.026
		Fluency	13.24	2.81	4.70	<0.001
		Inhibition	-	-	-	-
	Reasoning	Perceptual Speed	6.74	1.99	3.39	0.001
		Fluency	8.29	1.84	4.50	<0.001
		Inhibition	-	-	-	-
	Perceptual Speed	Fluency	11.20	2.98	3.76	<0.001
		Inhibition	−0.09	0.04	−2.11	0.035

Model	Factor	Co-varying with	Covariance (Estimate)	Covariance (Std. Error)	Covariance (z-score)	Covariance (*p*-value for z-score)
	Fluency	Inhibition	-	-	-	-

Note: The reduced model with only Decoding and Reasoning (Model 2-Reduced) contained no covariance paths.

Table 13

Change in misfit for the model with only Decoding and Reasoning (Model 2-Reduced) as latent variables were deleted from the dataset (measured by χ^2 during backward-building).

	β allowed to vary at random			β fixed to weight in Model 2					
Variable Removed	**df**	χ^2	**% R**	**df**	χ^2	**%R**	**Δ df**	**Δ** χ^2	***p* of Δ** χ^2
None	178	295.049	52.82	-	-	-	-	-	-
Inhibition	160	263.279	51.64	162	263.400	51.82	2	0.121	0.9413
WMC	97	137.995	50.80	99	138.032	51.06	2	0.037	0.9817
Fluency	61	96.763	48.68	63	97.243	52.48	2	0.480	0.7866
Perceptual Speed	25	48.290	50.61	27	48.293	50.86	2	0.003	0.9985

Table 14

Change in misfit for the model without Reasoning (Model 3) as measured by χ^2 during backward-building.

Path Removed	df	χ^2	Δ df	Δ χ^2	*p* of Δ χ^2
None	232	382.338	-	-	-
WMC ↔ Inhibition	233	382.369	1	0.031	0.8602
Fluency ↔ Inhibition	234	383.488	1	1.119	0.2901
Decoding ↔ WMC	235	386.437	1	2.949	0.0859
Inhibition → Comprehension	236	386.451	1	0.014	0.9058
Perceptual Speed → Comprehension	237	387.130	1	0.679	0.4099
Fluency → Comprehension	238	388.867	1	1.737	0.1875
Decoding → Comprehension	239	390.634	1	1.767	0.1837

Notes: ↔ indicates a covariance path

→ indicates a regression path

Table 15

Measurement-model factor loadings for the model without Reasoning (Model 3) and the reduced model with only Language Experience and WMC (Model 3-Reduced).

Model	Factor	Variable	Estimate	Standard Error	Loading (z-score)
3	Decoding	Orthographic Decision	1.00	n/a	n/a
		Phonological Decision	8.53	1.44	5.89
		Non-word Naming	1.49	0.41	3.60
	WMC	Reading Span	1.00	n/a	n/a
		Alphabet Span	1.44	0.20	7.26
		Minus Span	2.23	0.33	6.80

Model	Factor	Variable	Estimate	Standard Error	Loading (z-score)
		Visual Number Span	0.11	0.02	4.56
	Language Experience	Author Recognition Test	1.00	n/a	n/a
		Reading Questionnaire	0.10	0.02	6.32
		Cultural Intelligence	3.03	0.27	11.05
		Scientist Recognition Test	0.79	0.10	7.50
		Extended Range Vocabulary	1.11	0.15	11.81
		Advanced Vocabulary	4.99	0.11	10.40
		Nelson-Denny Vocabulary	3.58	0.42	11.90
	Perceptual Speed	Letter Comparison	1.00	n/a	n/a
		Finding As	2.57	0.50	5.17
		Number Comparison	0.67	0.14	4.84
		Identical Pictures	1.10	0.27	4.11
	Fluency	Word Beginnings	1.00	n/a	n/a
		Word Endings	0.87	0.10	8.27
		Word Beginnings & Endings	0.74	0.09	8.02
	Comprehension	Investigator-Generated	1.00	n/a	n/a
		Nelson-Denny	1.36	0.16	8.62
3-Reduced	WMC	Reading Span	1.00	n/a	n/a
		Alphabet Span	1.38	0.19	7.33
		Minus Span	2.19	0.32	6.89
		Visual Number Span	0.10	0.02	4.31
	Language Experience	Author Recognition Test	1.00	n/a	n/a
		Reading Questionnaire	0.11	0.02	6.83
		Cultural Intelligence	3.09	0.23	13.25
		Scientist Recognition Test	0.81	0.10	8.075
		Extended Range Vocabulary	1.76	0.12	14.69
		Advanced Vocabulary	1.13	0.10	12.26
		Nelson-Denny Vocabulary	5.04	0.34	14.86
	Comprehension	Investigator-Generated	1.00	n/a	n/a
		Nelson-Denny	1.31	0.14	9.15

Table 16

Measurement-model factor variances and unique variances for the model without Reasoning (Model 3) and the model with only Language Experience and WMC (Model 3-Reduced).

Model	Factor	Factor Variance	Factor Variance (Std. Error)	Variable	Unique Variance	Unique Variance (Std. Error)
3	Decoding	0.01	0.002	Orthographic Decision	0.01	0.002
				Phonological Decision	0.53	0.12
				Non-word Naming	0.21	0.02

Model	Factor	Factor Variance	Factor Variance (Std. Error)	Variable	Unique Variance	Unique Variance (Std. Error)
	WMC	33.77	6.28	Reading Span	31.76	4.79
				Alphabet Span	103.86	12.40
				Minus Span	400.82	41.48
				Visual Number Span	2.68	0.24
	Language Experience	11.82	1.97	Author Recognition Test	15.22	1.42
				Reading Questionnaire	0.78	0.06
				Cultural Intelligence	71.73	7.49
				Scientist Recognition Test	22.33	1.96
				Extended Range Vocabulary	14.45	1.68
				Advanced Vocabulary	12.74	1.27
				Nelson-Denny Vocabulary	102.79	13.04
	Perceptual Speed	21.49	6.86	Letter Comparison	84.05	8.33
				Finding As	132.95	25.02
				Number Comparison	26.73	2.88
				Identical Pictures	149.39	14.65
	Fluency	33.07	5.45	Word Beginnings	27.82	4.00
				Word Endings	39.66	4.46
				Word Beginnings & Endings	29.15	3.18
	Comprehension	0.001	<0.001	Investigator-Generated	0.003	0.001
				Nelson-Denny	0.01	0.002
	-	-		Stroop Inhibition	0.01	0.001
3-Reduced	WMC	35.28	6.18	Reading Span	29.93	4.73
				Alphabet Span	107.02	12.41
				Minus Span	400.79	41.39
				Visual Number Span	2.73	0.25
	Language Experience	11.54	1.53	Author Recognition Test	15.16	1.40
				Reading Questionnaire	0.78	0.06
				Cultural Intelligence	71.83	7.55
				Scientist Recognition Test	22.29	1.96
				Extended Range Vocabulary	14.25	1.69
				Advanced Vocabulary	12.68	1.27
				Nelson-Denny Vocabulary	106.593	13.32
	Comprehension	0.001	0.001	Investigator-Generated	0.003	0.001
				Nelson-Denny	0.01	0.002

Table 17

Co-variance path weights for the model without Reasoning (Model 3) and the reduced model with only Language Experience and WMC (Model 3-Reduced).

Model	Factor	Co-varying with	Covariance (Estimate)	Covariance (Std. Error)	Covariance (*z*-score)	Covariance (*p*-value for *z*-score)
3	Decoding	WMC	-	-	-	-
		Language Experience	−0.11	0.03	−3.98	<0.001
		Perceptual Speed	−0.16	0.06	−2.75	0.006
		Fluency	−0.28	0.06	−4.91	<0.001
		Inhibition	0.002	0.001	2.52	0.012
	WMC	Language Experience	7.72	1.71	4.52	<0.001
		Perceptual Speed	5.40	2.58	2.10	0.036
		Fluency	14.04	2.98	4.71	<0.001
		Inhibition	-	-	-	-
	Language Experience	Perceptual Speed	3.37	1.43	2.36	0.018
		Fluency	10.86	1.83	5.93	<0.001
		Inhibition	−0.05	0.02	−2.43	0.015
	Perceptual Speed	Fluency	11.25	3.00	3.75	<0.001
		Inhibition	−0.10	0.04	−2.50	0.013
	Fluency	Inhibition	-	-	-	-
3-Reduced	WMC	Language Experience	8.30	1.65	5.04	< 0.001

Table 18

Change in misfit for the model with only Language Experience and WMC (Model 3-Reduced) as latent variables were deleted from the dataset (measured by χ^2 during backward-building).

	β allowed to vary at random			β fixed to weight in Model 3					
Variable Removed	**df**	χ^2	**% R**	**df**	χ^2	**% R**	**Δ df**	$\Delta\chi^2$	***p* of** $\Delta\chi^2$
None	239	390.634	73.77		-	-	-	-	-
Inhibition	219	349.263	73.46	221	349.480	74.11	2	0.217	0.8972
Decoding	162	268.943	73.74	164	269.121	74.41	2	0.178	0.9148
Perceptual Speed	99	170.657	73.56	101	170.837	74.24	2	0.180	0.9139
Fluency	62	126.047	73.68	64	126.315	74.51	2	0.268	0.8746

Table 19

Change in misfit for the model without Language Experience and Reasoning (Model 4) as measured by χ^2 during backward-building.

Path Removed	df	χ^2	Δ df	$\Delta\chi^2$	*p* of $\Delta\chi^2$
None	105	193.566	-	-	-
WMC ↔ Inhibition	106	193.601	1	0.035	0.8516
Fluency ↔ Inhibition	107	194.351	1	0.750	0.3865
Decoding ↔ WMC	108	197.255	1	2.904	0.0884
Perceptual Speed → Comprehension	109	197.266	1	0.011	0.9165
Fluency → Comprehension	110	197.987	1	0.721	0.3958
Inhibition → Comprehension	111	199.140	1	1.153	0.2829

Notes: ↔ indicates a covariance path

→ indicates a regression path.

Table 20

Measurement-model factor loadings for the model without Language Experience and Reasoning (Model 4) and the reduced model with only Decoding and WMC (Model 4-Reduced).

Model	Factor	Variable	Estimate	Standard Error	Loading (z-score)
4	Decoding	Orthographic Decision	1.00	n/a	n/a
		Phonological Decision	8.94	1.35	6.63
		Non-word Naming	1.52	0.42	3.61
	WMC	Reading Span	1.00	n/a	n/a
		Alphabet Span	1.45	0.20	7.31
		Minus Span	2.28	0.34	6.79
		Visual Number Span	0.11	0.02	4.61
	Perceptual Speed	Letter Comparison	1.00	n/a	n/a
		Finding As	2.55	0.49	5.16

Model	Factor	Variable	Estimate	Standard Error	Loading (z-score)
		Number Comparison	0.67	0.13	4.93
		Identical Pictures	1.10	0.27	4.12
	Fluency	Word Beginnings	1.00	n/a	n/a
		Word Endings	0.93	0.11	8.16
		Word Beginnings & Endings	0.75	0.10	7.75
	Comprehension	Experimenter-Generated	1.00	n/a	n/a
		Nelson-Denny	1.62	0.33	4.93
4-Reduced	Decoding	Orthographic Decision	1.00	n/a	n/a
		Phonological Decision	9.79	2.00	4.90
		Non-word Naming	1.56	0.44	3.53
	WMC	Reading Span	1.00	n/a	n/a
		Alphabet Span	1.33	0.18	7.50
		Minus Span	2.22	0.33	6.71
		Visual Number Span	0.10	0.02	4.34
	Comprehension	Investigator-Generated	1.00	n/a	n/a
		Nelson-Denny	1.46	0.245	5.95

Table 21

Measurement-model factor variances and unique variances for the model without Language Experience and Reasoning (Model 4) and the model with only Decoding and WMC (Model 4-Reduced).

Model	Factor	Factor Variance	Factor Variance (Std. Error)	Variable	Unique Variance	Unique Variance (Std. Error)
4	Decoding	0.01	0.002	Orthographic Decision	0.01	0.002
				Phonological Decision	0.51	0.11
				Non-word Naming	0.21	0.02
	WMC	32.83	6.18	Reading Span	32.68	4.75
				Alphabet Span	104.82	12.31
				Minus Span	397.88	41.40
				Visual Number Span	2.66	0.24
	Perceptual Speed	21.75	6.90	Letter Comparison	83.79	8.32
				Finding As	132.15	24.97
				Number Comparison	26.85	2.83
				Identical Pictures	149.26	14.66
	Fluency	32.01	5.50	Word Beginnings	29.06	4.17
				Word Endings	37.40	4.48
				Word Beginnings & Endings	29.35	3.24
	Comprehension	0.002	0.001	Investigator-Generated	0.004	0.001
				Nelson-Denny	0.01	0.002

Model	Factor	Factor Variance	Factor Variance (Std. Error)	Variable	Unique Variance	Unique Variance (Std. Error)
	-			Stroop Inhibition	0.01	0.001
4-Reduced	Decoding	0.01	0.002	Orthographic Decision	0.01	0.002
				Phonological Decision	0.44	0.16
				Non-word Naming	0.21	0.02
	WMC	35.46	6.07	Reading Span	29.45	4.78
				Alphabet Span	111.13	12.27
				Minus Span	395.48	41.77
				Visual Number Span	2.71	0.25
	Comprehension	0.003	0.001	Investigator-Generated	0.004	0.001
				Nelson-Denny	0.01	0.002

Table 22

Co-variance path weights for the model without Language Experience and Reasoning (Model 4) and the reduced model with only Decoding and WMC (Model 4-Reduced).

Factor	Co-varying with	Covariance (Estimate)	Covariance (Std. Error)	Covariance (z-score)	Covariance (*p*-value for z-score)
Decoding	WMC	-	-	-	-
	Perceptual Speed	−0.16	0.05	−2.87	0.004
	Fluency	−0.28	0.05	−5.03	< 0.001
	Inhibition	0.002	0.001	2.83	0.005
WMC	Perceptual Speed	5.43	2.56	2.12	0.034
	Fluency	14.14	2.92	4.84	< 0.001
	Inhibition	-	-	-	-
Perceptual Speed	Fluency	11.06	2.98	3.70	< 0.001
	Inhibition	−0.10	0.04	−2.42	0.015
Fluency	Inhibition	-	-	-	-

Note: The reduced model with only Decoding and WMC (Model 4-Reduced) contained no covariance paths.

Table 23

Change in misfit for the model with only Decoding and WMC (Model 4-Reduced) as latent variables were deleted from the dataset (measured by χ^2 during backward-building).

	β allowed to vary at random			β fixed to weight in Model 4					
Variable Removed	df	χ^2	% R	df	χ^2	% R	Δ df	$\Delta\chi^2$	*p* of $\Delta\chi^2$
None	111	199.140	44.30	-	-	-	-	-	-
Inhibition	97	173.356	42.43	99	173.515	44.49	2	0.159	0.9236
Perceptual Speed	50	110.846	41.76	52	110.873	42.54	2	0.027	0.9866
Fluency	25	90.013	40.77	27	90.357	43.23	2	0.344	0.8420

Table 24

Change in misfit for the model with only Decoding and Vocabulary (Model 5) as measured by χ^2 during backward-building.

Path Removed	df	χ^2	Δ df	Δ χ^2	*p* of Δ χ^2
None	17	45.041	-	-	-
Decoding → Comprehension	18	46.497	1	1.456	0.2276

Note: ↔ indicates a covariance path and → indicates a regression path.

Table 25

Measurement-model factor loadings for the model with only Decoding and Vocabulary (Model 5).

Model	Factor	Variable	Estimate	Standard Error	Loading (z-score)
5	Decoding	Orthographic Decision	1.00	n/a	n/a
		Phonological Decision	9.41	2.03	4.63
		Non-word Naming	1.63	0.43	3.74
	Vocabulary	Extended Range Vocabulary	1.00	n/a	n/a
		Advanced Vocabulary	0.64	0.05	13.40
		Nelson-Denny Vocabulary	2.82	0.19	14.80
	Comprehension	Experimenter-Generated	1.00	n/a	n/a
		Nelson-Denny	0.74	0.09	8.36

Table 26

Measurement-model factor variances and unique variances for the model with only Decoding and Vocabulary (Model 5).

Model	Factor	Factor Variance	Factor Variance (Std. Error)	Variable	Unique Variance	Unique Variance (Std. Error)
5	Decoding	0.01	0.002	Orthographic Decision	0.01	0.002
				Phonological Decision	0.47	0.16
				Non-word Naming	0.21	0.02
	Vocabulary	36.64	4.35	Extended Range Vocabulary	13.55	2.04
				Advanced Vocabulary	12.51	1.34
				Nelson-Denny Vocabulary	111.19	16.87
	Comprehension	0.003	0.001	Investigator-Generated	0.003	0.001
				Nelson-Denny	0.01	0.002

Table 27

Co-variance path weights for the model with only Decoding and Vocabulary (Model 5).

Factor	Co-varying with	Covariance (Estimate)	Covariance (Std. Error)	Covariance (z-score)	Covariance (*p*-value for z-score)
Decoding	Vocabulary	−0.20	0.05	−4.03	<0.001

Highlights

- SEM revealed direct and indirect effects of individual-difference factors on comprehension
- Most constructs had indirect effects, including working-memory capacity
- Only language experience and general reasoning had direct effects
- Vocabulary dominated other measures in explaining variance in comprehension

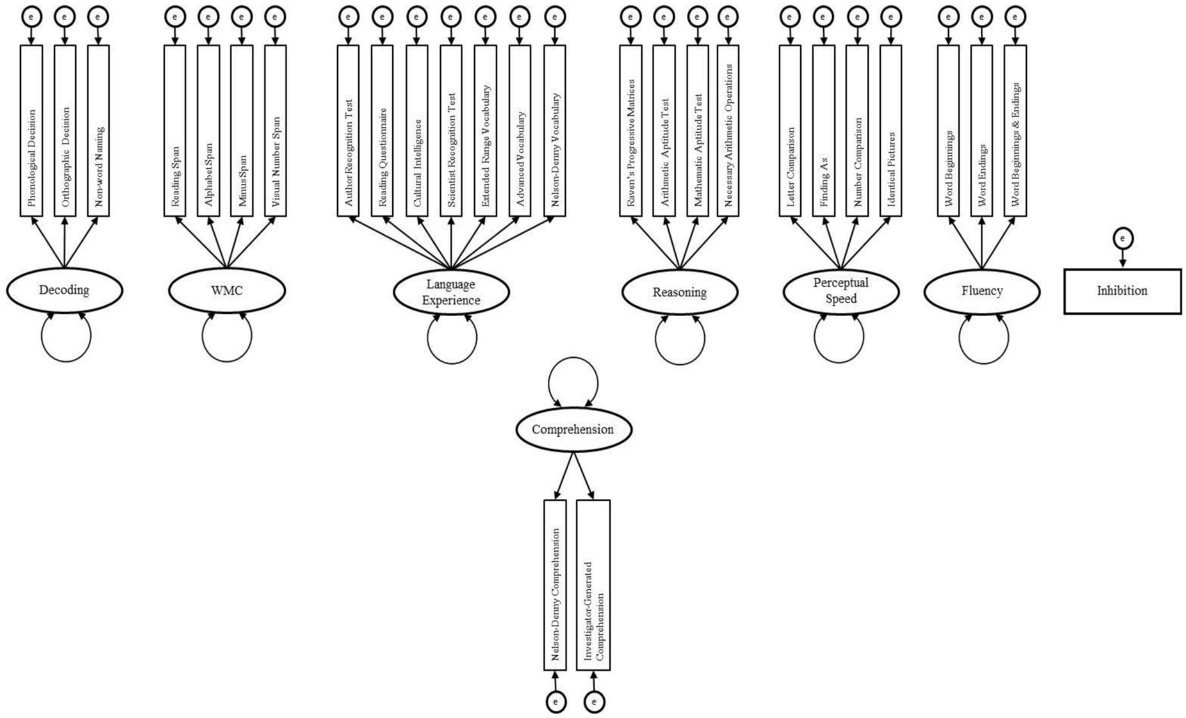

Figure 1.

Measurement model with comprehension as a latent variable.

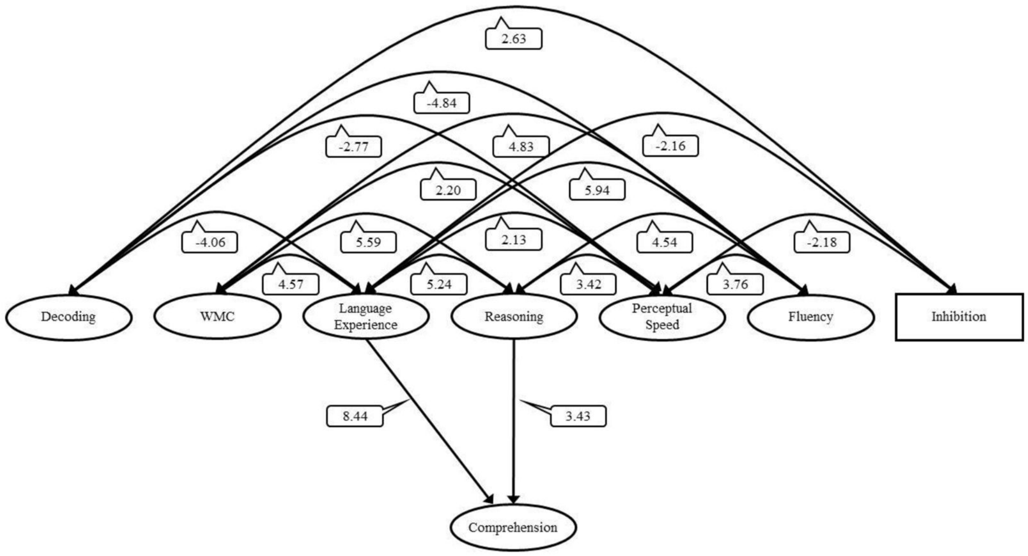

Figure 2.
SEM with all latent variables (Model 1).

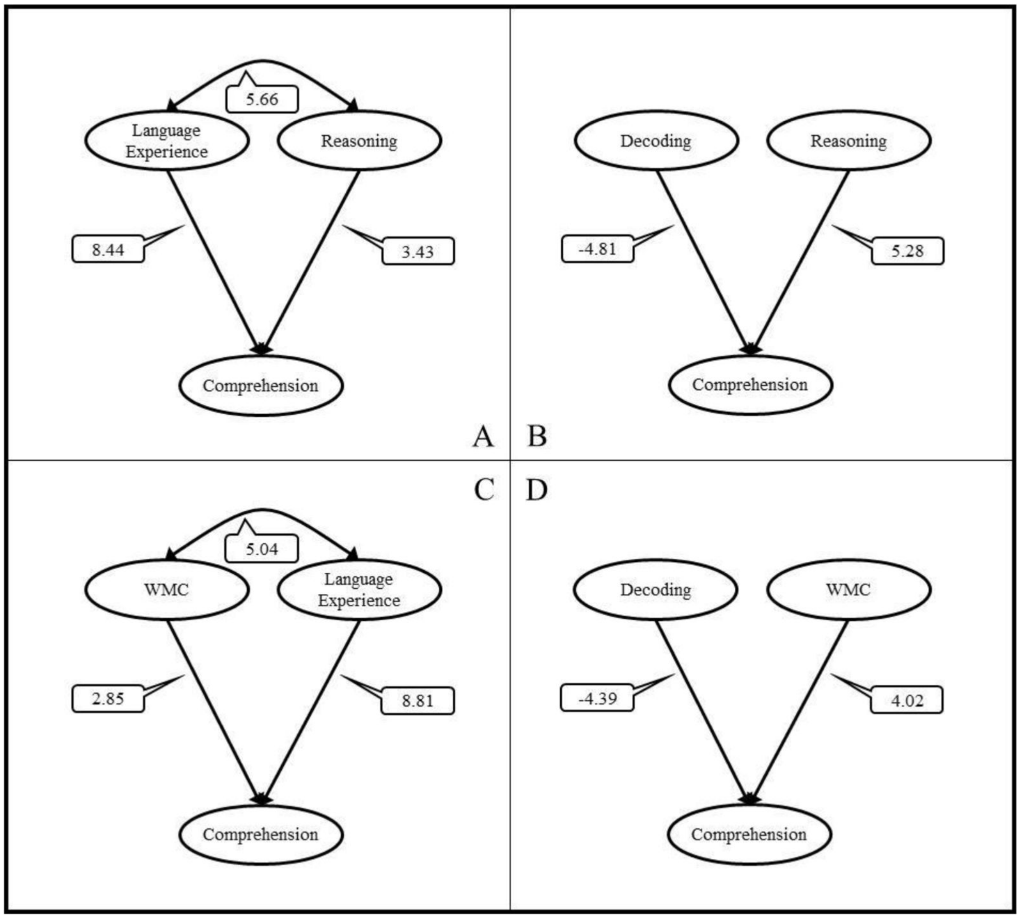

Figure 3.

Models 1–4 reduced to only significant and stable components. Panel A: Model 1- Reduced, Panel B: Model 2-Reduced, Panel C: Model 3-Reduced, Panel D: Model 4-Reduced

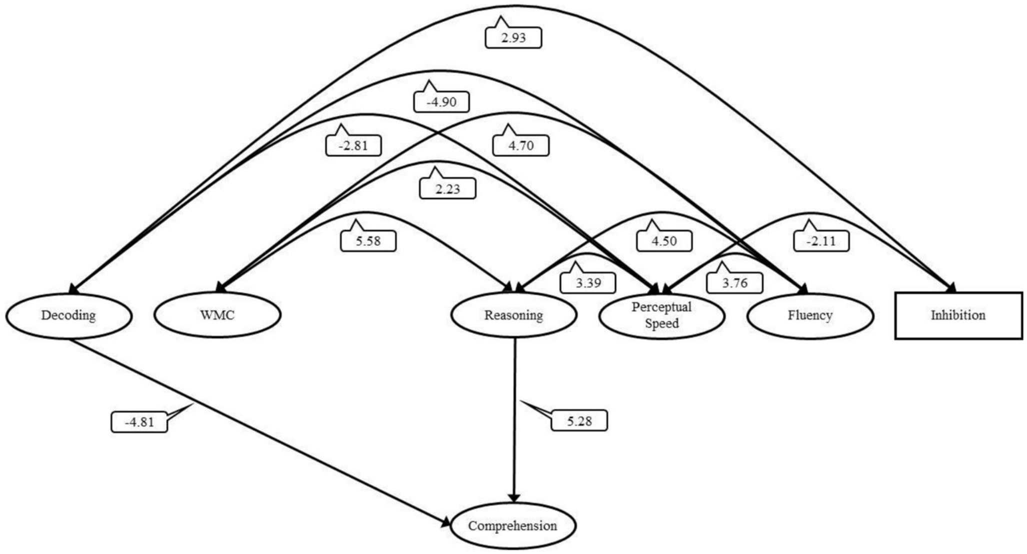

Figure 4.
SEM with Language Experience deleted from the model (Model 2).

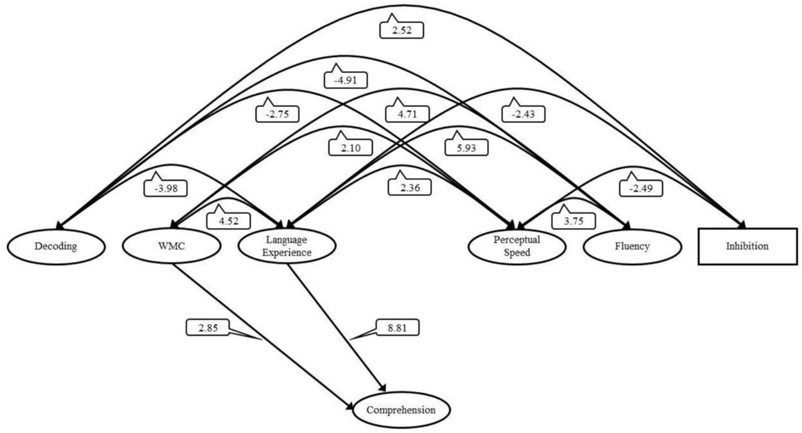

Figure 5.

SEM with Reasoning deleted from the model (Model 3).

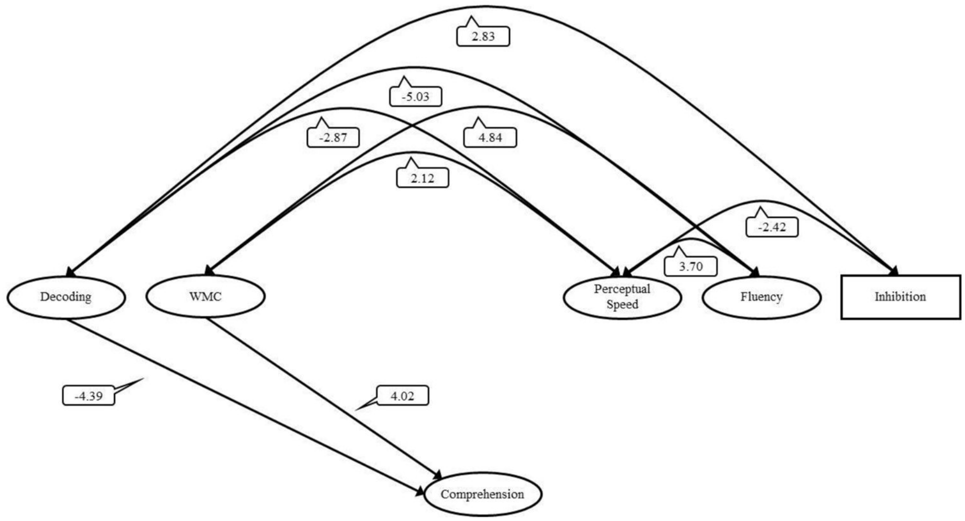

Figure 6.
SEM with Language Experience and Reasoning deleted from the model (Model 4).

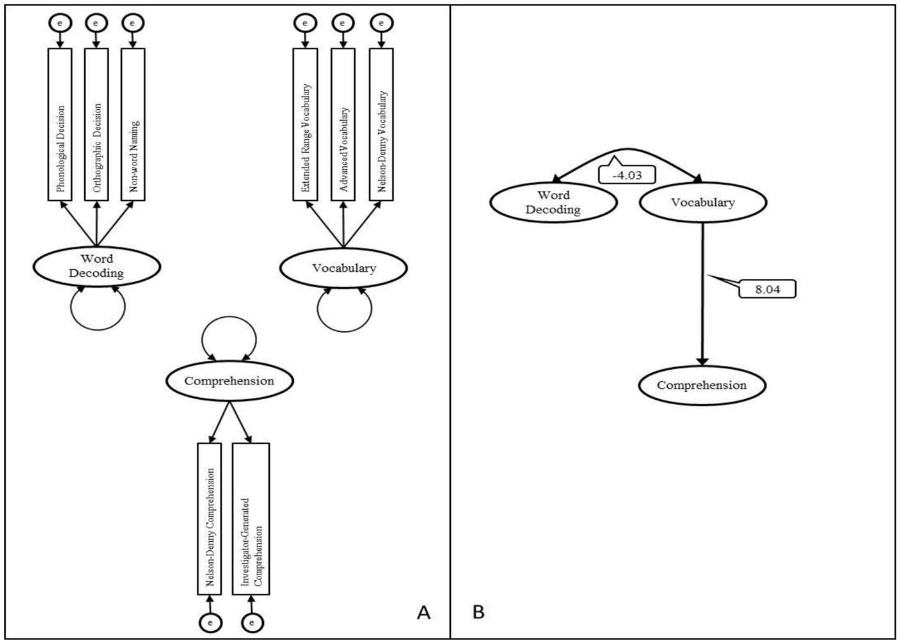

Figure 7.
Measurement Model (Panel A) and SEM (Panel B) with only Decoding and Vocabulary (Model 5).

Table 1

Descriptive statistics for the 29 individual difference variables and the two comprehension measures.

Variables	*N*	Minimum	Maximum	Mean	Standard Deviation
Decoding & Phono. Awareness					
Orthographic Decision (ms)	261	523.207	157.653	762.638	141.630
Phonological Decision (ms)	252	1157.615	8084.414	2659.039	1106.412
Non-word Naming (ms)	243	139.750	6479.044	1053.328	483.228
Phoneme Transposition *	224	0.040	1.000	0..876	0.131
Working-Memory Capacity					
Reading Span *	285	0.270	0.930	0.640	0.135
Alphabet Span *	284	0.130	0.970	0.733	0.121
Minus Span *	281	0.100	1.000	0.834	0.136
Visual Number Span *	278	0.000	0.710	0.345	0.073
Suppression/Inhibition					
Go-No-Go *	256	0.000	0.700	0.138	0.136
Stroop Interference (ms)	245	−257.809	1052.417	96.981	102.886
Print Exp. & Background Know.					
Author Recognition Test *	279	0.000	0.500	0.175	0.104
Reading Questionnaire	330	1.000	5.000	3.580	0.962
Cultural Intelligence *	262	0.120	0.910	0.573	0.138
Scientist Recognition Test *	279	0.000	0.640	0.247	0.109
Vocabulary					
Extended Range Vocabulary *	278	−0.090	0.720	0.319	0.148
Advanced Vocabulary *	270	0.000	0.690	0.345	0.143
Nelson-Denny Vocabulary *	283	0.630	0.980	0.866	0.079
General Reasoning					
Raven's Progressive Matrices *	280	0.290	1.000	0.723	0.129
Arithmetic Aptitude Test *	278	0.070	0.990	0.498	0.194
Mathematic Aptitude Test *	261	−0.150	0.960	0.366	0.154

Variables	*N*	Minimum	Maximum	Mean	Standard Deviation
Necessary Arithmetic Ops.*	274	−0.040	0.960	0.516	0.179
Perceptual Speed					
Letter Comparison*	274	0.040	0.740	0.191	0.054
Finding As*	274	0.080	0.690	0.312	0.083
Number Comparison*	275	0.100	0.530	0.284	0.063
Pattern Comparison*	262	0.570	1.000	0.962	0.061
Identical Pictures*	260	0.320	1.000	0.707	0.138
Verbal Fluency					
Word Beginnings	276	9.000	57.000	26.360	7.916
Word Endings	262	4.000	53.000	31.500	8.128
Word Beginnings & Endings	277	0.000	58.000	19.230	6.944
Comprehension					
Nelson-Denny*	263	0.222	1.000	0.788	0.157
Investigator-Generated*	303	0.460	0.922	0.773	0.091

* reported as proportions

Table 2

Bivariate correlations among the individual-difference and comprehension measures.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.	18.	19.	20.	21.	22.	23.	24.	25.	26.	27.	28.	29.	30.	31.
1. Orthographic Decision																															
2. Phonological Decision	**.52**																														
3. Non-word Naming	**.26**	**.20**																													
4. Phoneme Transposition	**−.19**	**−.23**	−.10																												
5. Reading Span	.05	−.07	−.12	**.17**																											
6. Alphabet Span	**−.14**	−.11	−.09	**.14**	**.45**																										
7. Minus Span	−.12	−.10	.00	**.23**	**.41**	**.27**																									
8. Visual Number Span	−.03	.10	−.02	.13	**.21**	**.23**	**.33**																								
9. Go-No-Go	**−.17**	−.09	**−.15**	.07	−.11	−.06	.12	−.00																							
10. Stroop Interference	.05	.13	.12	−.09	.01	.02	.00	−.03	−.10																						
11. Author Recognition Test	**−.18**	**−.22**	−.08	**.31**	.12	**.25**	.08	.02	−.06	.00																					
12. Reading Questionnaire	.09	.03	−.00	**.20**	**.13**	−.00	.04	.04	−.02	.07	**.35**																				
13. Cultural Intelligence	**−.17**	**−.32**	**−.21**	**.28**	**.26**	**.28**	**.16**	−.03	.04	−.10	**.51**	**.36**																			
14. Scientist Recognition Test	−.10	**−.18**	−.07	.10	**.15**	**.20**	.10	−.01	−.03	−.08	**.36**	**.17**	**.48**																		
15. Extended Range Vocabulary	**−.14**	**−.25**	**−.16**	**.26**	**.29**	**.31**	**.14**	−.01	−.05	−.06	**.58**	**.26**	**.64**	**.43**																	
16. Advanced Vocabulary	−.09	**−.20**	−.13	**.22**	**.19**	**.25**	.05	−.01	−.05	**−.15**	**.46**	**.28**	**.57**	**.36**	**.67**																
17. Nelson-Denny Vocabulary	**−.22**	**−.33**	**−.21**	**.35**	**.27**	**.32**	**.13**	−.08	−.06	**−.15**	**.58**	**.37**	**.71**	**.37**	**.73**	**.61**															
18. Raven’s Progressive Matrices	−.05	.07	.01	**.19**	**.24**	**.32**	**.33**	**.31**	−.08	.04	**.14**	−.02	.12	**.14**	**.22**	**.14**	**.18**														
19. Arithmetic Aptitude Test	**−.16**	−.06	−.11	**.21**	**.28**	**.31**	**.26**	**.22**	−.02	−.11	**.13**	−.10	**.27**	**.19**	**.29**	**.24**	**.29**	**.29**													
20. Mathematic Aptitude Test	−.11	−.06	−.09	**.21**	**.22**	**.26**	**.29**	**.16**	.03	−.02	**.16**	−.02	**.39**	**.21**	**.35**	**.26**	**.32**	**.28**	**.71**												
21. Necessary Arithmetic Operations	−.05	−.09	−.11	**.25**	**.31**	**.33**	**.32**	.11	−.02	−.08	**.24**	.03	**.37**	**.17**	**.37**	**.28**	**.42**	**.29**	**.63**	**.61**											
22. Letter Comparison	**−.16**	**−.13**	−.10	.13	.10	.12	.09	.06	.01	−.05	**.14**	.12	**.14**	.02	**.17**	**.14**	.10	.00	**.21**	**.19**	**.21**										
23. Finding As	**−.19**	**−.13**	−.06	**.17**	.05	.08	**.13**	.11	.00	**−.17**	**.16**	.11	**.13**	.00	**.12**	.06	**.17**	.03	**.13**	**.15**	**.18**	**.33**									
24. Number Comparison	**−.26**	−.05	**−.14**	.07	.01	.04	**.15**	**.16**	.04	−.11	.03	−.08	−.05	−.05	−.12	−.04	−.05	.04	**.25**	**.21**	**.17**	**.23**	**.38**								
25. Pattern Comparison	**−.15**	−.07	−.05	.06	.12	.04	.08	.03	−.04	−.04	**.15**	−.06	.12	**.14**	**.18**	.12	**.15**	.06	.03	.09	.11	.00	.11	.04							
26. Identical Pictures	**−.16**	**−.15**	−.06	.06	.08	**.13**	.10	**.17**	.08	.02	**.15**	.04	**.22**	.05	**.17**	**.14**	**.26**	.12	**.17**	**.20**	**.22**	**.18**	**.26**	**.20**	.08						
27. Word Beginnings	**−.24**	**−.31**	−.11	**.22**	**.18**	**.31**	**.20**	.11	−.05	**.16**	**.24**	.06	**.33**	**.18**	**.36**	**.32**	**.42**	.08	**.25**	**.26**	**.24**	**.17**	**.27**	**.12**	**.17**	**.19**					
28. Word Endings	**−.24**	**−.30**	.00	.09	**.15**	**.33**	**.15**	.09	−.08	−.02	**.23**	−.04	**.23**	**.13**	**.28**	**.24**	**.29**	**.16**	**.16**	**.20**	**.27**	.11	**.18**	**.14**	.12	**.20**	**.48**				
29. Word Beginnings & Endings	**−.25**	**−.29**	−.13	**.18**	**.19**	**.28**	**.14**	.09	−.04	−.03	**.26**	−.06	**.29**	**.21**	**.37**	**.28**	**.39**	**.15**	**.24**	**.22**	**.22**	.01	**.16**	.12	**.18**	**.16**	**.44**	**.44**			
30. Nelson-Denny Comprehension	**−.30**	**−.34**	**−.19**	**.29**	**.17**	**.16**	**.18**	−.03	.04	**−.22**	**.36**	**.13**	**.49**	**.22**	**.36**	**.38**	**.55**	**.24**	**.27**	**.31**	**.38**	**.18**	**.18**	**.24**	.08	**.16**	**.26**	**.20**	**.21**		
31. Investigator-Generated Comprehension	−.06	**−.22**	−.11	**.26**	**.35**	**.34**	**.27**	−.04	−.05	−.04	**.37**	**.21**	**.50**	**.31**	**.59**	**.47**	**.57**	**.27**	**.29**	**.35**	**.36**	.10	**.12**	−.03	.08	**.13**	**.29**	**.19**	**.25**	**.48**	

Note: Significant correlations ($p < 0.05$) are shown in bold.

Table 3

Principal components analysis of the remaining 26 individual difference variables.

Factor	Variables	1	2	3	4	5	6	7
Decoding	Orthographic Decision	−.022	−.023	−.319	.028	−.244	**.691**	−.032
	Phonological Decision	−.227	.102	−.397	.043	−.080	**.626**	.056
	Non-word Naming	−.133	−.069	.183	−.107	−.029	**.713**	.067
WMC	Reading Span	.240	.143	−.001	**.732**	−.093	−.085	.018
	Alphabet Span	.230	.210	.307	**.560**	−.059	−.085	.047
	Minus Span	.021	.192	.078	**.692**	.106	−.070	.024
	Visual Number Span	−.137	.084	.054	**.646**	.215	.138	−.061
Inhibition	Stroop Interference	−.109	−.012	.040	.006	−.086	.075	**.938**
Language Experience	Author Recognition Test	**.703**	−.005	.146	.038	.182	−.013	.080
	Reading Questionnaire	**.591**	−.272	−.319	.148	.258	.182	.197
	Cultural Intelligence	**.794**	.187	.078	.073	.057	−.189	−.001
	Scientist Recognition Test	**.549**	.144	.094	.048	−.144	−.077	−.096
	Extended Range Vocabulary	**.803**	.210	.192	.076	.003	−.075	.016
	Advanced Vocabulary	**.747**	.142	.151	.007	.013	−.017	−.121
	Nelson-Denny Vocabulary	**.819**	.169	.209	.053	.079	−.158	−.037
Reasoning	Raven’s Progressive Matrices	.051	**.638**	.134	.316	.131	.174	.082
	Arithmetic Aptitude Test	.124	**.835**	.072	.163	.106	−.109	−.078
	Mathematic Aptitude Test	.210	**.831**	.061	.095	.136	−.049	.035
	Necessary Arithmetic Operations	.282	**.718**	.083	.180	.143	−.015	−.038
Perceptual Speed	Letter Comparison	.130	.140	−.130	.041	**.607**	−.180	.103
	Finding As	.084	−.012	.157	.068	**.759**	.004	−.196
	Number Comparison	−.231	.217	.095	.064	**.617**	−.177	−.166
	Identical Pictures	.131	.172	.197	.035	**.489**	.005	.132
Fluency	Word Beginnings	.283	.097	**.596**	.147	.213	−.137	.278
	Word Endings	.160	.081	**.763**	.118	.144	.003	−.004
	Word Beginnings & Endings	.242	.146	**.686**	.114	−.003	−.118	−.075

Note: The highest factor loading for each measure is shown in bold font.