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Considering the Role of Executive Function in Reading Comprehension: A Structural Equation Modeling Approach

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Abstract

In the present study, we used latent variable structural equation modeling to investigate relations between oral language, decoding, and two components of executive function (cognitive flexibility and working memory) and reading comprehension in a sample of 271 native English-speaking 9.00- to 14.83-year-olds. Results of the mediation analyses indicated that both oral language and decoding fully mediated the relations between working memory and cognitive flexibility and reading comprehension. These findings suggest that executive function is likely associated with reading comprehension through its relation with decoding and oral language and provide additional support for the role of executive function in reading comprehension as a potentially crucial precursor to skilled reading.

Keywords

Executive function; reading comprehension; structural equation modeling; oral language; word recognition

Reading comprehension (RC) is a complex process that requires an integration of skills necessary to process information at the individual word- and sentence levels to subsequently understand what is being read. Yet, only 36% of eighth graders in the U.S. score at or above proficiency in RC (National Center for Education Statistics, 2017). This is troubling because reading proficiency robustly predicts academic outcomes (Hernandez, 2011). Thus, identifying the causes and correlates of reading development and/or difficulties remains important. In the current study, we examined relations among components of executive function (EF; cognitive flexibility [CF] and working memory [WM]), decoding, oral language, and RC in children with a wide range of reading abilities.

Bottom-up word-level processes likely work in conjunction with top-down language processes in ways that can influence RC (Perfetti, 1999; Perfetti & Hart, 2001). It is well established that decoding deficits frequently result in reading problems (Catts, Adlof, & Weismer, 2006; Perfetti & Hogaboam, 1975); however, oral language weaknesses have also

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been implicated in poor RC (e.g., Catts et al., 2006; Spencer & Wagner, 2018). More recently, additional higher-level cognitive skills (e.g., EF) have been cited as predictors of RC over decoding and oral language (e.g., Sesma, Mahone, Levine, Eason, & Cutting, 2009).

The Simple View of Reading (SVR; Hoover & Gough, 1990) posits that RC is the interactive product of linguistic comprehension and decoding. Since its inception, the SVR framework has been a cornerstone of reading research, and there has been a considerable amount of empirical evidence supporting its validity (Catts et al., 2006; Kendeou, van den Broek, White, & Lynch, 2009; Kieffer, Vukovic, & Berry, 2013; Kim, 2017). However, while both skills explain a substantial amount of variance in RC (e.g., Kim, 2017), there is evidence that additional cognitive skills, such as WM, inhibition, and attention, are directly and indirectly associated with RC and explain unique variance in RC over and above decoding and oral language (e.g., Arrington, Kulesz, Francis, Fletcher, and Barnes, 2014; Kieffer et al., 2013; Kim 2017).

Other more comprehensive theoretical models of reading address this limitation by acknowledging the role of skills beyond decoding and language comprehension on RC. For instance, in the construction-integration (C-I) model, Kintsch (1988) asserts that text-specific bottom-up (e.g., word recognition) and reader-based top-down processes (e.g., retrieval and activation of relevant background knowledge) interact in a way that allows the reader to create a mental model of the text and subsequently comprehend what is being read [see also the Reading Systems Framework (RSF); Perfetti, 1999]. In this way, interactive models highlight additional mechanisms through which individual differences in RC may emerge.

The Role of CF and WM

While the aforementioned theoretical models of reading do not formally incorporate EF, the description of the necessary processes for successful comprehension across multiple models of RC taps constructs central to EF (e.g., activation of word meanings in the C-I model and meaning retrieval in the RSF; Kintsch, 1988; Perfetti, 1999). And, although investigations have examined the relations between aspects of EF and RC (Ahmed et al., 2016; Kieffer et al., 2013; Kim, 2017; Lervag, Hulme, & Melby-Lervag, 2019), few studies have examined multiple components of EF within a single theoretical framework while also including a rich battery of oral language measures.

EF refers to a set of cognitive processes that aide in the ability to effectively plan, problem solve, and maintain/update information (Miyake et al., 2000). Many of these components have been formally or informally referred to in reading models (e.g., Kintsch, 1988), although explicit integration of EF into them so far has been lacking. Of note, when discussing the construct of EF, it is important to highlight the fact that in one of the most classic theoretical models of EF (Miyake et al., 2000), more recent findings have suggested that some EF processes are not distinct from others (Cirino et al., 2018; Miyake & Friedman, 2012), which is consistent with many other studies (Salthouse, Atkinson, & Berish, 2003; Wiebe, Espy, & Charak, 2008).

More specifically, Miyake and Friedman (2012) determined that among the three components of EF (updating, shifting, and inhibition), only updating (WM) and shifting (CF) emerged as uniquely separable constructs; inhibition did not emerge as a separable factor within the model (unity/diversity framework). Other investigations have resulted in similar findings (see Cirino et al., 2018). These findings are not altogether unexpected, as WM and CF are higher-level cognitive processes and therefore inhibition is likely an inherent aspect of them (Hale, Bronik, & Fry, 1997; Monsell, 2003). Given our focus on RC, which is more strongly related to higher- rather than lower-level cognitive skills (e.g., Landi, 2010), we decided that it was most parsimonious to include only WM and CF as exogenous variables within our models. Below, we provide rationale for how these two central aspects of the unity/diversity theory of EF may be related to decoding, oral language, and RC.

Decoding.

Decoding is a critical component of RC (Hoover & Gough, 1990). According to theoretical frameworks (see Coltheart, Rastle, Perry, Langdon & Ziegler, 2001; Seidenberg & McClelland, 1989; Zorzi, Houghton, & Butterworth, 1998), successful word reading depends on the reader's ability to naturally shift between multiple sources of information. Thus, it is perhaps not surprising that CF, or the ability to shift attention between tasks or concepts (Berg, 1948; Hughes, 1998), is related to decoding (Cartwright, Marshall, Dandy, & Isaac, 2010; Cole, Duncan, & Blaye, 2014).

Although WM is not explicitly discussed within these theoretical models, there is evidence that WM is correlated with decoding ($r = .37$-.42; Bowey, Cain, & Ryan, 1992 and Cutting & Scarborough, 2006). Traditionally, WM is described as a cognitive system that allows for the storage and manipulation of phonological and visuospatial information (Baddeley, 1986; Baddeley, Gathercole, & Papagno, 1998; Baddeley & Hitch, 1974). Given its role in phonological processing (Wagner & Torgesen, 1987), WM is thought to be a key contributing factor to language acquisition and processing (Baddeley, 1986; Baddeley et al., 1998) and may explain why children with decoding difficulties often have corresponding WM impairments (e.g., Beneventi, Tonnessen, Ersland, & Hugdahl, 2010; Plaza, Cohen, & Chevrie-Muller, 2002). In fact, WM accounts for 3–13% of the variance in decoding (Daneman & Carpenter, 1980; Gathercole, Alloway, Willis, & Adams, 2006; Gottardo, Stanovich, & Siegel, 1996; McCallum et al., 2006; Nevo & Breznitz, 2011) and may facilitate the acquisition of new words (e.g., Gathercole & Baddeley, 1993).

Oral language.

Oral language encompasses a wide variety of language-based skills. Given the broadness of its conceptualization (NICHD Early Child Care Research Network, 2005), we sought to include a wide variety of language-based skills within the current study, including vocabulary, listening comprehension, and morphological awareness, all of which have been implicated in RC (e.g., Deacon, Kieffer, & Laroche, 2014; Joshi & Aaron, 2000; Oulette, 2006). Research suggests that CF is potentially related to language processing more generally and may play an important role in its development (Guajardo & Cartwright, 2016). This is further evidenced by the fact that children with developmental language disorder (DLD) tend to have deficits in CF (Roello, Ferretti, Colonnello, & Levi, 2015). WM also predicts vocabulary, syntactic processing, and listening comprehension (Adams, Bourke, & Willis, 1999; Florit, Roch, Altoe, & Levorato, 2009; King & Just, 1991), and, similar to CF, children with DLD tend to have corresponding WM deficits (Montgomery, 2000).

RC.

Interactive theories of RC emphasize the importance of utilizing and integrating information from various sources. For instance, both the C-I model (Kintsch, 1988) and the RSF (Perfetti, 1999) assert that readers are continuously constructing and integrating *multiple* sources of information, including background knowledge, which facilitates inference-making, cohesion, and the overall RC process (Kintsch, 1988; Perfetti, 1999). Such cognitive processes may actually reflect CF to some extent, which does predict RC success (Cartwright, 2009, 2015; Cartwright et al., 2010, 2017) and accounts for variance in RC above vocabulary and decoding (Guajardo & Cartwright, 2016; Knudsen, de Lopez, & Archibald, 2018).

There is also a substantial amount of empirical evidence that supports the role of WM in RC (e.g., Daneman & Carpenter, 1980); WM significantly predicts 2–10% of the variance in RC above vocabulary and decoding (Goff, Pratt, & Ong, 2005; Seigneuric & Ehrlich, 2005; Seigneuric, Ehrlich, Oakhill, & Yuill, 2000). Moreover, WM deficits are prevalent in children with word recognition- and specific RC deficits (e.g., Cain & Oakhill, 2006; Cutting, Materek, Cole, Levine, & Mahone, 2009; Locascio, Mahone, Eason, & Cutting, 2010; Sesma et al., 2009; Siegel & Ryan, 1989; Swanson & Jerman, 2007). This suggests that poor RC can be due to lower- (e.g., phonological) and/or higher-level (e.g., WM) processes and is supported by interactive theories of RC. For example, the RSF (Perfetti, 1999) asserts that readers are continuously constructing and integrating multiple sources of information, including their own background knowledge to facilitate inference-making, cohesion, and the RC process. Therefore, a successful reader is one who is able to engage with multiple sources of information in the text while additionally tapping into his/her prior knowledge. This suggests that RC proficiency requires, at minimum, an adequate command over WM processes.

Prior Studies Examining Direct and Indirect Effects of EF on RC

The broad implications of EF to RC have led researchers to test more theoretically and computationally complex models of reading in recent years. More specifically, researchers have become increasingly interested in the direct and *indirect* effects of EF on RC via other language- and literacy-related skills. Given the aim of the current study, which is to examine the direct and indirect associations between EF (WM and CF) and RC via decoding and oral language, we include a greater discussion of prior investigations that have examined similar relations among these skills.

For instance, Arrington et al. (2014) used path analysis to examine the role of attentional control, WM, and RC in a sample of 1,134 adolescents. Attentional control, cognitive inhibition, and WM were directly related to RC. Further, WM and response inhibition significantly predicted decoding, and decoding mediated the relation between WM and RC. Christopher et al. (2012) used latent variable structural equation modeling (SEM) to investigate the contributions of WM, processing and naming speed, and inhibition to decoding and a combined oral language/RC construct in 483 adolescents. WM was significantly associated with decoding (β = .59) and comprehension (β = .64), showing that at least one aspect of EF plays a central role in the ability to recognize words and understand connected language/text (see also Cantin, Gnaedinger, Gallaway, Hesson-McInnis, & Hund, 2016 and Georgiou & Das, 2018). Kieffer et al. (2013) examined the direct and indirect effects of attention shifting and inhibitory control to RC through decoding and oral language in 120 fourth graders. Results showed that, after accounting for WM and processing speed, attention shifting and inhibitory control were directly related to RC (β = .17 and .21 for attention shifting and inhibitory control, respectively). Further, there was a weak albeit significant indirect effect from attention shifting to RC via oral language (β = .06).

Several limitations of previous studies that the current investigation seek to address include the fact that prior studies did not: (a) specify oral language, decoding, and/or RC as latent variables; (b) examine relations between EF and RC separate from oral language; and/or (c) include measures of verbal WM or CF, and/or multiple measures of oral language within a single model. These are important considerations because including multiple measures would increase the explanatory power of the constructs being assessed and allow for the specification of multiple-indicator latent variables, thereby reducing measurement error and increasing the reliability of the estimates. Furthermore, separating RC and oral language would make it easier to tease apart the exact nature of the associations.

Current Study

The aim of the current study was to further elucidate relations between CF, WM, oral language, decoding, and RC. Although evidence thus far clearly supports a role of EF in RC, that role has not been explicitly defined, particularly in terms of which specific components of EF are related to RC. Given the breadth of constructs that underlie EF, certain EF skills may be more or less useful in predicting RC; it is also not clear if decoding and oral language would mediate the relations between certain components of EF and RC. Therefore, understanding the exact nature of the interplay among these various skills is an important next step in understanding more about how EF is related to RC.

Based on the previously discussed theoretical frameworks of RC (Kintsch, 1988; Perfetti & Stafura, 2014) and prior investigations, we generated several hypotheses about the relations between CF, WM, oral language, decoding, and RC. First, we hypothesized that, in confirmation of the SVR framework, both decoding and oral language would be associated with RC given previous findings (Cutting et al., 2009; Cutting & Scarborough, 2006; Kendeou et al., 2009) and theoretical frameworks of RC (e.g., C-I model and RSF) that emphasize the importance of broad language skills in the RC process (e.g., syntax and morphology; Kintsch, 1988; Perfetti & Stafura, 2014). Second, and most central to the current study, we hypothesized that EF would be related to RC indirectly through the SVR components. This hypothesis was based on prior findings that other cognitive processes mediate the relations between WM and CF and RC (e.g., Kieffer et al., 2013; McVay & Kane, 2012; Nouwens, Groen, & Verhoeven, 2016 ; Unsworth & McMillan, 2013). Finally, we hypothesized that the variation explained in oral language would be greater than that of decoding. This hypothesis was centered on the fact that there are greater cognitive demands associated with oral and written language comprehension, and therefore greater variability, relative to decoding for older children (e.g., Catts, Hogan, & Adlof, 2005).

Methods

Participants

Participants were recruited through advertisements in schools, clinics, and pediatricians' offices. We applied several exclusionary criteria (see Appendix A) to reduce the likelihood of comorbidity among reading skills and other potentially confounding factors. The analytical sample included 271 children between 9.00 and 14.83 years (full sample $N =$ 274). Participants were identified as 66.8% Caucasian, 11.4% African American, 5.2% multi-racial, 1.8% Asian, and 14.7% did not specify; 50.9% of the sample was female. Participants had wide a range of socioeconomic backgrounds (Hollingshead Four-Factor Index scores ranged from 26 to 62; M_{SES} = 49.494). Parental informed consent and child assent were obtained at the beginning of the study. Study procedures were carried out in accordance with the Vanderbilt University Institutional Review Board.

Measures

Assessment occurred across two sessions. The measures were selected from a broader testing battery and are described in detail below. Raw scores were used unless otherwise noted.

CF.—Verbal and Perceptual Card Sorting from the Delis-Kaplan Executive Function System (D-KEFS; Delis, Kaplan, & Kramer, 2001) required participants to sort sets of cards into groups using as many different categorization rules as possible (combined α = .74).

WM.—The sentence span task (adapted from Swanson, Cochran, & Ewers, 1989) required participants to listen to sentences, verify their truthfulness, and recall the last word of each sentence (α = .86). The Digit Span subtest from the Wechsler Intelligence Scale for Children, Fourth Edition (WISC-IV; Wechsler, 2003) required participants to recall a series of orally-presented digits in the same order that they heard them or in reverse (α = .78). For the Spatial Span subtest from the WISC as a Process Instrument, Third Edition (WISC-III-PI; Kaplan, Fein, Kramer, Delis, & Morris, 1999), a series of blocks were tapped by an experimenter, and participants were required to tap them in order or in reverse (α = .76).

Oral language.—The Receptive and Expressive Vocabulary and Synonyms subtests from the Test of Word Knowledge (TOWK; Wiig & Secord, 1992) required participants to look at a set of pictures and select the picture that best represented an orally-presented word (receptive; α = .89), name pictures with one-word answers (expressive; α =.82), and choose the best synonym for the presented target word based on a list of four possible choices (synonyms; α = .88). Ambiguous Sentences from the Test of Language Competence-Expanded (TLC-E; Wiig & Secord, 1989) required participants to listen to a sentence and interpret alternate meanings (α = .83). The Know-It task (Barnes, Dennis, & Haefele-Kalvaitis, 1996) required participants to listen to a seven-part story and answer questions about the information presented in each section. Reliability for the Literal Questions subtest was somewhat low (α = .50) likely because there were only seven items; however, overall reliability for this task was high (α = .77).

The Test of Morphological Structure (TMS; adapted from Carlisle, 2000) required participants to listen to sentences and decompose morphologically related variants of a word to obtain the root word (decomposition; α = .89) and derive an appropriate morphological variant of a root word to complete a sentence (derivation; α = .88). The Test of Morphological Relatedness (adapted from Mahony, Singson, & Mann, 2000) required participants to determine whether orally presented derived and root words were related (α = .60; Spencer et al., 2018).

Decoding.—The Sight Word Efficiency (SWE) and Phonetic Decoding Efficiency (PDE) subtests from the Test of Word Reading Efficiency (TOWRE; Torgesen, Wagner, & Rashotte, 1999) measured timed word reading and decoding (SWE and PDE α = .97 and .96, respectively). The Letter-Word Identification (ID) and Word Attack subtests from the Woodcock-Johnson-III (WJ-III; Woodcock, McGrew, & Mather, 2001) measured untimed word and nonword reading (Letter-Word ID and Word Attack α = .94 and .91, respectively). *W* scores were used for WJ-III.

RC.—The Comprehension subtest from the Gates-MacGinite Reading Test, Fourth Edition (GMRT-4; MacGinite, MacGinite, Maria, & Dreyer, 2002) required participants to silently read a passage and answer comprehension questions (α = .93). The WJ-III (Woodcock et al., 2001) Passage Comprehension required participants to read a passage of text and fill in missing words within each passage (α = .88). *W* scores were used for WJ-III.

Socioeconomic Status (SES).—The Hollingshead Four-Factor Index (Hollingshead, 1975) assesses SES based on parents' educational and occupational information.

Analytic Approach

We decided to represent several observed indicators using averaged composite scores created using SPSS software (Version 25; IBM, 2017) prior to modeling. We then assessed the direct effects of WM and CF on RC as well as indirect effects via decoding and oral language using Mplus software (Version 7.11; Muthén & Muthén, 1998–2013). We conducted bootstrapping for the final models. Based on recommendations for small sample sizes and the observed (standardized) effect size estimates of the *a* and *b* paths, we obtained non-bias corrected bootstrapped 95% confidence intervals (CIs), which are less prone to Type I error (see Fritz, Taylor, & MacKinnon, 2012). Model fit was assessed using conventionally accepted guidelines of good fit (Hu & Bentler, 1999): Non-significant chi-square (χ^2) values, comparative fit and Tucker-Lewis indices greater than or equal to .95, and root mean square error of approximation and standardized root mean square residual values less than .05.

Results

Preliminary Analyses

Prior to SEM, data were screened for univariate and multivariate outliers and normality. Univariate outliers were identified using the median +/− two interquartile ranges criterion. Using this method, outliers accounted for 1.90% of the total data across cognitive measures. We replaced these values with the highest and lowest values within the range (1.71% of the data included outliers at the lower end and 0.19% of the data included outliers at the upper end). Following this, we identified multivariate outliers using Mahalanobis distance across the 20 cognitive variables. Three multivariate outliers were identified at $p < .001$ and were removed from all analyses. Skewness and kurtosis values were all within an acceptable range (see Tables A.1 and A.2 in the Appendices for descriptive statistics and correlations, respectively). We addressed missing data (~4%) using full information maximum likelihood estimation.

We then created averaged composite scores for vocabulary (TOWK Expressive Vocabulary, Receptive Vocabulary, and Synonyms; α = .88), decoding fluency (TOWRE SWE and PDE; α = .91), decoding accuracy (WJ-III Letter-Word ID and Word Attack; α = .90), and sentence span (Sentence Span All Words and Correct Order; α = .99). Initially, we created separate composites for morphological awareness (TMS Decomposition and Derivation, Test of Morphological Relatedness) and language comprehension (TLC-E Ambiguous Sentences and Know-It Task). However, reliability for these two composites were low (α = .69 and α = .33); thus, we combined these five assessments into a single morphological awareness/ language comprehension composite score, which resulted in greater reliability (α = .72). Following this, we specified a series of confirmatory factor analysis models for all constructs (see Table A.3 in the Appendix).

Initially, we specified WISC Spatial Span as an indicator of WM, but there was some indication that this measure cross-loaded onto both WM and CF factors (see Appendix B); thus, we decided to omit WISC Spatial Span from the analyses. This final model (Model C4) included five latent variables represented by GMRT and WJ Passage Comprehension (RC); the morphological awareness/language comprehension and vocabulary composite scores (Oral Language); the decoding accuracy and decoding fluency composites (Decoding); the sentence span composite and WISC Digit Span (WM); and D-KEFS Verbal and Perceptual Spans (CF; see Figure A.1 in the Appendix). This model provided a good fit to the data, χ^2 = 34.768 (25), p = .093; CFI = .995; TLI = .991; RMSEA = .038, p-close = .726, 90% CI [0.000, 0.066]; SRMR = .022 (see Table A.4 in the Appendix for factor loadings).

Mediation Models

We specified a partial mediation model to examine the direct and indirect effects of CF and WM on RC through decoding and oral language (see Figure 1a). Decoding and oral language were allowed to correlate in order to account for the shared variance between the two variables (see Preacher & Hayes, 2008). We included age and SES as control variables across all models, and unstandardized estimates are reported.

The initial partial mediation model provided adequate fit to the data (Model M1; see Table 1). Given model fit, we aimed to improve fit by taking a step-by-step modeling testing approach (i.e., constraining each non-significant parameter to zero, aside from control variables, within each subsequent model to examine the impact of omitting each parameter). We then compared each pair of nested models using chi-square difference testing. Using this approach, we found that the paths from WM to RC ($b = -0.209$, $p = .632$ in Model M1), CF to RC ($b = 0.458$, $p = .164$ in Model M2), and CF to decoding ($b = 0.523$, $p = .154$ in Model M3) were the weakest in each subsequent model specified. Thus, Model M2 did not include the path from WM to RC; Model M3 did not include paths from WM to RC and from CF to RC; and Model M4 did not include paths from WM to RC, CF to RC, and CF to decoding. Omitting these parameters did not result in significant chi-square differences between models (see Table 1), indicating that the most parsimonious final model (Model M4) was more appropriate than the other three models. The final model (see Figure 1b) provided adequate fit to the data, $\chi 2 = 96.272$ (38), $p < .001$; CFI = .972; TLI = .953; RMSEA = .075, 90% CI [0.057, 0.094], p-close = .014; SRMR = .036. A large proportion of the variance was explained for RC ($R^2 = .952$); EF explained more variance in oral language ($R^2 = .786$) relative to decoding ($R^2 = .569$).

Direct and indirect effects.—We report the direct and indirect path estimates and bootstrapped 95% CI[1] for the final model (Model M4) in Table 2. Oral language ($b = 1.506$; 95% CI [1.146, 1.949]) and decoding ($b = 0.274$, 95% CI [0.114, 0.408]) were both directly related to RC. WM was directly related to decoding ($b = 4.581$, 95% CI [3.530, 5.832]), and CF was directed related to oral language ($b = 0.572$, 95% CI [0.343,1.695]). WM was indirectly related to RC via decoding ($b = 1.253$, 95% CI [0.494, 2.054]) whereas CF was indirectly related to RC via oral language ($b = 0.862$, 95% CI [0.478, 2.588])

Discussion

In the current study, we examined relations between EF (CF and WM) and RC. As expected, oral language and decoding were related to RC; EF was also related to RC via oral language and decoding. Although the indirect association between EF and RC was not surprising given the theoretical and empirical evidence regarding relations between EF and reading-related skills (Cartwright, 2015; Daneman & Carpenter, 1980; Kintsch, 1988; Perfetti, 1999), the results of the present investigation further add to what is known about *how* EF relates to RC. As hypothesized, we found that EF accounted for a greater proportion of the variance in oral language than decoding. These findings are in line with previous research showing that EF is associated with both oral language and decoding (e.g., Adams et al., 1999; Beneventi et al., 2010; Christopher et al., 2012; Galaburda, 1999). The final model, which accounted for over 95% of the variance in RC, supports the notion that EF-related skills are a potentially important component of the RC process and emphasizes the need for further study.

Path estimates indicated that WM was related to decoding whereas CF was associated with oral language. These findings are in line with previous investigations showing that WM and

[1]Although we requested 5,000 bootstrap draws for the final model, 4,972 draws were completed for Model M4.

CF are important for decoding and language skills, respectively (Gottardo et al. 1996; Pauls & Archibald, 2016). The finding that EF skills are related to RC *via* decoding and oral language supports the notion that children's RC performance is related to several domain-general cognitive skills; yet, the specificity of these relations suggests that these associations may be dependent on the specific EF skill(s) examined.

While previous research has shown that EF and RC are correlated (Cain, Oakhill, & Bryant, 2004; Cartwright et al., 2010; Locascio et al., 2010), our findings add a layer of complexity by illustrating how these skills are interrelated and invite speculation as to *why* such relations exist. Reading and comprehending text requires a multitude of different processes, including the ability to retain and manipulate phonological information (WM; Baddeley, 1986) and shift between multiple sources of orthographic, phonological, and semantic information (CF; Zorzi et al., 1998). The complex integration of these processes is highlighted within multiple theories of word recognition (Coltheart et al., 2001; Zorzi et al., 1998) and RC (e.g., C-I model; Kintsch, 1988) as well as within the current findings.

Similarly, the comprehension of oral language also requires an individual to retain auditory input (WM; Plaza et al., 2002) and integrate novel linguistic information with previous knowledge (CF; Pauls & Archibald, 2016). This may explain why children who have deficits in oral language also have impairments across both domains of EF (e.g., Archibald & Gathercole, 2006; Pauls & Archibald, 2016). Such complexities may additionally provide some explanation for how decoding and oral language may mediate the relation between CF and WM and RC. For instance, given relations between EF and vocabulary development (Weiland, Barata, & Yoshikawa, 2014), we could speculate that EF may assist in the transition from understanding the meaning of a single word in isolation to developing a contextually-based understanding of a word or multiple words within a passage, which would be consistent with integrative models of RC that posit that both bottom-up (lower-level) and top-down (higher-level) cognitive processes facilitate RC (Kintsch, 1988; Perfetti & Stafura, 2014).

However, further investigation is needed to better elucidate the nature of these relations, as we did not find that EF was directly related to RC nor did we assess RC-specific components of EF in the current study. For instance, previous investigations have shown that visuospatial WM is associated with oral language (Vugs, Cuperus, Hendriks, & Verhoeven, 2013) as well as RC (Pham & Hasson, 2014), likely because of its role in language processing (i.e., the visuospatial sketchpad; Baddeley, 1974) and the importance of visual information processing for text reading (Cohen et al., 2000; LaBerge & Samuels, 1974). Therefore, the absence of direct relations between WM and oral language and between WM and RC in the current investigation may be partially due to the fact that WM was based only on measures of phonological WM in contrast to a visuospatial (or a combined phonological/visuospatial) WM factor.

The finding that WM and CF are associated with RC via oral language and decoding suggests that both skills are important for the comprehension and processing of language. For instance, models of word recognition (Coltheart et al., 2001; Seidenberg & McClelland, 1989; Zorzi et al., 1998) assert that word reading relies, at least partly, on the ability to successfully retrieve prior information about the words being read. Further, there is also empirical evidence that supports the idea that WM and CF are important for general language processing and RC (Adams et al., 1999; Cain et al., 2004; Cartwright, 2015; Cartwright et al., 2010; Daneman & Carpenter, 1980; Florit et al., 2009; Roello et al., 2015). Although WM and CF were not directly related to RC in the current investigation, their indirect association to RC through oral language and decoding is supported several interactive theories of RC (e.g., the C-I model, the RSF, and the landscape model; Kintsch, 1988; Perfetti, 1999; van den Broek, Young, Tzeng, & Linderholm, 1999), which acknowledge that WM processes and the ability to shift between multiple sources of information (CF) likely interact with more fundamental RC-related skills (i.e., word recognition and language) during text comprehension.

Theoretical and Practical Implications

Our results have several theoretical and practical implications. Regarding theory, the implications are threefold. First, the current investigation builds on theories of RC by demonstrating that observed relations between EF and RC are associated via components of RC rather than RC directly. Thus, the current findings highlight the need for theories to consider a more complex view of RC as well as additional alternative associations between EF, language comprehension, decoding, and RC. Second, the findings further build upon this framework by showing that CF and WM vary in their predictive utility for bottom-up (decoding) and top-down (oral language) processes. For example, WM was significantly associated with decoding but CF was not. This outcome may be explained by the fact that, in the current study, decoding included measures of nonword reading, which may rely more on WM-specific process (i.e., phonological memory; Gathercole, 1995). On the other hand, we found that CF was significantly associated with oral language, supporting the notion that CF may, in fact, play a role in language development (e.g., Pauls & Archibald, 2016). Third, the current results add to interactive theories of RC by further elucidating the process by which components of EF are related to RC. For instance, the RSF (Perfetti, 1999) posits that lexical knowledge mediates the relation between the reader's mental model and his/her construction and integration of knowledge (and subsequent RC). The results support this process-based model and explicitly identify additional cognitive processes that may be associated with RC.

The present findings have several implications for practice as well. First, our results could be viewed as implying that certain aspects of EF would be a positive addition to test batteries aimed at targeting children who may be struggling with RC; EF, oral language, and decoding explained a large proportion of the shared variance in RC, and EF was related to RC indirectly via oral language and decoding. Therefore, it may not be particularly advantageous to additionally include measures of EF as part of a *concurrent* screening battery for RC difficulties. However, the degree of shared variance amongst skills suggests that EF could integrate with decoding and oral language processes in important ways and that perhaps administering EF measures may play an important role in predicting downstream RC outcomes. However, these findings must be approached cautiously given that these data were correlational and also that there were no direct effects of EF on RC. Longitudinal studies will need to unpack the current findings in order to further elucidate how EF may facilitate RC over development (e.g., Cutting, Bailey, Aboud, & Barquero,

2015) and to identify the specific relations between components of EF and both decoding and oral language. Given that EF is comprised of a variety of different skills, several of which do not fully develop until adolescence (e.g., Anderson, 2002), it would be particularly informative for future longitudinal investigations to examine relations between EF and RC throughout adolescence.

Second, the observed relations between components of EF and oral language and decoding indicate that intervention programs aimed at building decoding and/or oral language may also potentially benefit from an EF component (e.g., Loosli, Buschkeuhl, Perrig, & Jaeggi, 2012; Peng & Fuchs, 2017). Of note, while certain EF training programs have demonstrated that some EF skills can be taught and do, in fact, result in gains in RC (e.g., CF; see Cartwright, 2002 and Cartwright et al., 2017), such findings are not consistent. For example, there is evidence that WM interventions do not necessarily transfer to RC (Dahlin, Neely, Larsson, Bäckman, & Nyberg, 2008; Dunning, Holmes, & Gathercole, 2013; for exceptions, see Chein & Morrison, 2010 and Dahlin, 2011). Therefore, it is likely that the integration of EF *within* RC interventions, rather than isolated EF training, will better facilitate RC growth. However, it remains important to examine the extent to which components of current RC interventions assist the development of EF (e.g., interventions that teach RC strategies may additionally promote metacognitive skills). Third, the finding that oral language and decoding mediate the relations between WM and CF further suggest that EF skills likely need to be targeted in conjunction with oral language and decoding (i.e., embedded within interventions aimed at strengthening RC skills), as opposed to in isolation. Overall, the findings of the present study are an important contribution that adds to what is known about EF and decoding, oral language, and RC.

Limitations and Conclusions

There are several limitations of the current investigation that must be addressed. First, although we had a rich battery of measures, our analytical modeling was limited by sample size. A larger sample would have allowed us to detect weaker associations, such as those between WM and oral language and CF and decoding. Second, model fit for the final mediation model was adequate, but not excellent, emphasizing the need for alternative models to be tested in future studies. Third, we measured only two domains of EF (WM and CF; e.g., Miyake & Friedman, 2012). While many would agree that the components examined in the present study are aspects of EF, prior research has shown that other measures of EF also predict RC (e.g., inhibition and attention shifting; Borella, Carretti, & Pelegrina, 2010; Christopher et al., 2012; Cutting et al., 2009; Kieffer et al., 2013). Fourth, our findings are generalizable only to English-speaking readers. Finally, the current investigation is not longitudinal, which limits our ability to make statements regarding whether these observed relations may shift over time.

In summary, our study adds to the growing literature concerning the role of EF in RC. In particular, it extends what is known about these relations by including multiple indices of EF not previously examined and by investigating these relations within a single model. WM and CF both emerged as being significantly associated with RC; this association was mediated by decoding and oral language. Future investigations should include additional measures of

EF, larger sample sizes, and different populations of readers as a means of further elucidating how these skills interact and are associated with RC. Incorporating a broader conceptualization of EF will provide a more comprehensive understanding of EF and RC and potentially identify additional targets for intervention programs designed to help children who struggle to read.

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Appendix A Participant Exclusionary Criteria

Participants were excluded if they had: (a) a previous diagnosis of intellectual disability; (b) known uncorrectable visual impairment; (c) treatment of any psychiatric disorder (other than ADHD) with psychotropic medications; (d) history of known neurologic disorder; (e) documented hearing impairment greater than or equal to a 25 dB loss in either ear; (f) known IQ below 80 or a score below 70 on the administered Wechsler Intelligence Scale for Children – 4th edition (WASI) after enrollment in the study; and/or (g) the history of or presence of a pervasive developmental disorder.

Appendix B Confirmatory Factor Analysis Model Testing Approach

Initially, we specified a model in which Spatial Span loaded onto the Working Memory factor (Model C1). However, the standardized loading was lower for this measure (λ = .482, $p < .001$) compared to the Sentence Span Task (λ = .798, $p < .001$) and Digit Span (λ = .763, $p < .001$), and when we examined the effect of specifying this measure as loading onto the Cognitive Flexibility factor instead of the Working Memory factor (Model C2), it resulted in a similar pattern of findings (λ = .485, $p < .001$ for Spatial Span compared to λ = .530, $p < .001$ for Verbal Sorting and λ = .686, $p < .001$ for Perceptual Sorting) and model fit (ΔAIC and BIC = 4.059). Thus, we specified a third model, in which Spatial Span cross-loaded onto both the Working Memory and Cognitive Flexibility factors (Model C3). Although Model C3 did not provide an overall better fit to the data than Model C1 ($\Delta\chi^2$ = 3.048(1), $p = .081$), Model C3 did provide significantly better fit than Model C2 ($\Delta\chi^2$ = 7.107(1), $p = .008$). This finding, coupled with the fact that the evidence was not strong for better fit across Models C1 and C2 (i.e., differences in AIC and BIC values that were less than 10; Dziak, Coffman, Lanza, & Li, 2012), we omitted Spatial Span from the final model (Model C4) and from subsequent analyses. This was done in order to specify Working Memory and Cognitive Flexibility factors that were relatively distinct constructs based on (a) correlations between latent variables (i.e., correlations were .736 for Model C1 and .740 for Model C2 compared to .702 for Model C4) and (b) the absence of overlap in their respective observed indicators.

Table A.1

Descriptive Statistics for All Measures and Composite Scores

Measure	*N*	Min.	Max.	Mean	*SD*	Skewness	Kurtosis
1. Age	271	9.00	14.83	11.660	1.355	0.319	−0.914
2. Sex	271	0	1	0.509	0.501	−0.037	−2.014
3. SES	257	26	62	49.494	7.638	−0.524	−0.227
4. TOWRE SWE	266	41	104	72.752	13.227	−0.329	0.116
5. TOWRE PDE	266	0	72	36.650	14.197	−0.518	−0.477
6. WJ-III Letter-Word Identification[a]	264	463	581	520.970	24.486	−0.631	0.066
7. WJ-III Word Attack[a]	262	456	545	508.328	19.140	−0.375	−0.120
8. TOWK Expressive Vocabulary	263	11	31	21.163	4.038	0.159	−0.355
9. TOWK Receptive Vocabulary	263	15	42	32.251	6.261	−0.559	−0.311
10. TOWK Synonyms	261	14	41	31.215	5.930	−0.632	−0.303
11. TMS Decomposition	254	19	28	25.150	2.976	−0.953	−0.373
12. TMS Derivation	254	6	28	20.823	5.289	−0.819	0.068
13. Test of Morph. Relatedness	253	8	12	9.700	0.915	−0.276	−0.153
14. TLC-E Ambiguous Sentences	265	2	39	22.464	8.589	−0.305	−0.762
15. Know-It Comprehension LQ	245	5.50	14.00	10.863	2.186	−0.748	−0.097
16. GMRT Reading Comprehension	259	5	48	32.432	11.022	−0.579	−0.830
17. WJ-III Passage Comprehension[a]	267	473	545	507.869	14.843	−0.451	−0.100
18. Sentence Span - All Words	264	0	12	6.367	2.267	0.149	−0.477
19. Sentence Span - Correct Order	264	0	12	6.163	2.267	0.096	−0.464
20. WISC-III-PI Spatial Span	258	5	25	14.829	3.421	0.271	0.153
21. WISC-IV Digit Span	259	8	26	16.367	3.779	0.641	0.154
22. D-KEFS Verbal Sorting	258	0	44	20.709	8.937	0.035	−0.289
23. D-KEFS Perceptual Sorting	258	7	77	41.597	14.783	−0.313	−0.149
24. Vocabulary[b]	261	15.00	37.67	28.209	4.950	−0.315	−0.567
25. Morph. Awareness/LC[b]	236	8.30	23.80	17.976	3.240	−0.615	−0.121
26. TOWRE[b]	266	20.50	88.00	54.701	13.118	−0.447	−0.202
27. WJ Decode[b]	260	459.50	559.50	514.808	20.943	−0.578	−0.148
28. Sentence Span[b]	264	0	12.00	6.265	2.255	0.126	−0.503

Note. Raw scores reported unless otherwise noted.

[a]W scores;

[b]Composite based on averaged scores; Min. = Minimum; Max. = Maximum; *SD* = Standard deviation; SES = Socioeconomic status; TOWRE = Test of Word Reading Efficiency; SWE = Sight word efficiency; PDE = Phonetic decoding efficiency; WJ = Woodcock-Johnson Tests of Achievement; TLC-E = Test of Language Competence, Expanded; TOWK = Test of Word Knowledge; TMS = Test of Morphological (Morph.) Structure; GMRT = Gates-MacGinitie Reading Test; LC = Language comprehension; LQ = Literal questions; WISC = Wechsler Intelligence Scale for Children; PI = Process Instrument; D-KEFS = Delis-Kaplan Executive Function System.

Table A.2

Correlations Across All Measures

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1. Age	–																						
2. Sex	−.111	–																					
3. SES	−.063	−.038	–																				
4. TOWRE SWE	.370**	.040	.181**	–																			
5. TOWRE PDE	.246**	.004	.228**	.830**	–																		
6. WJ-III Letter-Word Identification [a]	.339**	−.018	.245**	.797**	.849**	–																	
7. WJ-III Word Attack [a]	.248**	−.001	.259**	.720**	.862**	.850**	–																
8. TOWK Expressive Vocabulary	.347**	−.136*	.232**	.550**	.525**	.662**	.521**	–															
9. TOWK Receptive Vocabulary	.369**	−.039	.244**	.599**	.577**	.651**	.555**	.719**	–														
10. TOWK Synonyms	.409**	−.074	.233**	.626**	.643**	.737**	.621**	.739**	.772**	–													
11. TMS Decomposition	.353**	.067	.259**	.684**	.670**	.766**	.654**	.654**	.744**	.774**	–												
12. TMS Derivation	.369**	.024	.277**	.659**	.660**	.743**	.646**	.678**	.738**	.809**	.833**	–											
13. Test of Morphological Relatedness	.039	.012	.178**	.331**	.326**	.390**	.354**	.349**	.288**	.322**	.408**	.402**	–										
14. TLC-E Ambiguous Sentences	.271**	.020	.229**	.520**	.556**	.598**	.546**	.636**	.664**	.653**	.624**	.674**	.321**	–									
15. Know-It Comprehension LQ	−.009	.085	.177**	.291**	.301**	.290**	.263**	.341**	.407**	.406**	.391**	.385**	.152*	.409**	–								
16. GMRT Reading Comprehension	.081	.103	.352**	.637**	.690**	.731**	.657**	.635**	.671**	.675**	.739**	.716**	.419**	.606**	.479**	–							
17. WJ-III Passage Comprehension [a]	.330**	−.004	.302**	.720**	.691**	.794**	.672**	.682**	.685**	.720**	.740**	.752**	.396**	.656**	.442**	.775**	–						
18. Sentence Span - All Words	.257**	−.132*	.207**	.489**	.451**	.534**	.450**	.515**	.551**	.536**	.451**	.488**	.259**	.532**	.374**	.464**	.564**	–					
19. Sentence Span - Correct Order	.249**	−.135*	.207**	.496**	.476**	.552**	.465**	.516**	.555**	.537**	.468**	.512**	.268**	.537**	.372**	.483**	.577**	.978**	–				

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
20. WISC-III-PI Spatial Span	.317**	−.045	.172**	.346**	.315**	.319**	.328**	.317**	.340**	.350**	.287**	.293**	.135*	.283**	.183**	.311**	.344**	.370**	.389**	–			
21. WISC-IV Digit Span	.234**	.011	.217**	.508**	.571**	.557**	.559**	.422**	.459**	.470**	.476**	.493**	.180**	.448**	.279**	.489**	.519**	.614**	.617**	.339**	–		
22. D-KEFS Verbal Sorting	.206**	−.035	.168**	.360**	.331**	.393**	.340**	.323**	.373**	.385**	.406**	.434**	.193**	.382**	.158*	.418**	.404**	.293**	.297**	.265**	.226**	–	
23. D-KEFS Perceptual Sorting	.148*	.175**	.291**	.302**	.335**	.401**	.317**	.440**	.502**	.480**	.427**	.476**	.266**	.491**	.228**	.500**	.472**	.367**	.381**	.334**	.380**	.346**	–

Note. Across measures, N = 235–271. SES = Socioeconomic status; TOWRE = Test of Word Reading Efficiency; SWE = Sight word efficiency; PDE = Phonetic decoding efficiency; WJ = Woodcock-Johnson Tests of Achievement; TLC-E = Test of Language Competence, Expanded; TMS = Test of Morphological Structure; TOWK = Test of Word Knowledge; TMS = Test of Morphological Structure; LQ = Literal Questions; GMRT = Gates-MacGinitie Reading Test; WISC = Wechsler Intelligence Scale for Children; PI = Process Instrument; DKEFS = Delis-Kaplan Executive Function System.

* $p < .05$;

** $p < .01$

Table A.3

Fit Indices for Confirmatory Factor Analysis Models

Model	$\chi 2$	*df*	*p*-value	CFI	TLI	RMSEA	p-close	SRMR	AIC	BIC	Comparison	Nested				Non-Nested	
												$\Delta\chi^2$	Δdf	*p*-value		ΔAIC	ΔBIC
C1	46.720	34	.072	.994	.990	.037	.781	.027	17411.509	17565.921	C2 vs. C1	–	–	–		4.059	4.059
C2	50.779	34	.032	.992	.987	.043	.664	.027	17415.568	17569.980	C3 vs. C1	3.048	1	0.081		–	–
C3	43.672	33	.101	.995	.991	.035	.820	.024	17410.461	17568.464	C3 vs. C2	7.107	1	0.008		–	–
C4	34.768	25	.093	.995	.991	.038	.726	.022	16093.758	16237.397	–	–	–	–	–	–	–

Note. Model C1 = Spatial span loading onto the working memory factor; Model C2 = Spatial span loading onto the cognitive flexibility factor; Model C3 = Spatial span cross-loading onto the working memory and cognitive flexibility factors; Model C4 = Spatial span omitted from the analyses. χ^2 = Chi-square; *df* = degrees of freedom; CFI = Comparative fit index; TLI = Tucker-Lewis index; RMSEA = Root mean square error of approximation; SRMR = Standardized root mean square residual; AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; *N* = 268.

Table A.4

Factor Loadings for the Final Confirmatory Factor Analysis Model (Model C4)

Latent Variable	Indicator	Estimate	*SE*
Word Reading			
	TOWRE[a]	0.917	0.014
	WJ Decode[a]	0.965	0.011
Oral Language			
	Vocabulary[a]	0.910	0.015
	Morphological Awareness/Language Comprehension[a]	0.935	0.013
Reading Comprehension			
	GMRT Comprehension	0.863	0.019
	WJ-III Passage Comprehension	0.902	0.016
Working Memory			
	Sentence Span[a]	0.799	0.037
	WISC-IV Digit Span	0.773	0.038
Cognitive Flexibility			
	D-KEFS Verbal Sorting	0.519	0.058
	D-KEFS Perceptual Sorting	0.672	0.058

Note. Standardized estimates reported. All loadings are significant at $p < .001$;

[a]Composite; TOWRE = Test of Word Reading Efficiency; WJ = Woodcock-Johnson Tests of Achievement; GMRT = Gates-MacGinitie Reading Test; WISC = Wechsler Intelligence Scale for Children; D-KEFS = Delis-Kaplan Executive Function System. $N = 268$.

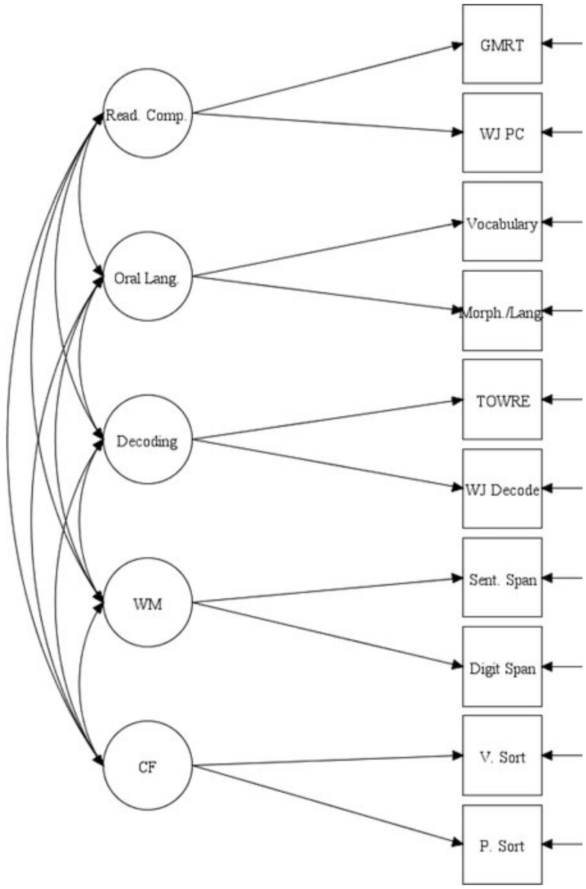

Figure A.1.

Final confirmatory factor analysis measurement model (Model C4). *Note*. Composite scores used for measures of vocabulary, morphological awareness/language comprehension, decoding, and sentence span tasks. Read. Comp. = Reading comprehension; Lang. = Language; WM = Working Memory; CF = Cognitive Flexibility; GMRT = Gates-MacGinitie Reading Test; WJ PC = Woodcock-Johnson Passage Comprehension; Morph. = Morphological awareness; TOWRE = Test of Word Reading Efficiency; WJ = Woodcock-Johnson Tests of Achievement; Sent. = Sentence; V = Verbal; P = Perceptual.

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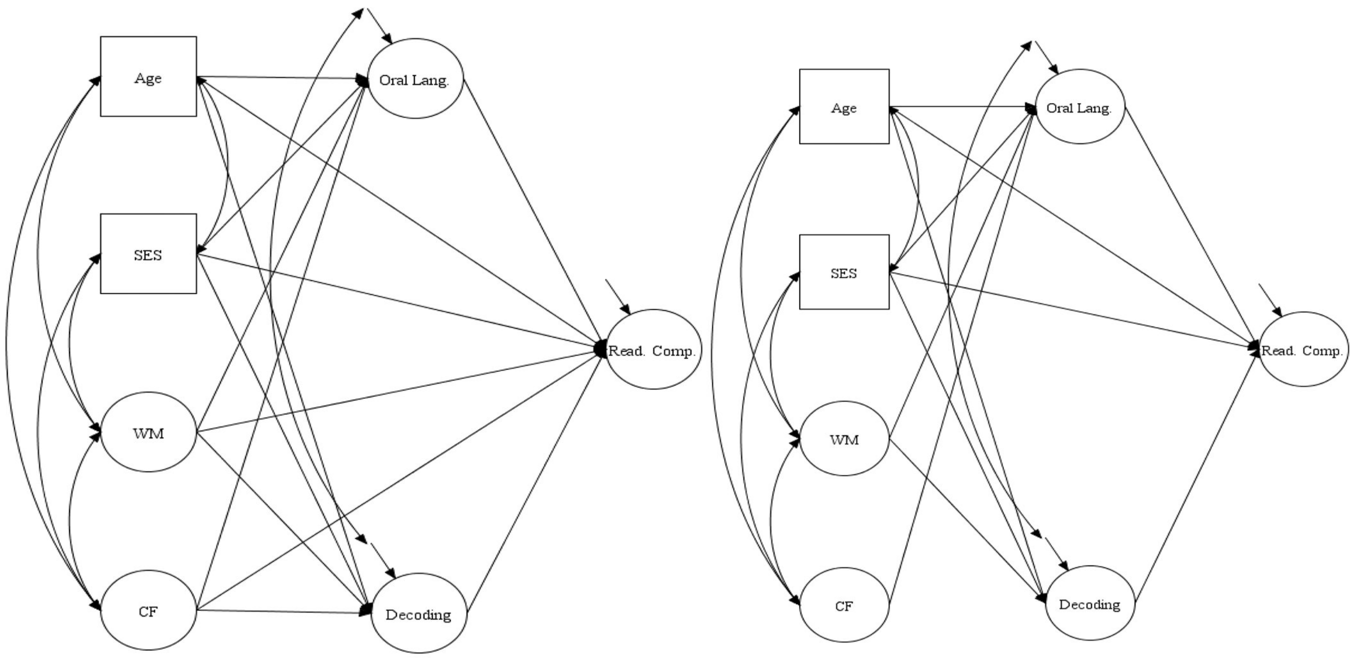

(a) Model M1

(b) Model M4

Figure 1.

Initial partial mediation model (a) and final mediation model (b). *Note*. Read. Comp. = Reading comprehension; Lang. = Language; SES = Socioeconomic status; WM = Working memory; CF = Cognitive flexibility.

Table 1

Fit Indices for Tested Structural Equation Mediation Models

	Fit Indices								Model Comparison			
Model	**χ^2**	***df***	***p*−value**	**CFI**	**TLI**	**RMSEA**	**p-close**	**SRMR**	**Comparison**	**$\Delta\chi^2$**	**Δdf**	***p*−value**
M1	91.538	35	< .001	.973	.950	.077	.011	.031	M2 vs. M1	0.247	1	.619
M2	91.785	36	< .001	.974	.952	.076	.015	.031	M3 vs. M2	2.359	1	.125
M3	94.144	37	< .001	.973	.952	.075	.014	.031	M4 vs. M3	2.128	1	.145
M4	96.272	38	< .001	.972	.953	.075	.014	.036		–	–	–

Note. χ^2 = Chi-square; *df* = degrees of freedom; CFI = Comparative fit index; TLI = Tucker-Lewis index; RMSEA = Root mean square error of approximation; SRMR = Standardized root mean square residual; $N = 271$.

Table 2

Direct and Indirect Effects of Cognitive Flexibility (CF) and Working Memory (WM) on Reading Comprehension (RC) for Model M4

				Bootstrapped 95% Confidence Intervals	
Path	**Construct**	**Estimate**	***SE***	**Lower**	**Upper**
Direct Effects on RC					
	DC	**0.274**	0.076	0.114	0.408
	OL	**1.506**	0.203	1.146	1.949
	Age	**−1.116**	0.308	−1.749	−0.524
	SES	0.079	0.046	−0.009	0.171
Indirect Effects via DC					
	WM	**1.253**	0.404	0.494	2.054
	Age	**0.323**	0.165	0.032	0.660
	SES	0.041	0.029	−0.011	0.103
Indirect Effects via OL					
	WM	1.252	1.385	−1.745	2.166
	CF	**0.862**	0.821	0.478	2.588
	Age	0.762	0.516	−0.172	1.389
	SES	−0.004	0.146	−0.308	0.108
Direct Effects on DC					
	WM	**4.581**	0.592	3.530	5.832
	Age	**1.181**	0.514	0.146	2.125
	SES	0.149	0.094	−0.044	0.324
Direct Effects on OL					
	WM	0.832	0.896	−1.100	1.347
	CF	**0.572**	0.522	0.343	1.695
	Age	0.506	0.328	−0.113	0.868
	SES	−0.003	0.094	−0.206	0.071

Note. Confidence intervals that do not contain zero (bolded) are statistically significant. Estimates are unstandardized. *SE* = Standard error; DC = Decoding; OL = Oral language.