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Direct and indirect contributions of executive function to word decoding and reading comprehension in kindergarten

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ABSTRACT

Extant research is increasingly recognizing the contribution of executive function (EF) to reading comprehension alongside established predictors like word decoding and oral language. The nature of the association between EF and reading comprehension is commonly investigated in older children and in those with reading impairments. However, less is known about this relationship in emerging readers in kindergarten, where word decoding and reading comprehension are highly intertwined. Moreover, a better understanding of the mechanisms by which EF influences reading comprehension is needed. The present study investigated direct contributions of EF to reading comprehension, as well as indirect contributions via word decoding in 97 kindergarteners. Results indicated that there was a significant indirect effect of EF on reading comprehension, with word decoding mediating this association. The direct contribution of EF to reading comprehension was not significant. Implications for reading instruction and intervention for early readers are discussed.

1. Introduction

The ultimate goal of reading is comprehension. Competence in reading comprehension in childhood holds implications for academic achievement throughout childhood as well as occupational and social outcomes in adulthood (Goldman & Pellegrino, 2015; Smart et al., 2017). In light of these important consequences, a large body of research has focused on understanding component skills that enable successful reading comprehension. There is general consensus that reading comprehension relies largely on the ability to decode words for young readers. Recently, studies have also highlighted the role of executive functions (EFs), a collection of goal-oriented cognitive skills, in reading comprehension. Currently, however, the pathways by which EF supports reading comprehension are understudied, especially in the context of established predictors such as word decoding. Moreover, it is unclear if and how EF contributes to reading comprehension in kindergarten, where comprehension and word decoding are highly intertwined. Constructing more specified models of how EF, word decoding, and reading comprehension relate in kindergarten is necessary to more efficiently target reading difficulties in young children.

1.1. Models of reading comprehension

Reading comprehension involves extracting meaning from a written text. This process is incredibly complex, and relies upon the successful integration of several components. Reflecting this inherent complexity, several theories and models of reading comprehension have been proposed. The Simple View of Reading (Gough & Tunmer, 1986; Hoover &

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Gough, 1990) conceptualizes reading comprehension as the product of word decoding and oral language comprehension. Word decoding can refer to simple mapping of print to sounds, but in reality encompasses a number of lexical and sublexical processes including phonological awareness and orthographic processing (Ehri, 2005; Goswami & Bryant, 1990). Oral language (sometimes referred to as linguistic or listening comprehension) refers to a host of spoken language skills such as morphology, syntax, vocabulary, and inference-making skills (Braze, Tabor, Shankweiler, & Mencl, 2007; Kirby & Savage, 2008; Lepola, Lynch, Laakkonen, Silvén, & Niemi, 2012). Thus according to the Simple View of Reading, one must be able both to accurately identify the words and to extract meaning from those words in order to understand the text one has read.

Other conceptualizations of reading comprehension have focused on the importance of social-cognitive processes (*the lattice model*; Connor, 2016), general cognitive abilities (*structure-building framework*; Gernsbacher, 1991), causal reasoning (*the causal network model*; Trabasso, 1989), top-down search strategies (*the constructionist theory*; Graesser, Singer, & Trabasso, 1994), activation of concepts (*the landscape model*; Van den Broek, Young, Tzeng, & Linderholm, 1999), background knowledge (*the direct and inferential mediation model*; Cromley & Azevedo, 2007) and the integration of knowledge from the text with schemata in long-term memory (*Construction-Integration model*; Kintsch, 1988, 2018). These models vary in the number of components included and the level of mechanistic explanation provided (see McNamara & Magliano, 2009 for more in-depth descriptions). These models can also be categorized as focusing on either component skills involved in reading comprehension (e.g. Simple View of Reading), or on mental processes involved in reading comprehension (e.g. Construction-Integration model; Kendeou, McMaster, & Christ, 2016).

In the present study focused on the role of EF in reading comprehension in kindergarten, a Simple View of Reading is adopted for several reasons. First, the Simple View is easily testable, and there is a large body of empirical studies supporting this model (e.g. Catts, Adlof, & Weismer, 2006; Kendeou, Van den Broek, White, & Lynch, 2009; Kershaw & Schatschneider, 2012; Kirby & Savage, 2008). Second, the Simple View has informed studies concerning the role of EF in reading (e.g. Cutting, Materek, Cole, Levine, & Mahone, 2009). Finally, the Simple View of Reading is developmentally appropriate for understanding reading comprehension in kindergarten. Other models of reading comprehension (e.g. construction-integration, causal network model) have been primarily studied in the context of adult reading, with a focus on lengthier narrative texts. The focus on core components in the Simple View renders it particularly informative for reading in kindergarten where basic skills are rapidly developing.

In line with the Simple View of Reading, word decoding and oral language both show associations with reading comprehension in early childhood (Catts, Hogan, & Fey, 2003; Vellutino, Tunmer, Jaccard, & Chen, 2007), middle childhood (Catts et al., 2006), adolescence (Tilstra, McMaster, Van den Broek, Kendeou, & Rapp, 2009), and adulthood (Sabatini, Sawaki, Shore, & Scarborough, 2010). However, studies have shown that the relative contribution of each component to reading comprehension is asymmetrical and varies with level of reading proficiency as children develop and learn. Specifically, word decoding is more salient for younger readers' comprehension, while oral language is more important for skilled readers (Ouellette & Beers, 2010; Storch & Whitehurst, 2002; Vellutino et al., 2007). As children master decoding skills, word decoding becomes fluent and is no longer a limiting factor in reading comprehension. In addition, by the end of elementary school, the goal of reading comprehension shifts from fact-based, inferential questions to more complicated material. These developmental changes mean that oral language becomes increasingly important for reading comprehension from middle childhood onward (Foorman, Herrera, Petscher, Mitchell, & Truckenmiller, 2015). For children in kindergarten just learning to read, comprehension is more closely tied to word decoding ability than to oral language. In other words, individual differences in word decoding and reading comprehension are highly intertwined in kindergarten, and word decoding has a much greater contribution to reading comprehension than oral language.

1.2. Executive function and reading comprehension

Research has increasingly emphasized the role of executive function (EF) in reading. EF refers to a collection of goal-oriented cognitive processes, typically conceptualized as including inhibitory control, working memory, and cognitive flexibility (Miyake et al., 2000). The present study focuses on inhibitory control, the ability to suppress prepotent responses to maintain current goals and working memory, the ability to hold and mentally manipulate information. From a theoretical perspective, inhibitory control may contribute to reading comprehension by suppressing irrelevant information when building understanding of a text (Cain, 2006). Inhibitory control might also assist readers in overriding previously learned reading habits, facilitating implementation of more effective strategies (Kieffer, Vukovic, & Berry, 2013). Working memory is thought to support reading comprehension in providing the capacity and resources needed to simultaneously decode unfamiliar words, retrieve semantic knowledge, and recall (Sesma, Mahone, Levine, Eason, & Cutting, 2009). One aspect of working memory that may be particularly relevant to reading comprehension is updating – the process of modifying existing content in memory to accommodate new information (Morris & Jones, 1990). Readers must update the mental representation of material as they are progressing through text to achieve adequate comprehension (Gathercole, Alloway, Willis, & Adams, 2006).

Although EF is an umbrella term consisting of the aforementioned components, in younger children EF is typically interpreted as a more unitary construct (Hughes, Ensor, Wilson, & Graham, 2009; Shing, Lindenberger, Diamond, Li, & Davidson, 2010; Wiebe, Espy, & Charak, 2008). For example, a study of working memory and inhibitory control in children and adolescents found that before 7 years of age, these constructs are not differentiated (Shing et al., 2010). Employing single, aggregate measures of EF therefore can maximize reliability in young children (Hughes et al., 2009). This conceptualization may also be more ecologically valid in relating to outcomes such as academic performance in young children, since typically various EF components are leveraged in accomplishing a goal-oriented task. In other words, although working memory and inhibitory control may make separate theoretical contributions to reading performance, in reality these processes work together in many academic or problem-solving tasks (Zelazo, Blair, & Willoughby, 2016; Zhou, Chen, & Main, 2012). In reading, intrusion errors (recalling non-target information) can result from challenges in updating relevant information, and from poor inhibition of irrelevant information. Difficulty inhibiting irrelevant information may partially depend upon the amount of information in working memory that requires inhibition – thus, there is evidence that working memory and inhibitory control can be interdependent (Butterfuss & Kendeou, 2018; Cirino et al., 2018).

A recent meta-analysis found an overall moderate but significant contribution of inhibitory control and working memory to reading comprehension across studies and age ranges (Follmer, 2018). Evidence for the role in EF in reading comprehension comes from several sources: studies of poor comprehenders, studies of poor decoders, studies of proficient readers, and intervention research. Studies comparing good and poor comprehenders matched on word decoding abilities (e.g. Borella, Carretti, & Pelegrina, 2010; Cain, 2006; Cutting et al., 2009; De Beni & Palladino, 2000; Locascio, Mahone, Eason, & Cutting, 2010; Sesma et al., 2009) link specific difficulties in reading comprehension to deficits in inhibitory control or working memory, even after controlling for other variables such as attention, word decoding, reading fluency, and vocabulary. A separate line of research has investigated the role of EF in individuals with reading comprehension that is discrepantly higher than word decoding skills. For example, a recent study found that the left dorsolateral prefrontal cortex, an area that subserves EF, was associated with increased discrepancy between reading comprehension and decoding above and beyond covariates in children 10–16 years old (Patael et al., 2018). These results suggest that EF – and corresponding brain regions – may boost reading comprehension above and beyond decoding at this age. In children without reading disorders, inhibitory control and working memory predict concurrent reading comprehension (Arrington, Kulesz, Francis, Fletcher, & Barnes, 2014; Cain, Oakhill, & Bryant, 2004; Kieffer et al., 2013) as well as future reading comprehension (De Franchis, Usai, Viterbori, & Traverso, 2017; Seigneuric & Ehrlich, 2005). Finally, some studies suggest that training EF may lead to gains in reading comprehension (Cirino et al., 2017; Dahlin, 2011), although evidence for the efficacy of such programs is equivocal (Melby-Lervåg, Redick, & Hulme, 2016). Taken together, these studies suggest that inhibitory control and working memory support reading comprehension in children.

1.3. Executive function and word decoding

In addition to supporting higher-level reading processes such as comprehension, EF may contribute to lower-level processes such as word decoding. Inhibitory control may be needed to suppress orthographically similar words when decoding (Seidenberg, Waters, Barnes, & Tanenhaus, 1984). Relatedly, inhibitory control may override prepotent responses to words in the decoding process, such as guessing a word "too early" based on incomplete phonological information (Messer, Henry, & Nash, 2016). Working memory updating may support the phonological processes necessary to decode a word. Especially when phoneme-grapheme correspondences are still being learned, children must detect, hold, and update individual speech sounds in working memory to enable blending for whole word decoding (Palmer, 2000; Rohl & Pratt, 1995).

Extant research focusing on connections between EF and word decoding contains some mixed findings. Studies report significant associations between working memory and word decoding for preschoolers (Welsh, Nix, Blair, Bierman, & Nelson, 2010) and children 8 to 16 years old (Arrington et al., 2014; Christopher et al., 2012; Jacobson et al., 2017; Kieffer et al., 2013; Messer et al., 2016; van der Sluis, de Jong, & van der Leij, 2007). Inhibitory control has also been found to significantly predict word decoding in middle childhood (Messer et al., 2016). In addition, a study comparing children with poor word decoding skills to controls found that poor decoders had significantly lower performance on inhibitory control and working memory tasks (Locascio et al., 2010). However, some studies have failed to find significant associations between both working memory and word decoding (Sesma et al., 2009), and inhibitory control and word decoding (Christopher et al., 2012; Kieffer et al., 2013). These studies examined children 8 years of age and older – stronger associations between EF and word decoding might be expected for kindergarten children, given the effortful nature of word decoding at this age. To date, however, there is limited research examining whether EF significantly predicts word decoding in kindergarten.

1.4. EF, word decoding, and reading comprehension

In summary, research has shown strong associations between word decoding and reading comprehension, and between EF and reading comprehension. Findings on associations between EF and word decoding are mixed. Given these linkages, there are several possible models relating these three variables (see Fig. 1). One possibility is that EF and word decoding each contribute to reading comprehension, but are not associated with each other (Fig. 1a). In line with this model, one study found no correlation between working memory and word decoding at ages 8 and 11, but each separately and significantly predicted concurrent reading comprehension (Cain et al., 2004). A second possibility is that EF and word decoding are correlated, but each still demonstrates unique effects on reading comprehension – some research findings have supported this model (Fig. 1b; Jacobson et al., 2017; Kieffer et al., 2013). EF might also moderate the relationship between word decoding and reading comprehension (Fig. 1c). In line with this, a study of adults showed that working memory interacted with word decoding in predicting reading comprehension, such that weaker relationships emerged between word decoding and reading comprehension for individuals with high working memory capacity (Hamilton, Freed, & Long, 2013). A fourth conceptualization is that EF has both direct effects on reading comprehension and indirect effects through word decoding (Fig. 1d; partial mediation). Data reported in one study from adolescent students fit this model for working memory – both direct and indirect effects on reading comprehension through word decoding were observed (Arrington et al., 2014). However, a separate study of fourth grade students found that inhibitory control showed only direct effects on reading comprehension – indirect effects through word decoding were not significant (Kieffer et al., 2013). Finally, the effect of EF on reading comprehension may be fully explained by the association between EF and word decoding (Fig. 1e; full mediation). In other words, word decoding may completely mediate the relationship between EF and reading comprehension. To date, extant studies have not reported findings of full mediation in English-speaking children. However, a study of Dutch-speaking children found that word decoding in first grade fully mediated the relationship between EF in kindergarten and reading comprehension in second grade (Segers, Damhuis, van de Sande, & Verhoeven, 2016).

In evaluating the relationships between EF, word decoding, and reading comprehension, considering the developmental stage of reading is paramount. In young readers, a large proportion of the variance in reading comprehension is explained by word decoding, with word decoding serving as a bottleneck to comprehension (Keenan, Betjemann, & Olson, 2008). For example, one study of first-grade students found a correlation of 0.97 between word decoding and reading comprehension (Byrne et al., 2007). Given the tight overlap between word decoding and reading comprehension in young readers, EF may not explain a large amount of additional variance in reading comprehension in kindergarten, and may not be able to compensate for poor word decoding at this age. However, it is highly plausible that EF supports word decoding in kindergarten – previous studies focusing on preschool have found that EF predicts skills necessary for word decoding (letter-word identification, phonological awareness), as well as word decoding itself (Blair & Razza, 2007; Welsh et al., 2010). Taken together, these findings suggest that in kindergarten the relationship between EF and reading comprehension may be mediated by word decoding.

1.5. The present study

The present cross-sectional study tests direct effects of EF on reading comprehension, as well as indirect effects through word decoding using path analysis. A sample of 97 kindergarten children was administered a test battery of EF, word decoding, and reading comprehension tasks. We hypothesized that EF would have an indirect effect on reading comprehension through word decoding, given the effortful nature of word decoding and the strong tie between word decoding and reading comprehension at this age. Given previous empirical evidence for a contribution of EF to reading comprehension in children, we also expected EF to have a smaller, direct effect on reading comprehension. There are several confounding factors that may be associated with study variables: socio-economic status (Bowey, 1995; Lawson, Hook, & Farah, 2018), gender (Chiu & McBride-Chang, 2006; Grissom & Reyes, 2018), and age (Adlof, Hogan, & Catts, 2005; Huizinga, Dolan, & van der Molen, 2006). In addition, oral language is expected to contribute to reading comprehension in accordance with the Simple View of Reading, but is not a main variable of interest in the present study. Given these associations, socio-economic status, gender, age, and oral

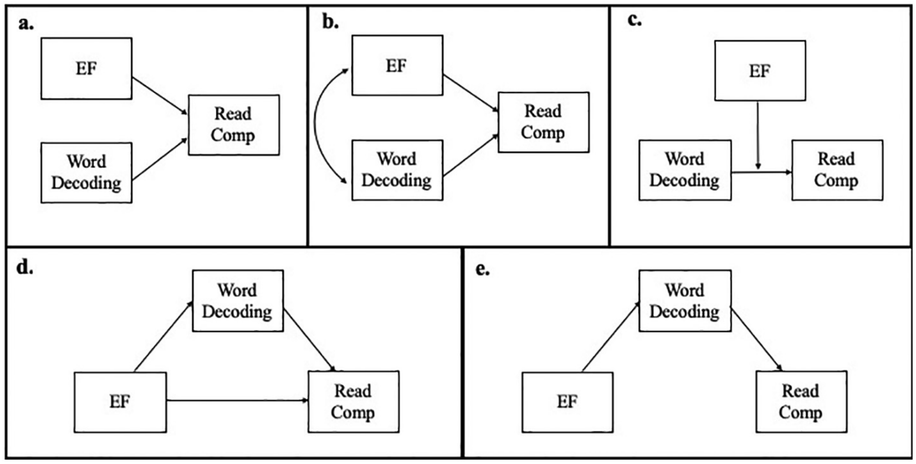

Fig. 1. Models linking EF, word decoding, and reading comprehension. Single headed arrows indicate direct relationships and double-headed arrows indicate covariance or correlation.

language are investigated as control variables.

This study adds to a growing body of literature seeking to understand associations between EF and reading in several ways. First, the majority of research on EF and reading comprehension has examined these variables in middle childhood or adolescence. Of the 29 studies reviewed in a recent meta-analysis on EF and reading comprehension (Follmer, 2018), only one study examined the relations between these two variables in children as young as 5, which did not include a measure of word decoding (Stipek & Valentino, 2015). However, learning how EF may contribute to reading processes in kindergarten is critical in understanding if and how EF could inform early identification and intervention strategies for reading disorders. Importantly, early reading intervention may help prevent "Matthew effects" with gaps in reading widening as schooling progresses (Hurry & Sylva, 2007). Second, although there is rich empirical data to support the relationship between EF and reading comprehension, there are few studies that explore potential mechanisms underlying this association. One author has recently noted that "future research that aims to identify mediating variables linking executive function and reading comprehension…is needed" (Follmer, 2018, p. 56). The present study sheds light on the pathways by which EF may influence reading comprehension in kindergarten by investigating the potential mediating role of word decoding. Understanding these pathways can contribute to the development of more targeted intervention and instruction points for young readers.

2. Methods

2.1. Participants and procedure

Children were recruited to participate in the fall of their kindergarten year from public schools in Northern California as part of a larger study investigating language and literacy acquisition. Participants were recruited through flyers, email announcements, and community events. All children were screened for diagnoses of any neurological or psychiatric disorders by asking parents the following question: "Has your child been diagnosed with any major developmental, neurological, or psychological conditions?" Parents that endorse the presence of any conditions are excluded from further participation in the study. Children were assessed on all measures directly by trained assessors, and questionnaires were administered to parents to obtain demographic data. Assessments were conducted in one-on-one settings in a quiet conference room in a university laboratory. There was suggested order of measures for each participant – because of limitations in test materials, sometimes measures were presented in an order determined by each individual assessor. To determine if there was a difference in scores based on test order, we conducted a one-way ANOVA after checking for equal variances with test order as a grouping variable, ranging from 1 (administered 1st) to 4 (administered 4th). There was no significant difference in scores on measures based on test order for oral language (p = .48), word decoding (p = .34), reading comprehension (p = .16), and EF (p = .76). As part of the larger study, children also underwent magnetic resonance imaging (MRI) scans and completed tasks pertaining to mathematics and other cognitive abilities, the results of which are not a focus of the present study so are not reported here. All study procedures were reviewed and approved by an institutional review board (UCSF IRB #13-11958), and all participating families provided informed consent.

Data for the current study from a total of N = 97 participants is reported here. The sample was 47.4% female and ranged from 5 to 6 years old, with a mean age of 68.4 months (SD = 4.1). Racial categories were identified as 2% Black/African American, 48% Caucasian/White, 19% Asian or Pacific Islander, 5% Hispanic/Latino, and 26% multiracial or other. The sample was of moderately high socio-economic status – only 5% of families were on government assistance, and the average number of maternal education years was 16.6 (SD = 2.3).

2.2. Measures

2.2.1. Demographic questionnaire

An online demographic questionnaire was sent to parents to collect information on age and gender. Parents were also asked about the highest level of education (in years) that the mother had received.

2.2.2. Oral language

Oral language was measured by the Oral Language cluster on the Woodcock-Johnson, 4th Edition, Tests of Oral Language (WJ-IV-Ol; F. A. Schrank, Mather, & McGrew, 2014). This cluster is a composite of expressive vocabulary (measured by the Picture Vocabulary subtest), as well as listening comprehension (measured by the Oral Comprehension subtest). The Oral Language cluster shows strong convergent validity with other validated tests of global oral language scores (correlations ranging from 0.60 to 0.80). Raw score consisted of a sum of the total items correct on the Picture Vocabulary and Oral Comprehension subtests. The WJ-IV Oral Language cluster has been shown to have excellent test-retest reliability in the tested age range (r = 0.88).

2.2.3. Word decoding

The Letter-Word Identification subtest from the Woodcock-Johnson, 4th Edition, Tests of Achievement, (WJ-IV-Ach; Fredrick A. Schrank, Mather, & McGrew, 2014) was used to measure word decoding. This untimed subtest begins with the child identifying letters and words and then asks them to pronounce written words. The WJ-IV-Ach Letter-Word Identification subtest has been shown to have excellent test-retest reliability in the tested age range ($r = 0.98$). Raw score consisted of the total number of items read correctly. In our sample, 84% of participants progressed from identifying letters to reading words.

2.2.4. Reading comprehension

Reading comprehension was assessed by the Passage Comprehension subtest of the WJ-IV-Ach. On early items, children match symbols and words to pictures, and then progress to reading short phrases, sentences, and passages and identifying an appropriate missing word. The WJ-IV-Ach Passage Comprehension subtest has been shown to have excellent test-retest reliability in the tested age range ($r = 0.98$). Raw score consisted of the total number of items correct. In our sample, 98% of participants moved beyond picture items to phrase items, and 49% of participants moved beyond phrase items to sentence and passage items.

2.2.5. Executive function (EF)

EF was measured using the Tasks of Executive Control (TEC), a standardized computer-administered measure of working memory, inhibitory control, and sustained attention (Isquith, Roth, & Gioia, 2006). The TEC integrates two measures commonly used to assess EF – an *n*-back paradigm to test working memory updating, and a go/no-go task to tap into inhibitory control. Our sample completed four sequential tasks combining levels of working memory load (0- or 1-back) and inhibitory control (no inhibit or inhibit). A block of practice trials with feedback preceded each task, with two opportunities to "pass" the practice (defined as making no more than 3 errors in a set of 10 stimuli). The tasks are sorting games where participants are asked to organize presented stimuli into one box for a certain toy, or a second box for everything else (0-back/no inhibit). After this condition, the instructions are the same except participants are instructed to not sort into any box given a certain cue (0-back/inhibit). In the third condition, if a toy appears two times in a row – then, the participant sorts the second toy into the certain box (1-back/no inhibit). The final condition is the same as the third condition except participants are again instructed to not sort into any box if the stimuli is presented with a certain cue (1-back/inhibit).

The TEC yields a number of scores for each task – for analysis, a composite factor score (response control) output by TEC scoring software was used, which combines measurements of accuracy (% correct) in responding to stimuli and consistency of response time across all four conditions. To create this factor score, the authors of the TEC subjected all available TEC data to principal factor analysis with oblique rotation, yielding a three-factor structure consisting of response control (used in the present study), selective attention, and response speed. We chose to use the response control factor score output by the TEC scoring software rather than a more unidimensional measure (e.g., number of errors or % accuracy alone) in order to tap performance across all tasks with both response time and accuracy. For more information on the factor analyses involved in computing this score, see Isquith et al., 2006. For this task, lower scores indicate better performance. For ease of interpretation, T scores were reverse coded for the present study so that higher scores indicate better performance. TEC has demonstrated validity with other EF measures such as the Behavior Rating Inventory of Executive Function (BRIEF), WISC-V Digit Span. TEC has also shown adequate reliability for children (split-half reliability = 0.75, test-retest reliability = 0.77).

3. Results

3.1. Descriptive statistics

Descriptive statistics are displayed in Table 1. There was almost no missing data except for two oral language scores and one word decoding score – the same participant was missing both scores. Two outliers were identified (one within vocabulary and one within reading comprehension) and were recoded to their nearest valid value within ± 3 SD. In addition, Cook's distance was used to identify outliers in predicting reading comprehension, and no outliers were found as indicated by the cut-off of one. For all tasks, the mean was greater than one standard deviation from the maximum or minimum value, indicating no presence of floor or ceiling effects. All variables were within acceptable values for skewness and kurtosis as indicated by the guidelines of (Kline, 2015): no skewness values exceeded an absolute value of 3 and no kurtosis values exceeded the absolute value of 10. However, the values of kurtosis greater than 3 for both word decoding and reading comprehension by some standards indicate a slightly leptokurtic distribution (George & Mallery, 2010). Thus, in the path analysis, estimation techniques for nonnormal outcomes will be used.

Table 1
Descriptive statistics for sample demographics, study variables, and potential confounding variables.

	N	Mean	SD/%	Range	Skew	Kurtosis
1. Gender (% female)	97		47.40	–	–	–
2. Age (months)	97	68.44	4.08	60–76	−0.13	−1.04
3. Maternal Edu (years)	97	16.78	2.41	8–21	−0.59	1.71
4. Oral Language	95	37.62	7.24	15–51	−0.91	1.01
5. Word Decoding	96	17.47	9.02	5–65	0.58	3.07
6. EF	97	53.38	10.31	23–72	−0.50	0.27
7. Read. Comprehension	97	10.65	4.23	4–27	1.54	3.02

3.2. Correlation analysis

Bivariate correlations are displayed in Table 2. Relevant to the proposed model, EF showed significant, positive correlations with both word decoding ($r = 0.33$, $p = .001$) and reading comprehension ($r = 0.34$, $p = .001$). There was a strong, positive correlation between word decoding and reading comprehension ($r = 0.84$, $p < .001$). Socioeconomic status (SES) as indexed by maternal education did not significantly correlate with any study variables, so will not be included as a control variable. Gender only correlated significantly with EF (with females having lower EF scores), so will not be included as a control variable. Oral language showed significant, positive correlations with age ($r = 0.25$, $p = .016$), EF ($r = 0.29$, $p = .004$), word decoding ($r = 0.33$, $p = .001$), and reading comprehension ($r = 0.31$, $p = .003$). Age significantly correlated with both word decoding ($r = 0.29$, $p = .004$) and reading comprehension ($r = 0.36$, $p < .001$). Thus, oral language and age are included in subsequent analyses as control variables.

Table 2
Pearson correlations between demographic variables, study variables, and potential confounding variables. Binomial correlations are reported for gender.

	1	2	3	4	5	6
1. Gender	–					
2. Age	−0.07	–				
3. Maternal Edu (years)	0.02	−0.08	–			
4. Oral Language	−0.11	0.25*	0.20	–		
5. EF	−0.34**	−0.04	0.16	0.29**	–	
6. Word Decoding	−0.04	0.29**	0.04	0.33***	0.33***	–
7. Read. Comprehension	−0.03	0.36***	−0.02	0.31**	0.34***	0.84***

* $p < .05$.
** $p < .01$.
*** $p < .001$.

3.3. Path analysis

To examine the direct and indirect (mediated) associations of EF with reading comprehension, path analysis was conducted in Mplus 8.0 (Muthén & Muthén, 2019) using full information maximum likelihood (FIML) to handle missing data and a maximum likelihood (ML) method of estimation. FIML is preferable to using listwise deletion in structural equation modelling, as it can yield less biased parameter estimates (Allison, 2003; Enders, 2001; Kline, 2015). The model in which word decoding mediates the relationship between EF and reading comprehension was tested. In this model, the effect of covariates (age, oral language) on word decoding and reading comprehension was controlled. The presence of mediation was examined by computing indirect effect estimates using bias-corrected bootstrapped (10,000 iterations) 95% confidence intervals of standard errors. A confidence interval that does not contain zero indicates a statistically significant effect (MacKinnon, 2008). Model fit was assessed by Confirmatory Fit Index (CFI), Tucker Lewis Index (TLI), root mean square error of approximation (RMSEA), and standardized root mean square residual (SRMR). Good fit is indicated by CFI values above 0.90, TLI values above 0.95, and RMSEA/SRMR values below 0.08 (Hooper, Coughlan, & Mullen, 2008; Kline, 2015). Of note, while larger samples are recommended for path analysis, our sample size still meets the recommended criteria of having a ratio of at least five participants per parameter (97 participants and 5 parameters equates to 19.4 participants per parameter; Bentler & Chou, 1988).

The tested model is depicted in Fig. 2 and path coefficients are detailed in Table 3. The model showed an acceptable goodness of fit using traditional indices (CFI = 0.996, TLI = 0.985, RMSEA = 0.057, SRMR = 0.054). R-square values indicated that the model explained 22.1% of the variance in word decoding ($p < .001$) and 71.7% of the variance in reading comprehension ($p < .001$). EF significantly predicted word decoding when controlling for age and oral language, such that higher scores on the EF task were associated with higher scores on the word decoding task ($\beta^* = 0.304$, SE = 0.044, $p < .001$). Word decoding was in turn a significant predictor of reading comprehension controlling for age and oral language ($\beta^* = 0.778$, SE = 0.056, $p < .001$). There was a significant indirect effect of EF on reading comprehension through word decoding ($\beta^* = 0.236$, SE = 0.040, $p < .001$, 95% CI: 0.146, 0.304). There was no significant direct effect of EF on reading comprehension ($\beta^* = 0.104$, SE = 0.060, $p = .083$, 95% CI: −0.010, 0.221). The presence of a significant indirect effect but not a significant direct effect of EF on reading comprehension indicates full mediation.

Table 3
Path coefficients among EF, word decoding, reading comprehension, and control variables.

Path	β*	SE	Bootstrapped 95% CI
Direct associations with reading comprehension			
Word decoding	0.778***	0.056	(0.632, 0.866)
EF	0.104†	0.060	(−0.010, 0.221)
Age	0.158*	0.066	(0.031, 0.292)
Oral language	−0.007	0.049	(−0.192, 0.092)
Direct associations with word decoding			
EF	0.304***	0.044	(0.194, 0.374)
Age	0.010***	0.002	(0.007, 0.013)
Oral language	0.213***	0.034	(0.140, 0.275)
Indirect association with reading comprehension			
EF via word decoding	0.236***	0.040	(0.146, 0.304)

β* = standardized beta, SE = standard error.
† $p < .10$.
* $p < .05$.
*** $p < .001$.

3.4. Testing alternative models

We also tested whether EF and word decoding uniquely contributed to reading comprehension (Fig. 1a and b) controlling for covariates using a linear regression. Visual inspection of a plot of studentized residuals versus unstandardized predicted values revealed no signs of heteroscedasticity or nonlinearity. Residuals were approximately normally distributed as assessed by a Q-Q plot, and there was no evidence of multicollinearity (all tolerance values were greater than 0.1). Results from the model are shown in Supplementary Table 1. Word decoding scores significantly predicted reading comprehension controlling for children's age, oral language, and EF ($\beta = 0.757$, $p < .001$). EF did not uniquely predict children's reading comprehension controlling for word decoding, age, and oral language ($\beta = 0.101$, $p = .092$). The model explained a total of 72.5% of the variance in reading comprehension.

To test whether EF moderated the association between word decoding and reading comprehension (Fig. 1c), an interaction product for mean-centered values of word decoding and EF was computed and entered in the model, which controlled for age and oral language. The interaction between children's word reading and EF was not significant in predicting reading comprehension ($\beta = 0.09$, $p = .182$). Results from the model are shown in Supplementary Table 1. The model explained a total of 73.0% of the variance in reading comprehension. Given the non-significant interaction, simple slopes were not probed.

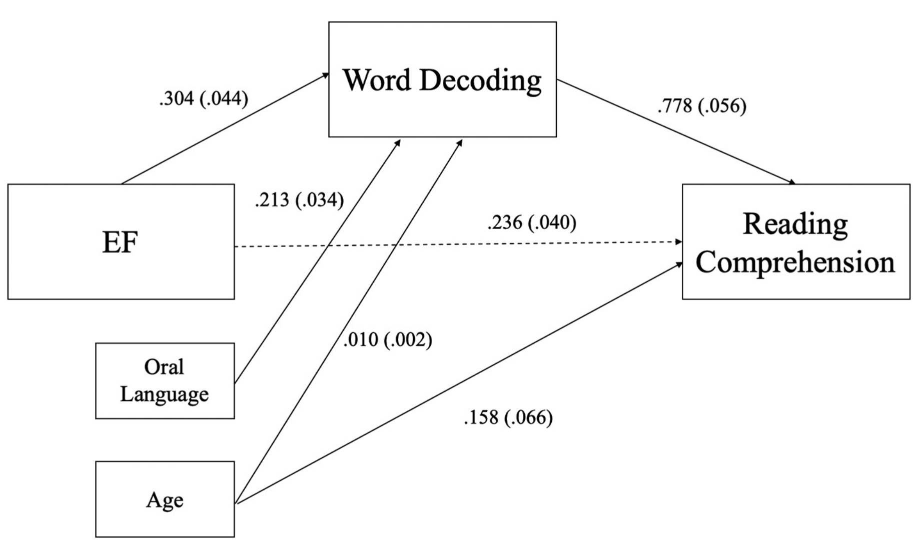

Fig. 2. Path analytic model examining direct and indirect effects of EF on reading comprehension. Direct effects are in solid lines while the indirect effect is indicated by a dashed line. The effects of confounding variables (oral language, age) on study variables were controlled although only significant paths in the model are shown. Standardized beta coefficients with standard error in parentheses are noted for each path.

4. Discussion

Although EF shows consistent associations with reading comprehension in prior studies, the pathways by which EF influences reading comprehension are unclear. Moreover, there is limited prior work on these relationships in kindergarten, where word decoding and reading comprehension are highly intertwined. The present study tested a mechanism by which EF may influence reading comprehension in kindergarten using path analysis. Results showed a significant indirect effect of EF on reading comprehension, with word decoding mediating this relationship (Fig. 1e). There was no significant direct effect of EF on reading comprehension.

Consistent with the Simple View of Reading, both word decoding and oral language were significantly correlated with reading comprehension, although the correlation was stronger in magnitude for word decoding ($r = 0.84$ compared to $r = 0.31$). In line with our hypothesized model, EF significantly correlated with reading comprehension. The magnitude of the correlation in our study ($r = 0.34$) is similar to the overall correlation between working memory and reading comprehension reported in a recent meta-analysis ($r = 0.38$), and higher than that reported for inhibitory control ($r = 0.21$; Follmer, 2018). In addition, EF significantly correlated with word decoding – overall, these correlations supported the proposed path model. Although not a focus of the present study, it is notable that in our correlational analyses, being female was associated with lower EF scores. This finding is interesting given a recent review where the authors concluded there is little support for gender differences in EF, and is something to consider in future studies (Grissom & Reyes, 2018).

Findings showed that EF predicted concurrent word decoding controlling for age and oral language. While some studies have found associations between EF components and word decoding (Arrington et al., 2014; Christopher et al., 2012; Jacobson et al., 2017; Kieffer et al., 2013; Locascio et al., 2010; Messer et al., 2016; van der Sluis et al., 2007), others have not (Christopher et al., 2012; Kieffer et al., 2013; Sesma et al., 2009). Notably, these studies tested EF and word decoding associations in children 8 years old and above, and did not include kindergarten children. Indeed, although Christopher et al. (2012) did not find significant EF-word decoding associations in a sample of 8–16 year olds, the authors concluded that "it is likely that children in the earlier stages of learning to read may require different cognitive processes or have different patterns of relations between the cognitive and reading constructs" (p. 481). Our results suggest that EF may contribute to word decoding abilities in kindergarten, where word decoding is a highly effortful process. In the present study, our EF task specifically tapped inhibitory control and the updating aspect of working memory. Inhibitory control may support the suppression of words that are similar in orthography to the word being decoded – for example, suppressing the word "hat" while reading "hot." Working memory may contribute to word decoding in kindergarten in efficiently updating representations of a word as phonological segments are being recognized – a process which is common in kindergarten as children encounter unfamiliar words. EF may also impact word decoding through its association with adaptive self-regulatory behaviors, enabling children to ignore distractions and stay focused on word decoding, which is cognitively demanding at this age (McClelland & Cameron, 2011).

Unsurprisingly, word decoding significantly predicted reading comprehension controlling for age, EF, and oral language. However, oral language did not significantly predict reading comprehension above and beyond age, EF, and word decoding. These results are in line with a recent meta-analysis that found a strong average correlation ($r = 0.74$) between word decoding and reading comprehension across 110 studies (Garcia & Cain, 2014). This meta-analysis also found that the contribution of word decoding to reading comprehension decreased with age, paralleling an increase in the contribution of oral comprehension across development. In our sample of kindergarten students, word decoding is likely not yet an automatized process. Reading comprehension is therefore constrained by word decoding ability, resulting in a less significant contribution of oral language skills.

EF contributed to word decoding which in turn significantly predicted reading comprehension in our study. Results supported a significant indirect effect of EF on reading comprehension through word decoding. The direct effect of EF on reading comprehension was not significant. Our results are in line with a recent study of 9-14-year-old readers, where word decoding fully mediated associations between EF (working memory and cognitive flexibility) and reading comprehension (Spencer, Richmond, & Cutting, in press). These findings add to models of reading in supporting one specific mechanism by which EF can influence reading comprehension in kindergarten, and hold clinical and educational implications for young readers. Scaffolding EF skills in kindergarten can ultimately support reading comprehension through boosting word decoding skills. Although there are notable limitations (Melby-Lervåg et al., 2016) some EF interventions have shown promising effects in young children (Diamond & Lee, 2011; Röthlisberger, Neuenschwander, Cimeli, Michel, & Roebers, 2012). Relatedly, EF can be used as an additional indicator of early reading difficulties, which may help implement interventions early to prevent widening achievement gaps in reading over the school years. Importantly, our results echo prior work in showing that reading comprehension is largely constrained by word decoding in kindergarten. Thus, EF interventions should not replace explicit decoding instruction, but rather supplement to boost word decoding and in turn support reading comprehension.

There was no significant direct effect of EF on reading comprehension. One explanation may be that word decoding and oral comprehension capture so much of the variance in reading comprehension that there is little additional variance to be explained. For example, a recent study found that a model containing word decoding and oral comprehension captured an astonishing 96% of the variance in reading comprehension (Lervåg, Hulme, & Melby-Lervåg, 2018). Thus, it is more likely that EF contributes to reading comprehension through either word decoding or oral comprehension, given that there is little variance in reading comprehension to explain directly. EF contributed to reading comprehension indirectly through word decoding in our study, although in older readers EF may additionally contribute through oral language (Kieffer et al., 2013).

Our results show a correlation between EF and word decoding and that EF is associated with word decoding beyond covariates. Thus, our findings do not support a model whereby EF and word decoding are unrelated, but each uniquely contribute to reading comprehension (Fig. 1a). Our results also do not support a model whereby EF and word decoding are correlated and each uniquely contributes to reading comprehension (Fig. 1b). This finding is in contrast to previous studies showing significant and independent contributions of both word decoding and EF to reading comprehension (Cain et al., 2004; Kieffer et al., 2013). Of note, these studies included children from 8-11 years old. As previously discussed, in kindergarten both EF and word decoding skills are undergoing rapid development and are highly intertwined, which may account for discrepancies between our findings and results with older children. EF also did not significantly moderate the association between word decoding and reading comprehension in our study – this pattern of findings has previously been demonstrated in an adult sample (Hamilton et al., 2013). In other words, the relationship between word decoding and reading comprehension was not impacted by child EF in our study, which may be due to the high dependence of reading comprehension on word decoding at this developmental stage. Finally, our results show full mediation (Fig. 1e) rather than partial mediation (Fig. 1d) of the relationship between EF and reading comprehension. As with the other conceptualizations, we interpret our findings to be specific to the developmental stage of our sample and our measures of EF and reading comprehension. We acknowledge that other conceptualizations are possible and even likely as children's reading and EF develops – however, in our sample our data support a model whereby word decoding fully mediates the relationship between EF and reading comprehension.

Results may also vary between studies depending on how reading comprehension is measured. Research has shown that different reading comprehension tasks show different magnitudes of associations with EF, word decoding, and oral language (Cutting & Scarborough, 2006; Eason, Goldberg, Young, Geist, & Cutting, 2012; Keenan et al., 2008). The present study used a cloze task, in which the child provides the missing word to fill in a blank given in a text. Previous work has suggested that cloze tasks may rely more on bottom-up, word decoding skills than other formats such as multiple-choice (Cutting & Scarborough, 2006; Francis, Fletcher, Catts, & Tomblin, 2005). This would suggest that the contribution of word decoding to reading comprehension could potentially be overestimated in the present study compared to other comprehension tasks. Relevant to EF, our reading comprehension task allowed children to view the text while supplying the missing word. This method places lower demands on the working memory aspect of EF than other tasks such as free recall, suggesting the contribution of EF in our study could be underestimated compared to other tasks. At the same time, the cloze technique may place higher demands on EF than multiple-choice tasks. Addressing this, a meta-analysis of 29 studies found that reading comprehension task type did not significantly moderate the relationship between EF and reading comprehension (Follmer, 2018). This question is complicated further by developmental considerations – types of text and consequently the comprehension measures deployed change as children progress through school. In our sample, only 49% of participants progressed from comprehension of phrases to comprehension of full sentences and passages, in line with expected performance for reading in kindergarten. Although sample size was small, we re-ran analyses using only the participants who progressed to sentences, and results did not change. Still, results from the present study may not be applicable to reading comprehension tasks with longer narrative passages that require more inferential skills. Thus, for the purposes of interpreting results of the present study, we acknowledge that the relative contributions of word decoding and EF to reading comprehension could vary with a different reading comprehension task.

Several limitations of this study should be acknowledged. First, our population consisted of families from middle- and high-SES backgrounds. We did not find associations between SES and EF or reading comprehension in our study, likely because our SES range was limited in variability. Still, it is important to replicate these findings among low-SES populations, who may experience more of a range of EF and reading comprehension scores. Second, we used one EF measure that taps into working memory and inhibitory control simultaneously. There is debate surrounding the reliability of compositing two or more EF tasks, with some authors suggesting focusing on single dimensions of EF at a time (Blair, Zelazo, & Greenberg, 2016). However, EF has been found to be a more unitary construct in younger compared to older populations, making the use of an EF composite more suitable in our sample (Wiebe et al., 2008). Of note, our task did not explicitly index cognitive flexibility, which has shown associations with reading comprehension in other studies (Cartwright, 2008). Indeed, a recent study with a large ($N = 8920$) sample size showed that working memory, cognitive flexibility, and inhibitory control showed distinct associations with reading in second grade (Morgan, Farkas, Hillemeier, Pun, & Maczuga, 2018). Third, our study is cross-sectional, and so developmental changes and causal directions could not be determined by our analysis. Fourth, our measurement of oral language did not include inference making skills, which has been shown to make unique contributions to reading comprehension as young as preschool (Lepola, Lynch, Kiuru, Laakkonen, & Niemi, 2016) – thus, we may be underestimating the contribution of oral language in our study. Finally, we acknowledge that our model of EF, word decoding, and reading comprehension may be limited in generalizability. Our sample contained kindergarten children with no history of family reading difficulties – results may be different with older children or in individuals with word decoding on specific reading comprehension deficits. Indeed, other studies have found support for different models of EF, word decoding, and reading comprehension among different populations (Arrington et al., 2014; Christopher et al., 2012; Kieffer et al., 2013; Locascio et al., 2010; Sesma et al., 2009). Thus, there are other plausible conceptualizations of how EF may contribute to reading depending on developmental stage and clinical status.

Despite these limitations, our study offers a notable contribution to research on the relative role of EF in supporting reading processes in young children. Our findings support efforts to promote EF early, since EF contributes to word decoding and in turn reading comprehension at this young age. Results suggest that decoding instruction and scaffolding EF in tandem may have the maximal impact on reading comprehension. Although our study conceptualized EF as contributing to reading comprehension, it is possible that this relationship is bidirectional over time (Fuhs, Nesbitt, Farran, & Dong, 2014). Therefore, future studies should continue to examine the unique, interactive, and transactional relationships of EF and reading comprehension as children develop.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lindif.2019.101783.

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