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Executive Function: Association with Multiple Reading Skills

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Abstract

Executive function (EF) is related to reading. However, there is a lack of clarity around (a) the relative contribution of different components of EF to different reading components (word reading, fluency, comprehension), and (b) how EF operates in the context of known strong language predictors (e.g., components of the Simple View of Reading or SVR), and other skills theoretically related to reading (e.g., vocabulary, processing speed) and/or to EF (e.g., short-term memory, motor function). In a large sample of 3rd to 5th graders oversampled for struggling readers, this paper evaluates the impact of EF derived from a bifactor model (Cirino, Ahmed, Miciak, Taylor, Gerst, & Barnes, 2018) in the context of well-known covariates and demographics. Beyond common EF, five specific factors (two related to working memory, and factors of fluency, self-regulated learning, and behavioral inattention/metacognition) were addressed. EF consistently showed a unique contribution to already-strong predictive models for all reading outcomes; for reading comprehension, EF interacted with SVR indices (word reading and listening comprehension). The findings extend and refine our understanding of the contribution of EF to reading skill.

Keywords

Executive Function; Word Reading; Reading Comprehension; Language; Simple View of Reading

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There are several well-researched reading comprehension frameworks. The Simple View of Reading (SVR; Gough & Tunmer, 1986) regards reading comprehension as a product of decoding and listening comprehension. Perfetti and colleagues' Reading Systems Framework (Perfetti, 1999; Perfetti & Stafura, 2014) recognizes a wider variety of knowledge sources that are combined within a cognitive system requiring transactions between perceptual stimuli, limited capacity resources, and long-term memory. In van den Broek, Young, Tzeng, & Linderholm's (1999) Landscape model, readers set goals for acceptable text coherence depending on a desired level of comprehension, and manipulate effort and resources to achieve those goals (see also van den Broek & Espin, 2012). These

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models of comprehension have in common a focus on cognitive domains beyond the strong predictors of early reading skill that include phonological awareness and rapid naming (Schatschneider, Carlson, Francis, Foorman, & Fletcher, 2002), and oral language. A key question then is whether and/or to what extent skills beyond these known language predictors are influential for reading. This question makes sense because components of reading are differentiable and language and non-language skills have variable relations to reading across development (e.g., Cirino et al., 2013; Oakhill, Cain, & Bryant, 2003); for example, dominance analyses showed that predictors of reading comprehension shift from fluency and verbal reasoning in 3rd grade to reasoning in 10th grade (Tighe & Schatschneider, 2014), but that working memory was not a dominant predictor in the context of strong reading and language predictors. Also, in later grades, inference-making, vocabulary and background knowledge make large contributions to reading comprehension (see Ahmed et al., 2016), as reading becomes a primary route for learning new information (Compton, Fuchs, Fuchs, Elleman, & Gilbert, 2008).

Although reading research at younger ages (appropriately) focuses on word recognition, for older students it also becomes necessary to also focus on fluency and comprehension, and in corollary, the “extra-language” processes important for reading. Of these extra-language processes, executive function (EF) has been the focus of considerable research (Butterfuss & Kendeou, 2017; Follmer, 2017). EF is a domain general control process important for goal-directed behavior (Cirino et al., 2018), and reading is one such goal oriented behavior (e.g., the goal being reading for understanding and new learning).

Few studies have addressed the myriad ways that EF may be assessed, and do not always consider the impact of these types of EF on multiple aspects of reading in the context of well-known predictors (e.g., phonological awareness, rapid naming, oral language). The goal of this study is therefore to comprehensively evaluate the role of EF and related skills for multiple reading outcomes and in the context of language and a variety of additional control variables. The current study draws from recent work on the evaluation of a framework for EF (Cirino et al., 2018). That study supported a bifactor model, with a common EF factor, and five specific EF factors: three focused on *performance based measures* (working memory as span and manipulation, with planning [WMSM/Plan], working memory as updating [WMU], and generative fluency [FLUENCY]); other factors included *self-regulated learning* (SRL) and *behavioral ratings* of metacognitive behaviors (MCOG). Each are discussed in turn below. Details of the rationale, development, and support for that structure of EF can be found in Cirino et al., (2018). The current study relates this empirically validated EF structure to reading skill.

Prior Theoretical and Empirical Work on EF and Reading

Butterfuss and Kendeou (2017) conceptually evaluated the role of specific EF processes (updating, inhibition, and shifting) as suggested by the model of Miyake, Friedman, Emerson, Witzki, & Howerter (2000) to reading, limiting their review to the way EF impacts discourse models of reading comprehension that emphasize mental representations (e.g., Kintsch, 1988; van den Broek et al., 1999). Butterfuss and Kendeou (2017) conclude that updating is essential for selecting and maintaining a coherent text representation, and that inhibition is key for suppressing irrelevant information. Shifting may assist with the integration of lower level reading processes (semantic and phonological information) and with the flexible allocation of attention, though with inconsistent empirical support and a somewhat underdeveloped theoretical role. These authors also called for the consideration of additional EF components (e.g., planning) for the reading process, and encouraged the integration of EF into models of reading.

Beyond the processes above (working memory, inhibition, shifting, planning), which are often assessed with cognitive, psychometric, laboratory tasks, "everyday" aspects of EF are often assessed via rating scales of self- or other-reports, sometimes referred to as indirect measures of EF (Follmer, 2017). These aspects of EF have differential and complementary relations with one another and with academic skill (e.g., Gerst, Cirino, Fletcher, & Yoshida, 2017; Toplak, West, & Stanovich, 2013). Such ratings often overlap with those of ADHD symptomatology, particularly behavioral inattention, which shows robust relationships with reading (Martinussen, Grimbos, & Ferrari, 2014; Miller et al., 2014; Spira & Fischel, 2005), often more than hyperactivity or impulsivity (e.g., Gray, Carter, Briggs-Gowan, Jones, & Wagmiller, 2014; Pham, 2013; Sims & Lonigan, 2013). It is however unclear whether such ratings reflect the impact of behavioral inattention on the reading process, or the reverse (Cirino, Fletcher, Ewing-Cobbs, Barnes, & Fuchs, 2007; Claessens & Dowsett, 2014; Fuchs et al., 2006; Roberts et al. 2015), or even whether measures of behavioral inattention relate to cognitive attentional processes. Reading comprehension in particular requires a significant investment of attention, particularly where the text content or the words themselves are difficult. This is often the case after early elementary grades, as students are expected to read more independently and use reading to understand material in content courses (e.g., social studies, science). Ratings of behavioral inattention also are related to ratings of metacognitive processes (e.g., Cirino et al., 2018).

In literatures other than neuropsychology (e.g., developmental, educational), the term self-regulated learning (SRL) is often used when discussing goal-directed endeavors. Both EF and SRL include the need for planning, monitoring ones performance, and reviewing progress to determine if goals have been met (e.g., Shallice, 1982; Ylvisaker & Feeney, 2002 *versus* Pintrich, 2004; Zimmerman, 2000). In addition, multiple authors have commented on the overlap of EF and SRL, construing the latter as the application of the former during task performance (Hofmann, Schmeichel, & Baddeley, 2012; Ilkowska & Engle, 2010). Thus, SRL shares theoretical "space" with more traditional neuropsychological conceptualizations of EF. SRL processes are clearly conceptually related to reading performance, in that understanding information from text requires preparation, active reading, monitoring and evaluation (Boekaerts, 1997; Pressley & Ghatala, 1990). Self-regulatory skills are also empirically related to reading comprehension (Connor et al., 2016; Minguela, Sole, & Pieschl, 2015; Smith, Borkowski, & Whitman, 2008), but have not been as systematically evaluated alongside performance-based measures and/or behavioral rating measures of EF.

Empirically, recent meta-analyses are relevant and important (Follmer, 2017; Jacob & Parkinson, 2015; Peng et al., 2018), but essentially address zero-order correlational relationships. Follmer (2017) focused on the relation of EF to reading comprehension, and found an average $r = .36$, with similar values across age, whether the reading comprehension measure was standardized or experimental, and whether the EF measure was direct (e.g., performance tasks) or indirect (e.g., rating scales). Similar values were also obtained for most aspects of EF (working memory, shifting, planning) though with smaller values, $r = .21$ for inhibition. Peng et al. (2018) focused on working memory, and showed similar-sized moderate relations with phonological coding, word decoding, vocabulary, and comprehension. Findings for comprehension were not moderated by modality (i.e., listening vs. reading comprehension), type of comprehension question, or type of text; however, the relation of working memory with vocabulary and comprehension were stronger for younger versus older readers. Peng et al. (2018) found that the relation of working memory to comprehension was no longer significant when both reading decoding and vocabulary were partialed, highlighting the need to consider complex constructs such as EF in the context of robust language variables.

At the specific study level, studies vary along numerous dimensions (e.g., age, population, type of EF considered, control variables), making it difficult to draw conclusions about how various types of EF relate to different types of reading. However, the role of working memory in particular is well documented (e.g., Cain, Oakhill, & Bryant, 2004; Christopher et al., 2012; Daneman & Carpenter, 1980), for both single word reading and reading comprehension (Christopher et al., 2012; Jacobson et al., 2017; Swanson, Orosco, & Kudo, 2017), albeit with concerns about the nature of its measurement (see Savage et al., 2007). WM is important for reading due to the integration necessary for letters in words, for information within text, and for semantic knowledge in long-term memory with text (Perfetti, 1999). The evidentiary base is thinner for the relation of other EF processes to reading. There is, however, mixed empirical support for inhibition (Altemeier, Abbott, & Berninger, 2008; Arrington, Kulesz, Francis, Fletcher, & Barnes, 2014; Keiffer, Vukovic, & Berry, 2013; Potocki, Sanchez, Ecalle, & Magnan, 2017; *versus* Barnes, Stuebing, Fletcher, Barth, & Francis, 2016; Christopher et al., 2012; De Franchis, Usai, Viterbori, & Traverso, 2017; van der Sluis et al., 2004), with lesser still evidence for planning (Cutting, Materek, Cole, Levine, & Mahone, 2009; Locascio, Mahone, Eason, & Cutting, 2010; Sesma, Mahone, Levine, Eason, & Cutting, 2009), shifting (Altemeier, et al., 2008; Jacobson et al., 2017; Kieffer, et al., 2013; Potocki et al., 2017), and verbal fluency (Bental & Tirosh, 2007; Cirino et al., 2017).

Although the above review includes twelve studies in children that evaluated *multiple* EF components and *multiple* aspects of reading, only the studies of Christopher et al. (2012) and Swanson et al. (2017) had larger sample sizes, utilized more than individual measures of EF (both had multiple measures of both working memory and inhibition), and included language control variables. Neither evaluated the range of EF considered in the present study, and neither explicitly considered the potential role of EF with regard to the Simple View of Reading. Thus, there is a need to evaluate this in more depth which has the potential to provide clarity to this literature. Indeed, Butterfuss and Kendeou (2017) note that “Because EF components are interrelated and interdependent, further research is needed to understand how each function contributes uniquely and in relation to each other” (p. 17). Follmer (2017) also noted that despite extant work, more work is needed both on the measurement of EF, as well as the use of latent variable models to examine components that are specific to EF.

Three other aspects are important to consider – the role of other cognitive skills, the types of reading considered, and the age/type of sample/population considered. Regarding cognitive skills, it is known that performance measures of EF require multiple skills including language, processing speed, short-term memory, etc. – the task impurity problem (Burgess, 1997; Miyake et al., 2000). This can make the particular unique or "value added" contribution of EF ambiguous, and therefore, it is important to consider the effect of EF in the context of these other cognitive skills, particularly those that are also relevant for reading.

Regarding reading outcomes, because of the complexity of reading comprehension, and because different measures are known to have variable relations with Simple View skills of decoding and listening comprehension (Cutting et al., 2009; Cutting & Scarborough, 2006; Francis et al., 2005; Keenan, Betjemann, & Olson, 2008; Miller et al., 2014; Potocki et al., 2017), it is also highly relevant to consider how EF intersects with such Simple View skills and other language variables, and to evaluate such relations for different types of reading comprehension (e.g., cloze passages that focus on word level meaning and production versus multiple choice literal and inferential questions).

Regarding context, extant data varies widely in terms of the type of population examined. Some have focused on unselected samples (Altemeier et al., 2008; Bental & Tirosh, 2007; Christopher et al., 2012; De Franchis et al., 2017; Kieffer et al., 2013; Potocki et al., 2017); while others focus on students with reading difficulty (Arrington et al., 2014; Cutting et al., 2009; Locascio et al., 2010; Sesma et al., 2009; Swanson et al., 2017). Other studies focus on minority youth (Jacobson et al., 2017); others with Spanish as a first language (Swanson et al., 2017). Understanding the role of EF for reading may be particularly important in populations with a high proportion at risk for reading difficulties, because it is for such students that one would seek to bolster achievement either directly (addressing reading) or indirectly (via EF).

The Present Study

The novelty and significant contribution of this study is that it adds critical knowledge by *comprehensively* evaluating the role of EF for multiple reading outcomes in a large sample (with many struggling readers) that considers multiple language and other cognitive covariates, and also how EF intersects with the Simple View of Reading. It does so within an age range (late elementary) where most prior studies have focused, given that it is a key point in development for both reading (e.g., Speece, Ritchey, Silverman, Schatschneider, Walker & Andrusik, 2010), and for EF (e.g., Anderson, Anderson, Northam, Jacobs, & Catroppa, 2001; Best, Miller, & Jones, 2009; Luciana & Nelson, 2002). Based on the evidence above and the complex nature of EF, we expected EF to relate more robustly with correspondingly complex aspects of reading (i.e., reading comprehension more than decoding or fluency). We did not hold particular hypotheses with regard to the different types of EF that would be most predominant for different reading skills, given that meta-analyses indicate similar sizes of these basic relations; we did expect the common factor to be the most salient predictor given that it by definition represents what is shared across measures of EF. We expected these patterns to still be evident when a host of demographic, language-related, and other cognitive covariates were considered.

We also hypothesized that EF might moderate the relationship of "Simple View of Reading" (SVR) skills (decoding and listening comprehension) to reading comprehension. Specifically, SVR components are expected to relate strongly to reading, but in the context of high EF, these links might be weakened. The logic is that EF can be deployed in the service of reading comprehension when it is high, to hold in mind the words within and across sentences, to make inferences, or to adjust the pace of decoding to ensure comprehension; such attributes may compensate for weakness in decoding and/or listening comprehension. In contrast, weaker EF leaves open fewer compensatory avenues particularly for less skilled readers, although some threshold level of EF may be important for listening comprehension to function. This logic echoes that put forth by Cutting and colleagues (Aboud et al., 2016; Cutting, Bailey, Barquero, & Aboud, 2015).

Because the SVR already specifies an interactive effect of decoding and listening comprehension, it is possible that EF additionally interacts with these components (i.e., a three-way interaction), though SVR components may be impactful whether they are multiplicative versus additive (e.g., Joshi & Aaron, 2000). What is less clear and to our knowledge has not been studied, is whether these putative interactive effects occur for EF, construed broadly or only for specific components (such as working memory, self-regulatory skill, etc.). A further question is whether EF interacts with specific language processes (e.g., phonological awareness) in moderating the relation of language processes to decoding and fluency. Again, we hypothesized stronger impacts of language for reading when EF is lower relative to when EF is higher. While there are plausible conceptual reasons to suppose that such interactions might exist, there is no known prior empirical data available to address this; however, the answer to such questions may be informative for better understanding the nature of EF's contributions to reading.

Methods

Participants

Participants were 846 students in grades 3 (*n*=186), 4 (*n*=484), 5 (*n*=176), across two sites in the southeastern U.S. In grades 3 and 5, the only exclusionary criteria was known limited-English proficiency (LEP) status. As the present study occurred in the context of a 4^{th} grade reading intervention study (Vaughn, Solis, Miciak, Taylor, & Fletcher, 2016), struggling readers (< 16^{th} %ile on Gates MacGinitie Reading Test, see below; MacGinitie, MacGinitie, Maria, Dreyer, & Hughes, 2007) are oversampled in grade 4. Of note, however, there was still a range of reading performance in 4^{th} grade (and a non-selection reading comprehension measure was also included), and the analyses took the oversampling into account through weighting (elaborated below). The intervention itself does not strongly impact the results of the present study because: (a) many measures for many participants are based on reading and EF measures given at pretest, prior to the intervention; (b) where this was systematically not the case (teacher-rated measures of behavioral inattention and metacognition), results did not differ for struggling readers assigned to intervention versus control; and (c) when the timing of when the student assessment was conducted was included as an additional covariate, substantive results described below were the same.

Measures

There were five classes of measures: demographic and cognitive covariates, language, EF predictors and reading outcomes. These measures are described below, and Supplemental Table S1 includes distributional and psychometric data for each measure. This table presents standardized scores wherever available to demonstrate sample performance. Some values for individual EF measures were low, a common issue with such measures, and is one reason why factor scores were analyzed. Actual analyzed measures were composites or factors based on combinations of the raw score versions of each measure, as indicated below (raw means and standard deviations appear in Supplemental Table S2 (see below).

Demographic variables.—These included age, sex, limited English proficient status, free lunch status (SES), and race/ethnicity.

Language.—For phonological awareness (PA), the Elision subtest of the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen, & Rashotte, 1999) was used. The Elision subtest is an untimed measure of the ability to segment words into smaller parts. Rapid automatized naming (RAN) was assessed with the Rapid Letter Naming subtest from the CTOPP (Wagner et al., 1999), which is a timed measure of letter reading where participants are asked to read letters out loud as quickly as possible. Vocabulary was assessed with Verbal Knowledge of the Kaufman Brief Intelligence Test – 2 (K-BIT-2; Kaufman & Kaufman, 2004). In this measure, participants hear a word or phrase and point to a picture displaying its meaning. The Oral Comprehension subtest of the Woodcock-Johnson-III Tests of Academic Achievement (WJ-III; McGrew & Woodcock, 2001; Woodcock, McGrew & Mather, 2001) assessed listening comprehension by assessing participant's ability to understand short orally-presented passages and supply missing words using presented cues.

Cognitive covariates.—These included composite measures of Motor function, Processing Speed, and Short-Term Memory because of their known relations with either reading or EF. For each domain, composites were created by averaging z-scores standardized across the whole sample. The Motor composite was made up of two measures: a timed measure of graphomotor skill (e.g., tracing) from the NEPSY-II Visuomotor Precision subtest (Korkman, Kirk, & Kemp, 2007), and a timed measure of dexterity where participants place cylindrical pegs into holes, from the Purdue Pegboard test (Lafeyette Instruments, 1999). The Processing Speed composite was captured by three measures. First, the response time to “go” trials on a Go-No-Go task (Redick, Calvo, Gay, & Engle, 2011; programmed in Inquisit 3, 2003), a computerized measure that captures participants' response times to an oft-presented stimuli. Second, response times from 0-back trials from an N-back paradigm utilizing letters, and shapes (Kirchner, 1958; programmed in Inquisit 3, 2003), a computerized measure, captured participants' response time when any stimulus is presented. Third, the time to complete the Letter Sequencing (where participants are asked to quickly connect letters scattered across a page in alphabetic order) and Number

Sequencing (where participants are asked to quickly connect numbers scattered across a page in numeric order) conditions of the Trail Making Task from the Delis-Kaplan Executive Function System (D-KEFS; Delis, Kaplan, & Kramer, 2001) assessed speed with low cognitive or motor demands. The Short-Term Memory composite included two measures: the forward version of the Corsi Block-Tapping Task (Corsi, 1972; programmed in Inquisit 3, 2003), an untimed computerized measure where participants recall sequences in the same order they were presented; and the Word Recall subtest of the Working Memory Test Battery for Children (WMTB-C; Pickering & Gathercole, 2001), where participants are read a list of words and asked to recall the words in the same order they were presented.

EF.—There were 27 measures, administered in planned-missingness fashion that nonetheless provided adequate covariance coverage through randomly assigning students to receive one of six patterns of measures. The final bifactor model resulted in a common EF factor (with loadings from all 27 measures), and specific factors of (a) working memory as span and manipulation, with planning (WMSM/Plan); (b) working memory as updating (WMU); (c) generative fluency (FLUENCY); (d) metacognitive behavioral report (MCOG); and (d) self-regulated learning (SRL). Results of this model are reported in Cirino et al. (2018), including detailed information on individual measures. For purposes of the current study, factor scores were extracted from this model and used as predictors, as the goal of the present study was less on establishing the structure of EF, but using a supported existing structure (Cirino et al., 2018) to evaluate its impact on reading outcomes. Brief descriptions of the original measures follow, according to the specific factor under which they fall.

WMSM/Plan.—There were five measures. The WMTB-C (Pickering & Gathercole, 2001) Listening Recall subtest presents participants with an increasing number of sentences and asked to recall the last word of each sentence; raw weighted span length was used as the index variable. Second, the Corsi Block-Tapping Task (Corsi, 1972; Inquisit 3, 2003), backward version, is an untimed computerized measure where participants remember sequences in the reversed order relative to how they were presented; raw weighted span length was used as the index variable. Two measures were obtained from the Tower of London (Inquisit 3, 2003; Shallice, 1982), which is an untimed computerized measure of planning where participants are asked to make as few moves as possible to match a target configuration (both raw accuracy score and number of additional moves were used). Fifth, WJ-III Planning (McGrew & Woodcock, 2001; Woodcock et al., 2001) has participants trace complex paths and maintain specific rules; the W score was used from this measure.

WMU.—Four measures were used. These were all obtained from an N-back paradigm (Inquisit 3, 2003; Kirchner, 1958), where participants are required to respond to a stimulus that is presented twice in a row (1-back) or that matches a stimulus from two trials before (2-back). The four tasks where 1- and 2-back conditions for two different stimuli (Letters and Shapes); the discriminability (d prime) score was utilized.

Fluency.—There were three measures. D-KEFS Design Fluency (Delis et al.,2001) has two conditions (Filled Dots, Empty Dots) where participants quickly connect either filled or empty dots to “draw” random line combinations, following a rule. D-KEFS Verbal Fluency

(Delis et al., 2001) Letter fluency requires participants to generate words to a given letter in one minute, whereas Category fluency requires participants to generate words belonging to a given category. For all three measures, the measure used is the raw score for designs/words generated.

SRL.—There were three measures, taken from the Contextual Learning Scale (Cirino, 2012). The subscales (Effort/Self-Efficacy, Skill/Preference, and Learning Strategies) are rated by students regarding the extent to which they agree with statements that speak to learning-related categories. The raw scores across items for each scale was used.

MCOG.—There were six measures. Five were subscales of the Metacognitive Scale of the Behavior Rating Inventory of Executive Function-Teacher Form (BRIEF-T; Gioia, Isquith, Guy, & Kenworthy, 2000). These subscales were rated by teachers regarding the extent to which students engage in certain behaviors. The subscales were Initiate, Monitor, Planning/ Organization, Organization of Materials, and Working Memory. The sixth measure was from the Strengths and Weaknesses of ADHD Symptoms and Normal Behavior Scale (SWAN; Swanson, et al., 2012), Inattention subscale, rated by teachers regarding such behavior. For both the BRIEF-T and SWAN, raw scores were used from each scale.

Six other measures did not load on a particular EF sub-factor, but did load on the general factor. These included D-KEFS Design Fluency Switching (Delis et al., 2001) which is similar to the measure described above, but in this case, the student must alternate between connecting filled versus empty dots. For D-KEFS Verbal Fluency Switching (Delis et al., 2001), the measure is again similar to that described above, but this time, participants must produce category exemplars going back and forth between two categories. For both designs and words subtests, the raw score produced in one minute was used. The D-KEFS Color Word Interference (Delis et al., 2001) Inhibition/Switching subtest requires participants to switch between naming a printed word that is a color, versus the color of ink in which the word is written. The D-KEFS Trail Making Test (Delis et al., 2001) Number-Letter Switching subtest requires to switch between connecting letters and numbers with a pencil in alphabetic and numeric order. For both the color-word reading, and number-letter subtests, the time taken was the measure used. The Go-No-Go task (Inquisit 3, 2003; Redick, et al., 2011) “no-go” discriminability score (d prime for accurate inhibition trials was used. Finally, the Stop Signal (Inquisit 3; Logan & Cowan 1984) task is an adaptive computerized measure of inhibition where participants must refrain from responding after a cue to respond is initiated; the stop signal reaction time was the measure used.

Reading.—Single word reading was assessed with the WJ-III Letter Word Identification subtest (McGrew & Woodcock, 2001; Woodcock et al., 2001) where participants read a list of letters and words aloud. Single word reading fluency was assessed with the Test of Word Reading Efficiency-2 (TOWRE-2; Torgesen, Wagner, & Rashotte, 2012) Word Reading Efficiency subtest, a timed measure of sight word reading where participants are given 45 seconds to correctly read a list of words. Reading comprehension was assessed with two measures: the Gates-MacGinitie (MacGinitie, 2000; MacGinitie et al., 2007) Reading Comprehension subtest, where participants read a text and answers multiple choice questions; and the WJ-III Passage Comprehension (McGrew & Woodcock, 2001; Woodcock et al., 2001) subtest, a cloze measure of comprehension of written text where the participant provides a word to complete a presented passage. All reading tests are widely used, and have excellent psychometric characteristics. Standard scores were used in analyses, though raw scores yielded highly similar results.

Analyses

Reading outcomes were regressed on EF factor scores, demographics, cognitive, and language covariates. We also included interactions of general and specific EF factors with SVR variables (for reading comprehension), or with phonological awareness (for single word decoding and word reading fluency). All non-demographic variables were continuous, and were centered to ease interpretability in the context of interactions. Assumptions were examined and outliers/influential observations examined via regression diagnostics (e.g., residual plots, studentized residuals, leverage, and tolerance) for their impact on results, with adjustments as indicated below. We computed squared semi-partial coefficients to examine unique effects; their collective impact and shared variance with other variables in the model were also examined. Models presented below account for the fact that students are nested within classrooms, and so all parameters, significance, and effect sizes are computed from multilevel models, including R^2 values, which are estimated with guidance from the literature (Olejnik & Algina, 2003; Peugh, 2010; Selya, Rose, Dierker, Hedeker, & Mermelstein, 2012; Tippey & Longnecker, 2016). Analyses were also weighted to account for the predominance of struggling readers in grade 4, such that individual students' data contributed differentially to overall models. The effect was to recapitulate the overall reading mean of the population of students in these schools (i.e., the weighted mean equaled the mean of all students). For linear relationships, weighting has a bigger effect on means than covariances, and so the weighting procedure did not strongly influence results (further details are in Cirino et al., 2018).

Results

Means, standard deviations, and zero order correlations of the demographic, language, EF, and other cognitive measures, along with reading measures, are provided in Supplemental Table S2. In general, demographic variables showed variable and modest relations with reading variables; the distribution of some of these variables was limited, which likely reduced the magnitude of relations. Fine motor skill, processing speed, and short-term memory showed weak to moderate relations with reading performances. There were robust correlations of language measures with reading. Common EF relations with reading were similar in size to those of language measures, but only the MCOG specific factor showed consistent relations with reading performance.

Predictive models addressed the relations among EF and reading components for each reading outcome separately, and included all the predictor variables referenced above, including interactions. For each reading outcome, the models were built sequentially to include a) all demographic, language and cognitive covariates in a baseline model, b) one general and six specific EF's, c) interactions of EF with language factors, and d) all other interactions. In this way, the final model can differentiate between shared versus unique effects; the results of these final models are presented in Table 1.

Single Word Reading

Forty-five observations (5.3%) had missing values on one or more of the included variables, and 14 observations were outliers and/or otherwise influential (1.7%); these observations were excluded. The unconditional ICC was .27. The first model included all demographic, cognitive, and specific language factors (^{2} (1) = 56.83, $p < 0.001$, −2LL = 5742, AICC = 5746, BIC = 5752), with a pseudo-R^2 (reflecting the squared correlation of predicted and actual reading comprehension scores) of .54 (Peugh, 2010). Adding the 6 EF factor scores (1 common and 5 specific) led to a significant increase in the proportion of variance explained, pseudo-$R^2\Delta$ = 2.7%, ^{2} (1) = 48.40, $p < 0.001$, −2LL = 5693, AICC = 5697, BIC = 5702. Interactions of EF with language factors (18 in all – the 6 EF factors with each of vocabulary, PA and RAN) were then added to this model, interactions involving RAN indicated multicollinearity (tolerance values ~7), and therefore these interactions were excluded. The remaining 12 interactions collectively added little, pseudo-$R^2\Delta$ = 0.3%, ^{2} (1) = 51.15, $p < 0.001$, −2LL = 5718, AICC = 5722, BIC = 5728 (see Table 1 for the parameter estimates from the full model). Among main effects, there were unique contributions of MCOG, $p < .001$, along with effects of PA, $p < .001$, RAN, $p < .001$, and VOC, $p < .001$, and with other covariates including motor, $p = .014$, age, $p < .001$, and contrasts involving grade, p's < .010. The only significant 2-way interaction was of PA with MCOG, $t = -2.68$, $p = .008$; the other 11 interactions were not significant (all $p > .05$). Squared semi-partial correlations revealed that the largest unique contributors in terms of effect size were age (9.5%) and grade (2.0%), PA (9.8%), VOC (2.4%), and RAN (1.9%), as well as MCOG (1.8%); all other individual contributions were < 1%. However, it is notable that unique effects constituted only 28.3% of the overall pseudo-R^2 (57%), suggesting substantial shared variance (57–28.3/57 = 50%) among predictors. The conditional ICC in the final model was .21.

Single Word Reading Fluency

There were 63 observations excluded for missing values (n=46 or 5.4%), or due to outliers and/or influential values (n=17 or 2.1%). The unconditional ICC was .25. The baseline model was significant, pseudo-R^2 = .53, $p < .001$; ^{2} (1) = 37.79, $p < 0.001$, −2LL = 5915, AICC = 5919, BIC = 5925. Adding 6 EF factors showed pseudo-$R^2\Delta$ = 3.2%, ^{2} (1) = 30.05, $p < 0.001$, −2LL = 5858, AICC = 5862, BIC = 5868. As above, interactions involving RAN produced multicollinearity and were excluded. Collectively, the interaction terms yielded no change in pseudo-R^2, with no significant two-way interactions; in the final model, pseudo-R^2 = .55; ^{2} (1) = 30.70, $p < 0.001$, −2LL = 5887, AICC = 5891, BIC = 5897. There were unique main effects of EF, $p = .02$, WMSM/Plan, $p < .001$, FLUENCY, $p = .006$, SRL, $p = .015$, and MCOG, $p = .016$, along with effects of PA, $p < .001$, RAN, $p < .001$, age, $p < .001$, and contrasts involving grade, $p < .001$, and race/ethnicity, $p < .001$ (parameter estimates in Table 1). Squared semi-partial correlations were largest for age (10.3%) and grade (2.3%), for RAN (11.1%) and PA (1.4%), and for WMSM/Plan (1.2%); collectively contributing 26.3% of the overall pseudo-R^2, suggesting substantial shared variance (48%) among predictors. Conditional ICC for the full model was .17

Reading Comprehension (Gates-MacGinitie)

Some observations were excluded due to missing values (*n*=47 or 5.5%), or outliers and/or influential values (*n*=11 or 1.3%). The unconditional ICC was .36. The baseline model included demographics, cognitive, and the SVR variables (single word reading and listening comprehension) and their interaction, pseudo-R^2 = .64, p < .001; ^{2} (1) = 10.33, p < 0.001, −2LL = 5672, AICC = 5676, BIC = 5682. Subsequently adding the 6 EF factors and all their interactions with language yielded pseudo-$R^2\Delta$ = 2.47%; ^{2} (1) = 7.17, p < 0.01, −2LL = 5618, AICC = 5622, BIC = 5628. F(24,748) = 3.92, p < .001. The final model containing all covariates and three-way interactions was significant, ^{2} (1) = 6.07, p = 0.014, −2LL = 5732, AICC = 5736, BIC = 5741, pseudo-R^2 = .67.

There were unique contributions of common EF, MCOG, single word reading, listening comprehension, processing speed, English proficiency, and contrasts involving grade (all p < .001). The largest unique contributors were grade contrast (4 v. 3, 4.1%) and English proficiency (2.3%), single word reading (10.4%) and listening comprehension (2.1%), and common EF (1.0%); these represented 19.9% of the overall pseudo-R^2 (69%), indicating 69% shared variance. In addition, there were two significant 2-way interactions each involving listening comprehension – with single word reading, t = 2.30, p = .021; and with common EF, t = 2.49, p = .013. There were also significant 3-way interactions of single word reading and listening comprehension (SVR) with common EF, t = −2.72, p = .007, and with WMU, t = 2.43, p = .015; other 3-way interactions were not significant (all p > .05). The conditional ICC for the full model was .05.

To aid interpretation of the 3-way interactions (all continuous variables), Figure 1 (panels a and b) illustrates the interactions involving common EF, and WMU. Simple slopes of the relation between listening comprehension and reading comprehension are shown at low (−1 SD) and high (+1 SD) centered values of single word reading, by similarly centered values of common EF (panel a). When common EF is low, the 2-way Simple View interaction is prominent: when single word reading is low, then there is no relation between listening and reading comprehension, but as single word reading improves, the relation of listening to reading comprehension increases. In contrast, with high common EF, there is no Simple View interaction; rather, both listening comprehension and single word reading had only main effects on reading comprehension.

A similar process was used to probe the 3-way interaction of WMU with single word reading and listening comprehension, but here the Simple View interaction only held when WMU was *high* (panel b). With strong WMU, the relation of listening to reading comprehension varies such that it is strong when decoding is strong, and weak when single word reading is weak. In contrast, when WMU is weak, the relation of listening to reading comprehension is consistent across the range of single word reading skill. For both models, however, reading comprehension is highest when listening comprehension, single word reading, and EF (however measured) are also highest.

Reading Comprehension (WJ-III Passage Comprehension)

Some observations were excluded due to missing values (*n*=46 or 5.4%), or outliers and/or influential values (*n*=16 or 2.0%). The unconditional ICC was .35. The baseline model yielded pseudo-R^2 = .72; ^{2} (1) = 49.11, $p < 0.001$, −2LL = 5022, AICC = 5026, BIC = 5032 (including demographic, cognitive, and SVR variables). Adding the 6 EF factor scores yielded pseudo-$R^2\Delta$ = 2.29%; ^{2} (1) = 27.28, $p < 0.001$, −2LL = 4969, AICC = 4973, BIC = 4978, and the final model with all interactions was significant, pseudo-R^2 = .75; ^{2} (1) = 27.26, $p < 0.001$, −2LL = 5088, AICC = 5092, BIC = 5098. There were unique main effects of age, English proficiency, sex, lunch status, and of contrasts involving grade, and race/ethnicity (all *p*'s < .001 except age where $p = .040$). Main effects were also noted for single word reading and listening comprehension, and for common EF, WMSM/Plan, and SRL (all $p < .01$). Four of the 13 2-way interactions were significant each involving single word reading, with listening comprehension (SVR), $t = 2.56$, $p = .011$; with MCOG, $t = -2.30$, $p = 0.022$; with common EF, $t = -2.04$, $p = .041$; and with WMSM/Plan $t = 2.13$, $p = .034$.

There was also a 3-way interaction of SVR variables with WMSM/Plan, $t = 2.25$, $p = .025$, which is interpretable in a manner analogous to that of the 3-way interaction involving WMU for the Gates MacGinitie. That is, in the context of strong WMSM/Plan, the relationship of listening comprehension to reading comprehension increases with decoding skill. The other five 3-way interactions (with common EF and other specific EF factors) were not significant, all $p > .05$. Squared semi-partial correlations showed effects for age (5.1%), single word reading (9.4%), listening comprehension (2.7%), and common EF (1.7%); these constituted 18.9% of the overall pseudo-R^2 (75%), indicating 75% shared variance, which is more shared variance than the word reading models above. Parameter estimates are found in Table 2. The conditional ICC was .14.

Discussion

The goal of the present study was to comprehensively evaluate the impact of EF and related factors for reading in late elementary school students. For single word reading, predictor variables collectively explained 57% of the variance, with EF factors adding ~3% to already-strong (demographic and language-based) prediction models. There was minimal impact of laboratory (performance) measures of EF; in contrast, behavioral ratings of EF (MCOG) were significant. For single word reading fluency, the model explained 55% of variance, and there were unique effects for multiple EF components, including common EF, WMSM/Plan, Fluency, SRL, and MCOG, collectively adding ~3% to strong baseline models. For both single word reading and word reading fluency, there was substantial shared variance among predictors, and interactive effects of EF with language were not further contributory. For reading comprehension, results were somewhat different, with stronger overall prediction (pseudo-R^2 = 67% and 75%), more clear impact of common EF for both outcomes, with variable contributions from other factors. At the same time, these models exhibited substantially more shared variance (70% and 75%) relative to single word models. The overall unique added contributions were ~3%, similar to the word reading and fluency outcomes. These models also demonstrated the hypothesized interactive effects of EF with SVR variables, though not always in the same direction.

The present results extend smaller-scale studies (Cutting et al., 2009; Locascio et al., 2010; Potocki et al., 2017; Sesma et al., 2009) and complement meta-analyses and reviews (Butterfuss & Kendeou, 2017; Follmer, 2017; Jacob & Parkinson, 2015) demonstrating that EF uniquely contributes to reading skill. However, present results are noteworthy for at least three reasons. First, given the array of demographic and linguistic covariates considered, baseline models were quite strong, accounting for ~70% variance in reading comprehension. Adding further predictive power to such models implies a reduction in a relatively small portion of unknown prediction, some of which is error of measurement, and so even the small added value could be considered impressive. Second, the high proportion of shared variance observed implies that unique effects, though important, need to be considered in the broader context of cognitive skills (including language) working together to influence the reading process, and these contributions are very difficult to separate from one another.

Third, EF was found to be important for all three types of reading outcomes, though the way EF operates appears to vary depending on the reading skill considered. This is not particularly surprising, as prior studies that have explicitly evaluated prediction of both lower level (accuracy, fluency) and higher level (comprehension) reading outcomes have come to mixed conclusions, with some (Kieffer et al., 2013; Potocki et al., 2017; Sesma et al., 2009) finding that EF related only to reading comprehension, whereas others (Altemeier et al., 2008; Arrington et al., 2014; Christopher et al., 2012; Jacobson et al., 2017; Swanson et al., 2017) found support for EF predicting both types of outcomes. It is notable that those that find effects for word reading and fluency tend to be the larger sample-size studies. In general, the range of predictors was broader for word reading fluency than for single word reading, and only teacher-rated attention and EF (MCOG) was uniquely predictive for both of these outcomes. This could suggest that behavioral and cognitive control of effort may impact the demonstrated facility to read words, at least at these ages, when even struggling readers have some level of decoding skill. The additional predictive power of EF performance measures for single word reading fluency may reflect the additional demands of such a measure for students with generally adequate word identification skills (mean WJ LWID standard score = 96; mean TOWRE SWE standard score = 87).

For reading comprehension, yet more complex effects were observed. In addition to unique main effects of EF (which were observed for both measures of reading comprehension), we hypothesized that the SVR interaction would hold when EF is lower rather than higher (i.e., a negative three-way interaction), which was found (see Figure 1a). At low levels of (common) EF, reading comprehension is driven by linguistic factors that interact with one another, in line with that proposed by the Simple View. However, at higher levels of EF, not only is the relation of listening comprehension to reading comprehension strong, but EF can act to partially compensate for lower decoding skill – for example, the three-way interaction for the Gates MacGinitie showed that in the context of high EF, reading comprehension can be adequate even with low decoding (so long as listening comprehension is also high). How might this be translated into the reading situation? Individuals with low decoding, but strong EF and listening comprehension, may employ strategies to help them decode unknown words (e.g., making strategic “guesses” from context). Word decoding strategies in contextual reading were not studied here; however, it is of interest that strategy-use has been found to mediate the relation of working memory and other complex cognitive tasks (e.g., Unsworth & Spillers, 2010) and that training encoding strategies attenuates working memory differences between lower and higher span individuals (Robison & Unsworth, 2017). Conversely, if both decoding and listening comprehension are low, then EF is relatively unhelpful. These "compensatory" findings lend subtlety and an extension to our current understanding of the role that EF plays in reading. The current findings suggest some avenues by which hypotheses about the role of EF in word reading might be tested more experimentally.

In contrast to the negative 3-way interaction for common EF with SVR variables, there were other 3-way interactions that were *positive* and both involved working memory – updating in working memory (WMU) with regard to the Gates MacGinitie, and for manipulation and span factors of working memory including planning (WMSM/Plan) with regard to WJ-III Passage Comprehension. In these cases, the SVR interaction is present only with strong performance on these specific EFs. One possibility is that of a "threshold" effect. For example, some level of EF skill (e.g., working memory) may be *required* for the interplay of decoding and listening comprehension. This seems reasonable, given that a trade-off is required between effort spent recognizing/recalling/decoding individual words versus understanding their meaning while making inferences and engaging background knowledge; this trade-off is likely to be skewed when there are strengths versus weaknesses in the skills involved. Therefore, it may be that students need to possess some minimal level of WM in order to promote maximum instructional receptivity.

The present results imply that in some conditions, the contributions of SVR variables may be additive rather than multiplicative. This is relevant because although the Simple View specifies reading comprehension as the product of decoding and oral language (Gough & Tumner, 1986), there is debate about whether an additive combination of these components is more appropriate (Georgiou, Das, & Hayward, 2009; Joshi & Aaron, 2000; Savage, 2006). Foorman, Herrera, Petscher, Mitchell, and Truckenmiller (2015) examined Simple View variables with regard to comprehension to evaluate the role of vocabulary and syntax uniquely versus as a portion of common oral language (by utilizing a bifactor model); however, one of their findings was that common oral language was clearly and often the only significant predictor of reading comprehension across grades 4 to 10, accounting for 72 to 99% of the variance across grades; decoding fluency was not uniquely related in that context. Kershaw and Schatschneider (2012) found that in 3rd grade, an additive model was sufficient, and that the product may be most relevant in samples with the full range of skill. That is consistent with the sample utilized here, many of whom (in 4th grade) were selected for low reading comprehension (and therefore, likely, its correlates), but where the overall sample contained a range of reading proficiency. Thus, while the *form* (i.e., additive versus multiplicative) of the relation among SVR variables continues to be debated, the present study adds to this conversation by demonstrating not only support for a view in which the product of SVR variables is at play, but also that comprehension, in particular, is multiply determined, including by EF, and that these factors operate in conjunction with the SVR.

The present results build on a recently developed framework for the contribution of EF to academic skills. Cirino et al. (2018) notes that to properly delineate the impact of a skill in a multivariate context, it is relevant to examine its structure, its predictive value, and its potential to directly impact outcomes (e.g., intervention). Cirino et al. (2018) evaluated the first of these, and this study evaluates the second. What remains to be demonstrated is how best to take advantage of these potential compensatory or threshold effects, or predictive effects more generally.

The most straightforward interpretation is to "train" such skills directly, with the expectation that gains would spontaneously transfer to academic skills. For EF, working memory is a common example of such training. However, as several recent meta-analyses have indicated (Jacob & Parkinson, 2015; Melby-Lervåg & Hulme, 2013; Shipstead, Redick, & Engle, 2012), while gains on tasks closely related to the training tasks are evident, transfer to academic outcomes is weak; this point has been echoed across different literatures outside the realm of reading (e.g., Sala & Gobet, 2017). A second option might be to manipulate the hypothesized basis for transfer between cognitive and academic skill performance when training EF or when combining cognitive and academic interventions. For example, in keeping with findings on how strategy use mediates the relation of WM and some complex cognitive skills (Unsworth & Spillers, 2010), it might be of interest to test whether working memory training that includes strategies such as rehearsal, would show transfer to comprehension (see Peng & Fuchs, 2017).

It is unlikely that assessing students on EF (or other cognitive characteristics) and assigning them to groups with different intervention protocols would be effective, particularly at scale, and given the cost of doing so (Miciak, Taylor, Denton, & Fletcher, 2015; Miciak et al., 2016). A more fruitful way to advantage students with regard to EF may not be to change EF itself, but instead to build supports to maximize available EF so that these resources can be used in the service of reading. This might occur in at least two ways. First, consistent with many suggestions for strong intervention in either reading (Kamil et al., 2008) or math (Fuchs et al., 2008), EF as a self-regulatory skill can be promoted by increasing motivation and scaffolding, which is important because these factors may fluctuate in a more "state-like" fashion relative to performance-based EF skills. Second, reducing complex linguistic demands in instructional materials, and providing learning supports that diminish working memory loads for learners might indirectly lead to improved reading (see Fuchs et al., 2013, for an example in the context of a math intervention).

Although the focus of the present work is on reading outcomes, there is good reason to suggest that EF could hold value for the prediction of other academic domains (e.g., mathematics), or to other outcomes more generally. In fact, EF's contribution to math might be even stronger than it is for reading, where common predictors include both domain general and domain specific predictors, but account for less variance in outcomes relative to reading (Cowan & Powell, 2013; Fuchs et al., 2010). At the same time, some aspects of mathematics (e.g., word problem solving) are likely to draw on several of the same skills associated with reading comprehension (Fuchs, Fuchs, Compton, Hamlett, & Wang, 2015). Finally, whereas the relation of phonological awareness to reading is well-established and robust, predictors of mathematics are more numerous, though more consistently implicate broad predictors such as working memory that fall within the domain of EF. Future studies might explore other domains of mathematics proficiency such as higher order outcomes (e.g., algebra) or word problems outcomes. In other words, the framing of the present study might be used to examine the impact of EF in a similar manner across other academic domains.

Limitations

The present study is not without limitations. First, additional reading outcomes might have produced different relations with EF (e.g., evaluating decoding more explicitly with nonwords; discerning fluency for contextualized reading). Nonetheless, we did target three crucial domains. Second, the study was conducted in urban settings and in schools that had perhaps higher risk profiles than average. While this is relevant from the perspective of samples for whom EF supports might be especially beneficial, it does limit generalization. Similarly, evaluating either younger or older students could also have yielded different patterns of results. Third, the study was conducted in concert with an intervention study (Vaughn et al., 2016), and while most measures were completed at pretest, teacher rating scales were not (though these ratings did not differ among struggling readers who were versus were not in intervention). Fourth, much of the differential prediction (components of EF that were significant beyond common EF) that occurred involved SRL and MCOG, which were obtained via self-report and teacher-report, respectively, and so are not traditional, performance-based measures of EF as are often seen in the neuropsychological literature. Finally, the EF-related findings had generally modest unique effect sizes, particularly relative to specific language skills or key demographics such as age/grade, and therefore replicating some of these effects would be important. While these limitations do not change the substantive conclusions we make, future studies may extend these findings to different contexts.

Conclusions

This study showed that EF has clear and unique contributions to reading processes, including decoding, fluency, and comprehension, even in the context of strong covariates. The strength of relationship was similar for all outcomes, though for decoding and fluency, main effects were common, whereas for reading comprehension, the impact of EF interacted with Simple View variables. The present study advances our understanding of the factors involved in different types of reading skill, especially those related to the Simple View and EF, and how they work with one another to support the reading process.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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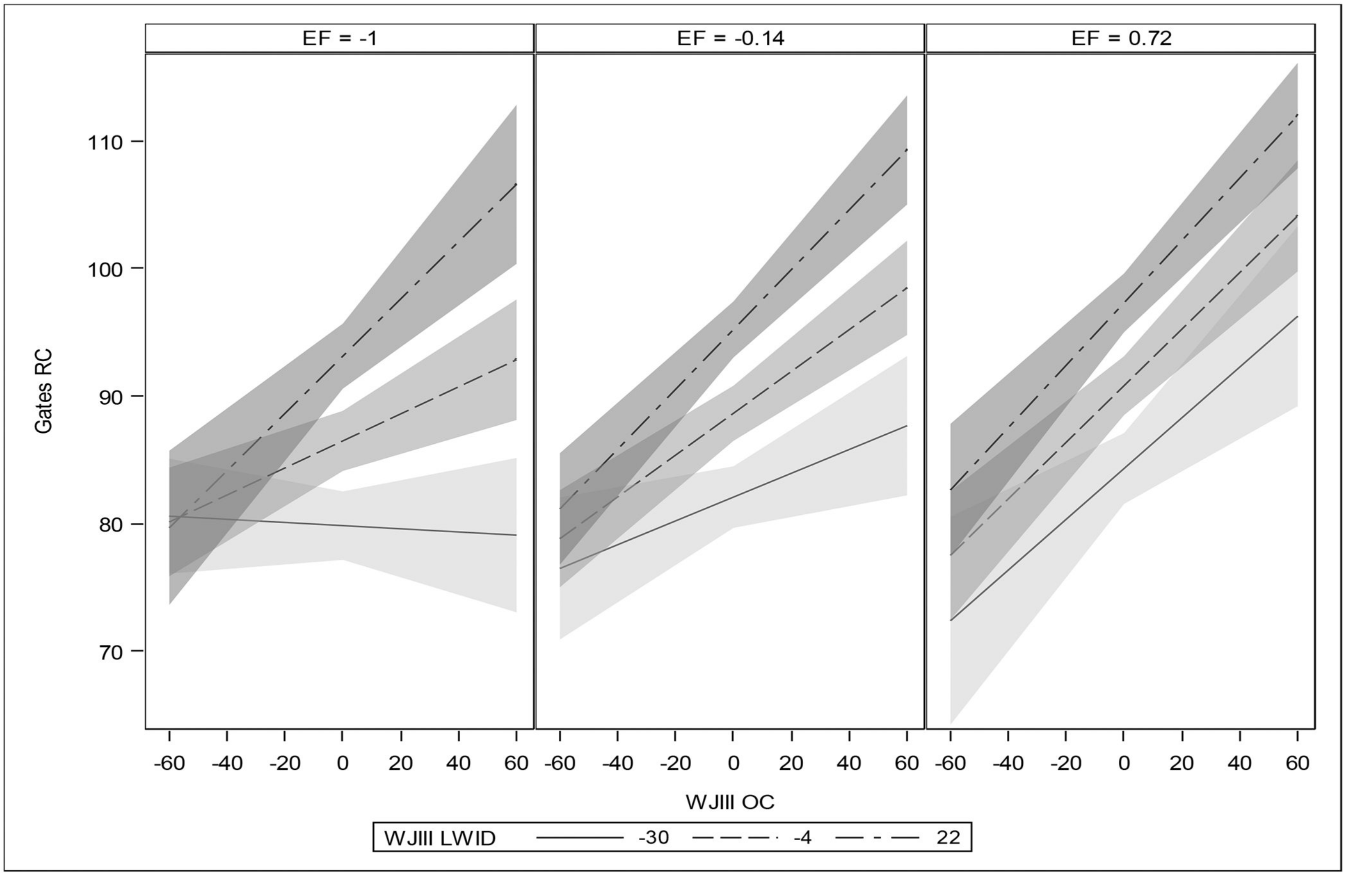

Figure 1a.
Performance on reading comprehension (Gates MacGinitie) is shown as a function of common executive function (EF; panels from left to right, representing low, average, and high EF, respectively), listening comprehension (WJ-III Oral Comprehension subset, WJ-III OC; along x axis), and single word reading (WJ-III Letter-Word Identification, WJ-III LWID, represented by low (lightest gray), average, and high (darkest gray) LWID slopes within each panel). Bands around slopes reflect standard error, and graphs are considered at the sample mean of all other variables in the model.
Three way interaction of common executive function (EF) with simple view variables (decoding and listening comprehension) on reading comprehension.

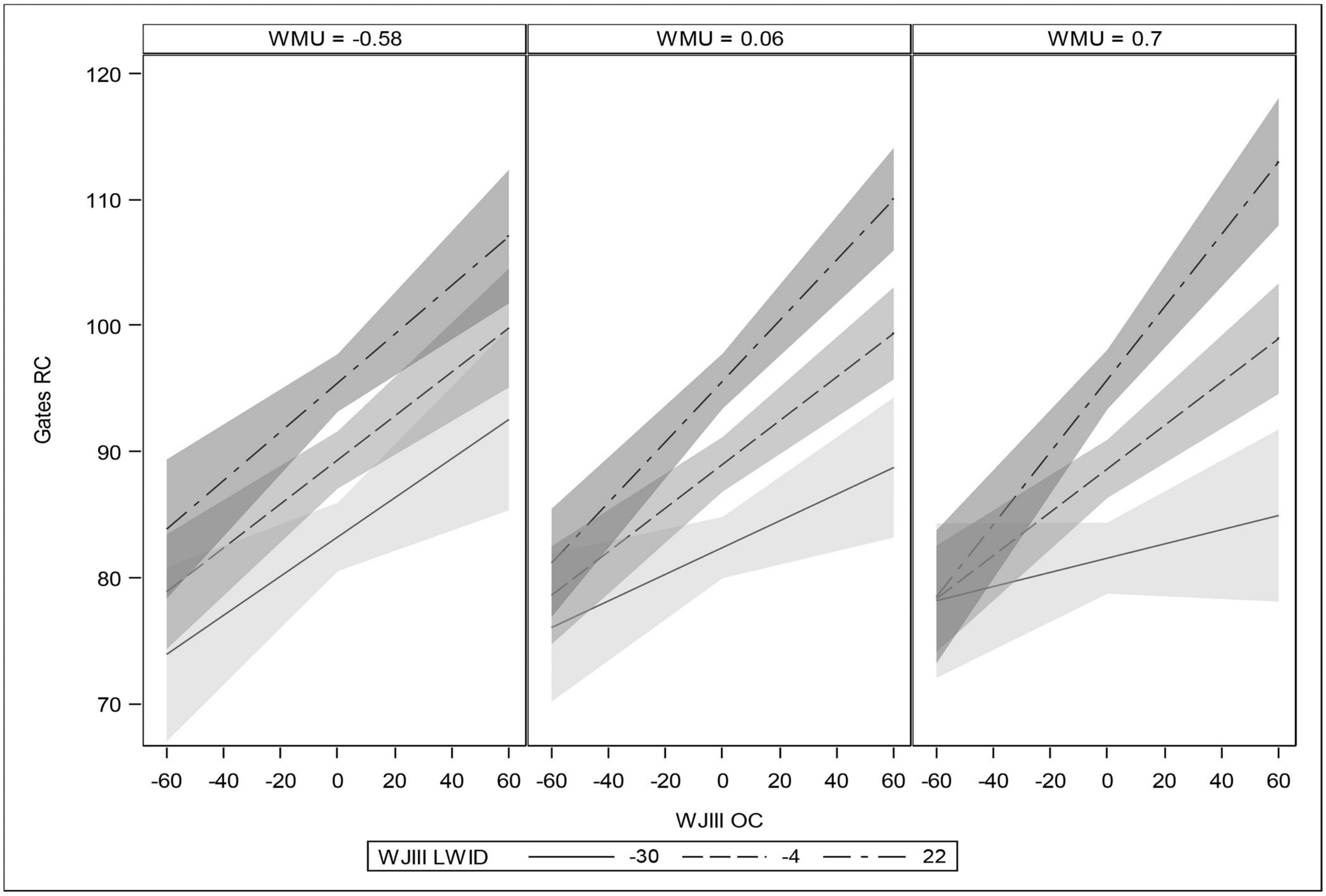

Figure 1b.
Performance on reading comprehension (Gates MacGinitie) is shown as a function of working memory-updating (WMU). See note for Figure 1a for other details.
Three way interaction of working memory-updating (WMU) with simple view variables (decoding and listening comprehension) on reading comprehension.

Table 1.

Parameter Estimates for Single Word Reading and Fluency Models.

	Single Word Reading		Single Word Reading Fluency	
	B **(SE)**	***Semipartial ω²***	***B (SE)***	***Semipartial ω2***
Intercept	96.95** (3.34)		80.50** (4.40)	
Demographics		.		.
Age	−8.40** (0.65)	0.095	−9.92** (0.74)	0.103
English Proficiency	2.31 (1.21)	0.001	2.61 (1.36)	0.002
Sex (Female)	0.09 (0.64)	−0.001	−0.29 (0.73)	0.000
SES (Free/Reduced Lunch)	0.66 (0.97)	0.000	0.29 (1.16)	−0.001
Grade 3 vs. 4	3.04* (1.22)	0.003	−0.73 (1.33)	0.000
Grade 5 vs. 4	−9.04** (1.48)	0.020	−10.65** (1.65)	0.023
Ethnicity (White vs. Hispanic)	0.76 (0.91)	0.000	2.78* (1.06)	0.003
Ethnicity (Black vs. Hispanic)	−0.61 (0.84)	0.000	1.38 (0.96)	0.001
Ethnicity (Other vs. Hispanic)	−0.97 (2.12)	0.000	1.75 (3.44)	0.000
Cognitive variables		.		.
Motor	−1.06* (0.43)	0.003	0.93 (0.49)	0.001
Speed	−0.51 (0.43)	0.000	−0.65 (0.50)	0.000
Short Term Memory (STM)	0.64 (0.49)	0.000	0.98 (0.56)	0.001
Language variables	.		.	
Phonological Awareness (PA)	0.91** (0.07)	0.098	0.40** (0.08)	0.014
RAN	0.04** (0.01)	0.019	0.11** (0.01)	0.111
Vocabulary	0.42** (0.06)	0.024	0.03 (0.07)	0.000
Executive functioning (EF)		.		.
EF	0.87 (0.53)	0.001	1.38* (0.61)	0.002
WMSMP	−0.91 (0.51)	0.001	−2.58** (0.56)	0.012
WM as Updating (WMU)	0.24 (0.52)	0.000	−0.80 (0.59)	0.000
Fluency	−0.53 (0.41)	0.000	1.30* (0.47)	0.004
Self-Regulated Learning (SRL)	0.50 (0.33)	0.001	0.94* (0.38)	0.003
Metacognition	2.17** (0.38)	0.018	1.06* (0.44)	0.003
Two-way interactions		.		.
EF x PA	−0.04 (0.08)	0.000	−0.11 (0.10)	0.000
WMSMP x PA	0.16 (0.11)	0.001	0.12 (0.12)	0.000
WMU x PA	−0.12 (0.11)	0.000	0.17 (0.12)	0.001
Fluency x PA	0.01 (0.09)	−0.001	0.00 (0.10)	−0.001
SRL x PA	0.01 (0.07)	−0.001	0.05 (0.08)	0.000
Metacognition x PA	−0.22* (0.08)	0.003	−0.07 (0.10)	0.000
EF x Vocabulary	0.08 (0.06)	0.000	0.01 (0.07)	−0.001
WMSMP x Vocabulary	−0.08 (0.07)	0.000	−0.03 (0.08)	−0.001

	Single Word Reading		Single Word Reading Fluency	
	B **(SE)**	***Semipartial ω²***	***B (SE)***	***Semipartial ω2***
WMU x Vocabulary	0.02 (0.08)	−0.001	0.02 (0.09)	−0.001
Fluency x Vocabulary	0.07 (0.07)	0.000	0.09 (0.08)	0.000
SRL x Vocabulary	−0.01 (0.05)	−0.001	−0.08 (0.06)	0.001
Metacognition x Vocabulary	0.04 (0.06)	0.000	−0.02 (0.07)	−0.001

Note. See text for description of variables. Continuous variables were standardized (M = 0; SD = 1). Decimal places were increased for some significant effects to increase the displayed precision of results. Numbers in parentheses are standard errors. RAN = rapid naming; WMSMP = WM as span and manipulate, with planning.

*$p < .05$;

**$p < .001$

Table 2.

Parameter Estimates for the Reading Comprehension Models.

	Gates MacGinitie		Woodcock Johnson	
	***B* (SE)**	***Semipartial ω²***	***B* (SE)**	***Semipartial ω²***
Intercept	93.56** (2.96)		99.30** (2.07)	
Demographics				
Age	−0.84 (0.60)	0.000	−5.03** (0.40)	0.051
English Proficiency	8.65** (1.14)	0.023	2.50* (0.77)	0.003
Sex (Female)	−1.10 (0.59)	0.001	−1.19* (0.40)	0.003
SES (Free/Reduced Lunch)	−1.47 (0.91)	0.001	−1.73* (0.61)	0.002
Grade 3 vs. 4	−9.58** (0.96)	0.041	−1.47* (0.71)	0.001
Grade 5 vs. 4	0.73 (1.23)	0.000	−1.63 (0.87)	0.001
Ethnicity (White vs. Hispanic)	−0.59 (0.85)	0.000	−2.75** (0.57)	0.007
Ethnicity (Black vs. Hispanic)	1.34 (0.75)	0.001	−1.59* (0.51)	0.003
Ethnicity (Other vs. Hispanic)	−1.53 (2.01)	0.000	−3.81* (1.44)	0.002
Cognitive Variables				
Motor	−0.15 (0.40)	0.000	0.07 (0.26)	0.000
Speed	−1.44** (0.41)	0.005	−0.28 (0.28)	0.000
Short Term Memory (STM)	0.74 (0.48)	0.001	−0.16 (0.31)	0.000
Executive Functioning				
EF	2.50** (0.51)	0.010	2.46** (0.34)	0.017
WMSMP	−0.71 (0.51)	0.000	−1.08* (0.35)	0.003
WM as Updating (WMU)	−0.43 (0.56)	0.000	−0.57 (0.36)	0.000
Fluency	0.68 (0.41)	0.001	−0.05 (0.28)	0.000
Self-Regulated Learning (SRL)	0.41 (0.32)	0.000	0.45* (0.22)	0.001
Metacognition	1.71** (0.36)	0.009	−0.02 (0.25)	0.000
Simple View of Reading				
Word Reading	0.25** (0.02)	0.104	0.18** (0.01)	0.094
Oral Comprehension	0.18** (0.03)	0.021	0.15** (0.02)	0.027
Word Reading x Oral Comprehension (SVR)	0.002* (0.001)	0.002	0.002* (0.0007)	0.002
Executive Functioning				
EF	2.50** (0.51)	0.010	2.46** (0.34)	0.017
WMSMP	−0.71 (0.51)	0.000	−1.08* (0.35)	0.003
WM as Updating (WMU)	−0.43 (0.56)	0.000	−0.57 (0.36)	0.000
Fluency	0.68 (0.41)	0.001	−0.05 (0.28)	0.000
Self-Regulated Learning (SRL)	0.41 (0.32)	0.000	0.45* (0.22)	0.001
Metacognition	1.71** (0.36)	0.009	−0.02 (0.25)	0.000
Two Way Interactions				
EF x Decoding	0.00 (0.02)	0.000	−0.02* (0.01)	0.001
WMSMP x Decoding	0.00 (0.02)	0.000	0.03* (0.01)	0.001
WMU x Decoding	0.03 (0.02)	0.000	0.01 (0.02)	0.000
Fluency x Decoding	−0.03 (0.02)	0.001	0.01 (0.01)	0.000

	Gates MacGinitie		Woodcock Johnson	
	B **(SE)**	***Semipartial*** ω^2	***B*** **(SE)**	***Semipartial*** ω^2
SRL x Decoding	0.00 (0.01)	0.000	−0.01 (0.01)	0.000
Metacognition x Decoding	0.01 (0.02)	0.000	−0.03* (0.01)	0.001
EF x Oral Comprehension	0.06* (0.02)	0.002	0.01 (0.02)	0.000
WMSMP x Oral Comprehension	−0.04 (0.03)	0.000	−0.03 (0.02)	0.000
WMU x Oral Comprehension	0.01 (0.03)	0.000	0.00 (0.02)	0.000
Fluency x Oral Comprehension	0.00 (0.03)	0.000	−0.02 (0.02)	0.000
SRL x Oral Comprehension	−0.04 (0.02)	0.001	0.03* (0.01)	0.001
Metacognition x Oral Comprehension	0.00 (0.02)	0.000	0.01 (0.01)	0.000
Three-Way Interactions				
EF x SVR	−0.002* (0.0008)	0.003	0.00 (0.00)	0.000
WMSMP x SVR	0.00 (0.00)	0.000	0.002* (0.0008)	0.001
WMU x SVR	0.003* (0.001)	0.002	0.00 (0.00)	0.000
Fluency x SVR	0.00 (0.00)	0.000	0.00 (0.00)	0.000
SRL x SVR	0.00 (0.00)	0.000	0.00 (0.00)	0.000
Metacognition x SVR	0.00 (0.00)	0.000	0.00 (0.00)	0.000

Note. See Table 1 for abbreviations and notes.

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