Proceedings of the Annual Meeting of the Cognitive Science Society

Title

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Journal

Proceedings of the Annual Meeting of the Cognitive Science Society, 41(0)

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Publication Date

2019

Distinguishing Effects of Executive Functions on Literacy Skills in Adolescents

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Abstract

This study investigated direct and indirect effects of executive functions (EF) on reading comprehension in 87 adolescents (*mean age* = 14.0 years, *SD* = 1.5). The operation span task was used to measure the *updating* aspect of working memory, the plus-minus task to measure *task-switching*, and the numerical Stroop task to measure *inhibitory control*. Literacy skills tasks assessed nonword decoding, text recall/inference, and passage comprehension. Regression models indicated that EF measures accounted for significant variance in literacy skills after controlling for age and fluid intelligence. Working memory was associated with passage comprehension, task-switching with nonword decoding, and inhibitory control with nonword decoding as well as text recall/inference. Parallel mediation models tested for indirect effects of EF constructs via decoding and text recall/inference. Working memory showed direct and indirect effects on passage comprehension, the latter mediated by text recall/inference. Task-switching was associated with decoding, but its relation to passage comprehension was not significant. Inhibitory control showed indirect effects on passage comprehension via decoding and text recall/inference. Results indicate overlapping but distinct contributions of EF to literacy skills.

Keywords: reading comprehension, literacy skills, decoding, text recall/inference, executive functions, working memory, task-switching, inhibitory control

Introduction

Reading comprehension is an active process that involves weaving together information contained within a text to construct a coherent, accurate representation of its meaning (Kintsch, 1994). Various theoretical models have proposed that reading comprehension relies on the interplay of literacy subskills, including *decoding* (i.e., mapping orthographic units onto phonological units), *recall* (i.e., activation of previously encountered information), and *inference* (i.e., drawing conclusions to make sense of information). These subskills, in turn, rely on sustained attention and other manifestations of executive functions (EF). The goal of the current study was to explore direct and indirect associations between EF, literacy subskills, and reading comprehension. Our purpose was to shed light on sources of individual differences in reading ability, which in turn inform theoretical models of reading.

The *simple view of reading* identifies decoding and linguistic comprehension as two critical skills supporting readers in constructing meaning from text (Gough & Tunmer, 1986; Hoover & Gough, 1990). Decoding involves the utilization of spelling-to-sound (grapheme-to-phoneme) rules to translate printed text into spoken language. Through decoding, readers are able to sound out words quickly and accurately, and thus gain fluency in recognizing letters in words and words in text.

The *dual route model* (Coltheart, 2006) further distinguishes the processes involved in decoding words. According to this model, word reading occurs either through a lexical route, which involves accessing lexical representations through familiar spelling patterns, or through a non-lexical (phonological) route, which utilizes knowledge of letter-sound associations (i.e., phoneme-to-grapheme correspondence rules) to sound out words. Although the two routes are thought to be separable, readers utilize both routes in parallel, which may place considerable demands on EF.

In addition to decoding, models of the development of reading emphasize the importance of text recall and inference skills (Cain, Oakhill, & Lemmon, 2004; García & Cain, 2014). The *construction-integration model* outlines the process by which readers construct meaning from text (Kintsch & Mangalath, 2011): Readers achieve coherence by organizing information across sentences and linking it with broader contextual and background knowledge (Graesser, Singer, & Trabasso, 1994; Kintsch & Mangalath, 2011). Text representations may encode information verbatim or may encode the gist (Reyna, Corbin, Weldon, & Brainerd, 2016). In constructing such representations, readers rely on recall and inferential processes that bridge information (e.g., to resolve ambiguities, identify pronominal referents, establish causal relations), bring together verbatim and gist representations, and subsequently validate inferences against general knowledge (Singer, Harkness, & Stewart, 1997). Such operations are demanding of cognitive resources, especially working memory (Peng et al., 2018).

EF and the Development of Literacy Skills

EF broadly refers to a constellation of cognitive skills thought to be essential in the planning, monitoring, and control of cognitive processes. According to the unity and diversity framework, EF has three main components: working memory (also referred to as updating), task-switching, and inhibitory control (Miyake et al., 2000). The current study focused on individual differences in these three EF components and how they each influence decoding, text recall/inference, and reading comprehension in adolescents. As children become more fluent readers capable of recognizing familiar words with automaticity, less cognitive effort needs to be exerted to decode text, thus freeing up cognitive resources to better comprehend and critically understand the meaning behind the text (Kuhn et al., 2010; LaBerge & Samuels, 1974).

Working memory involves maintaining and/or updating information in response to task demands (Baddeley, 2012). As shown in a recent meta-analysis (Follmer, 2018), working memory appears to have a moderate positive association with reading comprehension (r = .38, 95% CI [.34 : .43]). It is less clear whether working memory bears an equally strong relation to decoding skill. In a study with 7- to 8-year-olds, Oakhill, Cain, and Bryant (2003) found that measures of working memory, text integration, and metacognitive monitoring accounted for individual differences in reading comprehension, whereas performance on phoneme deletion, a phonological awareness task, explained variance in word reading. Their findings suggest that working memory may have a limited association with decoding, and a more direct association with reading comprehension.

Task-switching, or the ability to shift between different conceptual representations and rule sets, supports a wide variety of academic tasks including reading (Best, Miller, & Jones, 2009). Meta-analyses have reported a significant, albeit weak, association (r = .21, 95% CI [.11 : .31]) between task-switching and reading achievement in children (Yeniad, Malda, Mesman, van Ijzendoorn, & Pieper, 2013) and a moderate correlation (r = .39, 95% CI [.20 : .56]) between task-switching and reading comprehension in participants ranging from age 6 years to adults (Follmer, 2018). In a study involving 1st and 2nd graders, Cartwright et al. (2017) found that variation in reading comprehension was associated with performance on a color-shape cognitive flexibility task (a measure of task-switching), even after accounting for decoding ability. To date, few studies have examined direct associations between decoding and task-switching, though there is some evidence of a significant, albeit weak, association (Kieffer, Vukovic, & Berry, 2013).

To construct accurate text representations, readers also need to suppress competing sources of information and interpretations that may be concurrently activated (Gernsbacher & Faust, 1991). The mechanism of suppression is thought to stem from inhibitory control processes. An association between reading comprehension and inhibitory control has been reported in various studies with children (e.g., Kieffer et al., 2013), although a recent meta-analysis (Follmer, 2018), spanning ages from 6 years to adults, reported that the association between reading comprehension and inhibitory control was relatively weak (r = .21, 95% CI [.13 : .30]). The strength of this association in decoding is not well established.

Control Variables: Fluid Intelligence and Age

Over childhood and adolescence, reading ability typically improves. This age-related trend likely stems from accumulated experience with oral and written language in the context of formal education (Stanovich, 1986), as well as maturation of linguistic and cognitive abilities, such as improved lexical access (Logan, Schatschneider, & Wagner, 2011) and EF (Christopher et al., 2012). Prior research also suggests that fluid intelligence, i.e., the ability to solve novel reasoning problems, may correlate with specific EF components (Brydges, Reid, Fox, & Anderson, 2012), as well as early literacy skills (Blair & Razza, 2007). However, other studies suggest that individual differences in EF, most notably in working memory, largely account for the contribution of fluid intelligence to literacy skills in children and adolescents (Alloway & Alloway, 2010). In addition, not all EF components appear to be equally correlated with measures of fluid intelligence. Some prior research has reported a strong association between fluid intelligence and working memory (Unsworth, Fukuda, Awh, & Vogel, 2014), but not between fluid intelligence and task-switching or inhibitory control (Friedman et al., 2006). Taken together, previous research suggests the need to control for age and fluid intelligence in efforts to elucidate the unique contribution of EF components to reading skills, including decoding, text recall/inference, and reading comprehension.

Research Objectives

The current study used a battery of assessments to explore relations between components of EF (working memory, task-switching, inhibitory control) and literacy skills (decoding, text recall/inference, and passage comprehension). First, we sought to determine the extent to which the three components of EF were uniquely and directly associated with each literacy skill after controlling for other factors known to be related to reading ability (i.e., fluid intelligence and age). Second, we examined indirect associations between each EF component in relation to passage comprehension as mediated by nonword decoding and text recall/inference. We hypothesized that: (1) some aspects of EF would account for variation in the reading subskills of nonword decoding and text recall/inference; (2) some aspects of EF would account for variance in reading comprehension; and that (3) indirect associations between aspects of EF and reading comprehension would emerge by way of the reading subskills of nonword decoding and text recall/inference.

Method

Participants

Teachers from partnering schools (two middle schools and two high schools in New York City) brought their classes to a university research lab where their students were invited to participate in various computer-based studies including the current study. Only students whose parents had provided written consent were eligible to participate. The sample comprised of 87 students in grades 6 to 12 (49 females, 35 males, and 3 who did not disclose gender), ranging in age from 12 to 17 years (*mean* = 14.0, *SD* = 1.5).

Tasks and Measures

Working Memory. *The operation span task*, a complex span measure shown to correlate with moderately challenging to difficult arithmetic and reading tasks (Unsworth, Heitz, Schrock, & Engle, 2005), was used to assess working memory. Reliability on operation span tasks has been found to range between .70 to .80, depending on scoring methods (Conway et al., 2005), or approximately .77 using split-half reliability coefficient alphas (Kane et al., 2004). In the task used here, participants were instructed to perform simple arithmetic operations (e.g., (3 x 4) + 11 = ?) and indicate whether an answer was correct or incorrect. Between each arithmetic problem, participants were shown a letter to remember. The task presented three blocks of trials, with each trial consisting of an arithmetic problem followed by a letter. At the end of each block, the participant was asked to recall the letters in that block in the order presented. As an index of working memory, we calculated the proportion of correctly ordered letters across the three blocks of trials.

Task-switching. *The plus-minus task* was given as a measure of task-switching (Miyake et al., 2000); reliability of scores on this task has been estimated as approximately .60 using split-half reliability (Del Missier, Mäntylä, & Bruine de Bruin, 2010). In our version of the task, participants were shown three lists of 30 two-digit numbers and asked to perform numerical computations as quickly as possible on each number in the list. For List 1, participants were instructed to add 3 to each two-digit number; for List 2, they were instructed to subtract 3 from each number; for List 3, they were instructed to alternate between adding or subtracting 3 from each number. Standardized mix cost scores (z-scores) were used as an index of task-switching, based on prior studies (e.g., Miyake et al., 2000).

Inhibitory Control. We administered a shortened version of the *numerical Stroop task* (McVay & Kane, 2012) as a measure of inhibitory control. Reliability estimates of the numerical Stroop task indicate sufficient reliability (Cronbach α = .71; McVay & Kane, 2012). Our numerical Stroop task presented three blocks of trials in which participants were asked to identify the number of figures shown in an image on the computer screen. In Block 1 (five trials), the participant was shown a series of Xs (ranging from 1 to 9) and instructed to indicate the number of Xs presented (e.g., 5 in response to X X X X X). In Block 2 (five trials), they were shown a series consisting of a repeated digit (ranging from 1 to 9), with the length of the series also varying between 1 and 9 and consistent with the number of digits present (e.g., 4 4 4 4). In Block 3 (five trials), the digit and the number of digits in the series was never the same (e.g., 5 5 5) with the participant instructed to indicate the number of digits while ignoring the digit value. We calculated the number of correct responses in Block 3 as an index of inhibitory control.

Decoding Ability. We used a *nonword decoding task* to assess participants' ability to apply knowledge of grapheme-phoneme correspondences to pronounce letter strings. The nonword decoding task was based on an orally administered task, previously developed for research purposes (Hogan, Catts, & Little, 2005). It used five nonwords that followed phonotactic constraints of standard American English: *bos*, *bune*, *cim*, *gep*, *phoncher*. Participants were shown each nonword along with five options for a phonetically equivalent alternate spelling, with instructions stating, "Select the spelling that most closely matches the pronunciation of the word provided." For the item where the target nonword was *bos*, options included *bose, boz, doz, pose*, and *doze* (correct response is *boz*). Scores were calculated as the proportion of items answered correctly.

Text Recall and Inference. The *component reading processes task* is a multicomponent assessment of the ability to integrate knowledge while comprehending text (Hannon & Daneman, 2001). We used a modified computerized version that assessed participants' ability to recall information and make inferences across statements. Participants were given two three-sentence paragraphs describing relations between three nonwords (nouns), with each sentence relating a pair of nonwords (e.g., *A RILI resembles a DARF but is slower and larger.*) and appearing on a separate line. Participants read the first paragraph and answered four questions, then read the second paragraph and answered four additional questions. Participants were given up to 40 seconds to read each paragraph before being prompted with a set of questions that were presented without the paragraph in view.

Subscores (proportions of correct responses) calculated for each question type (i.e., recall and inference) were highly correlated, $r_p(85) = .49$, $p < .001$, after controlling for age. Subsequently, scores for text recall/inference were computed as the average between the two subscores.

Passage Comprehension. We administered a practice test from the New York State 12th grade English Language Arts Regents Exam (NYSED, 2012). The test presented two passages (one expository, one narrative) of equivalent length (i.e., 38 and 41 sentences; 551 and 559 words). Each passage had an accompanying 7-item multiple-choice test, with four response options per item. Accuracy (percentage correct) was used as the measure of reading passage comprehension.

Fluid Intelligence. A set of *Raven's progressive matrices* (Raven, 2000) was used to assess nonverbal fluid intelligence. The task consisted of five incomplete visual matrices, each with 5 to 8 possible options from which to choose a pattern to complete the matrix. The task has been shown to have robust indicators of reliability, with a test-retest Pearson correlation coefficient of .93 (Burke, 1972). Scores were computed as the proportion of correct responses.

Background Variables. A demographics questionnaire was administered following the research tasks. It included questions about the participant's gender, age, and first language learned (coded as English or not English). These variables were included as possible control variables in preliminary regression models predicting literacy skills.

Procedure

Upon arrival to the lab, students were provided with information about the study. After assenting to participate they were seated at computer stations to complete the computer-based tasks, administered via Qualtrics software. Students completed the reading passage comprehension test either before or after the computer-based tasks; this was randomized across participants.

Results

Table 1 presents descriptive statistics for the assessments of literacy skills and EF tasks.

Table 1. Descriptive statistics (*N*=87).

Measure	*M* (*SD)*
Raven's Progressive Matrices	61.6% (18.1%)
Executive Functions	
Operation Span Average	47.4% (28.4%)
Plus-Minus Mix Cost (*z*)	0.00 (1.00)
Numerical Stroop	48.5% (38.7%)
Literacy Skills	
Nonword Decoding	52.4% (28.4%)
Text Recall/Inference	52.7% (22.6%)
Reading Passage Comprehension	68.4 % (20.9%)

Preliminary Correlational Analyses

We examined partial correlations (controlling for age) across measures of literacy skills. After adjustment for multiple comparisons (Bonferroni-controlled $\alpha = .0167$), significant correlations were observed between the scores on the passage comprehension test and both nonword decoding, $r_p(85) = .37$, $p < .001$, and text recall/inference, $r_p(85) = .44$, $p < .001$. Nonword decoding and recall/inference were not significantly associated, $r_p(85) = .19$, $p = .084$.

We also examined partial correlations (controlling for age) between measures of EF (operation span for working memory, mix costs on the plus-minus task for task-switching, and numerical Stroop for inhibitory control) and fluid intelligence (Raven's progressive matrices). After adjustment for multiple comparisons (Bonferroni-corrected $\alpha = .0083$), none of the partial correlations were statistically significant, see Table 2. There was a trend towards an association between fluid intelligence and working memory, $r_p(85) = .27$, $p = .012$.

Table 2. *Descriptive Statistics and Age-controlled Partial Correlations for EF Variables (N=87)*

	WM	TS	IC
Working Memory			
Task-switching	–.03		
Inhibitory Control	–.02	.07	
Fluid Intelligence	.27	–.12	.18

WM: Operation Span, TS: Plus-Minus Mix Cost (z-score), IC: Numerical Stroop

Regression Analyses of Reading Subskills

Regression models were used to assess whether EF components accounted for variation in literacy skills.

Nonword Decoding. The overall model was significant, $F(6, 80) = 6.59$, $p < .001$, $R^2 = 33$. Task-switching and inhibitory control were significantly associated with nonword decoding, see Table 3.

Table 3. Multiple regression with nonword decoding as the outcome measure (*N*=87).

Variable	*β*	*SE*	*t*	*p*
Age	.18	.02	†1.68	.098
Fluid Intelligence	.19	.16	†1.81	.074
Recall-Inference	.00	.15	–.03	.974
Working Memory	.08	.11	.73	.468
Task-switching	.27	.03	**2.87	.005
Inhibitory Control	.31	.08	**3.06	.003

****p* < .001, ***p* < .01, **p* < .05, †*p* < .10

Component Reading Processes: Recall/Inference. The overall model was significant, $F(6, 80) = 8.81$, $p < .001$, $R^2 = .40$. Age, working memory, and inhibitory were significantly associated with text recall/inference, see Table 4.

Table 4. Multiple regression with text recall/inference as the outcome measure (*N*=87).

Variable	*β*	*SE*	*t*	*p*
Age	.32	.01	**3.22	.002
Fluid Intelligence	.13	.12	1.32	.190
Nonword Decoding	.00	.08	–.03	.974
Working Memory	.21	.08	*2.14	.035
Task-switching	.07	.02	.70	.483
Inhibitory Control	.27	.06	**2.78	.007

****p* < .001, ***p* < .01, **p* < .05

Reading Passage Comprehension. The overall model was significant, $F(7, 79) = 10.34$, $p < .001$, $R^2 = .48$. Fluid intelligence, nonword decoding, text recall/inference, and working memory were significantly associated with scores on the reading passage comprehension test, see Table 5.

Table 5. Multiple regression with reading passage comprehension as the outcome measure (*N*=87).

Variable	*β*	*SE*	*t*	*p*
Age	–.03	.01	–.29	.776
Fluid Intelligence	.21	.11	*2.25	.027
Nonword Decoding	.21	.07	*2.11	.038
Recall-Inference	.29	.10	**2.77	.007
Working Memory	.28	.07	**3.01	.004
Task-switching	.08	.02	.98	.332
Inhibitory Control	–.00	.05	–.02	.987

****p* < .001, ***p* < .01, **p* < .05

Mediation Analyses

Mediation analyses were run to test whether EF components had indirect associations with reading passage comprehension via nonword or text recall/inference skills. Constraints due to the number of observations and free parameters prevented a single model from being analyzed lest it be under-identified (Kline, 2015). Thus, three separate parallel mediation models tested for direct and indirect effects of EF measures on reading passage comprehension; see Figure 1 for the analytic model. Note that in the models for each EF construct, age and fluid intelligence were added as covariates associated with passage comprehension.

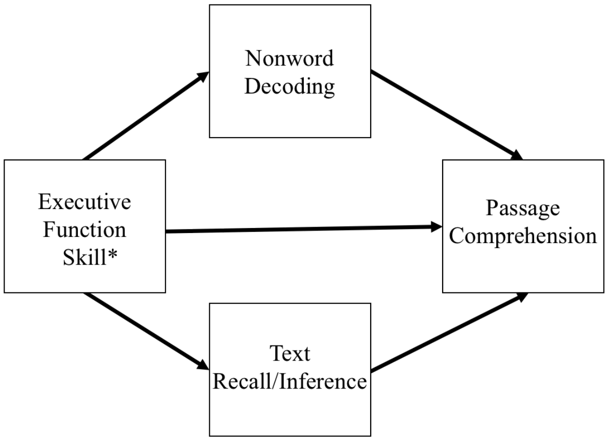

Figure 1. Parallel mediation model showing a direct path from EF skill to reading passage comprehension, and indirect paths through nonword decoding and text recall/inference. Each EF skill was entered as a predictor into one of three separate models with this form.

Indirect Effects of Working Memory. The first mediation analysis confirmed a statistically significant association between working memory and reading passage comprehension, total effect: $\beta = .46$, 95% CI [.45, .48], $SE = .07$, $z = 4.71$, $p < .001$; direct effect: $\beta = .29$, 95% CI [.28, .31], $SE = .07$, $z = 2.97$, p = .003. Tests of indirect effects indicated significant mediation via text recall/inference, $\beta = .12$, 95% CI [.11, .13], $SE = .03$, $z = 2.62$, $p = .009$. The indirect effect by way of nonword decoding was not significant, $\beta = .05$, 95% CI [.05, .06], $SE = .02$, $z = 1.72$, $p = .087$. These results suggest the association between working memory and passage comprehension is direct; however, text recall/inference partially mediates the association.

Indirect Effects of Task-switching. The mediation analysis failed to provide evidence that task-switching ability was associated with passage comprehension, total effect: $\beta = .16$, 95% CI [.15, .16], $SE = .02$, $z = 1.56$, $p = .12$, direct effect: $\beta = .09$, 95% CI [.08, .09], $SE = .02$, $z < .01$, $p = .36$.

Indirect Effects of Inhibitory Control. The mediation analysis indicated that inhibitory control was associated with reading passage comprehension, but the effect was indirect; for the total effect: $\beta = .22$, 95% CI [.21, .23], $SE = .05$, z = 2.14, $p = .032$; for the direct effect: $\beta = –.06$, 95% CI [–.07, –.04], $SE = .06$, $z = –.39$, $p = .60$. Tests of mediation indicated a significant indirect effect of inhibitory control on passage comprehension via nonword decoding, $\beta = .12$, 95% CI [.11, .12], $SE = .03$, $z = 2.41$, $p = .016$, and a significant indirect effect of inhibitory control on passage comprehension via text recall/inference, $\beta = .16$, 95% CI [.15, .17], $SE = .03$, $z = 2.93$, $p = .003$. These results suggest that inhibitory control influences passage comprehension through its associations with both decoding and text recall/inference abilities.

Discussion

The current study aimed to identify relations between specific EF components (working memory, task-switching, inhibitory control) and literacy skills (nonword decoding, text recall/inference, and reading passage comprehension) in adolescents. Understanding sources of individual differences in literacy skills has implications for developing interventions and refining theoretical models of reading. Such research is urgent given estimates that 1 out of every 10 children in the United States experiences reading difficulties, even among children with average or above average levels of intelligence (National Institutes of Health, 2010).

As a preliminary step in modeling effects of EF on literacy skills, we ran correlational analyses. These indicated a lack of unity across EF measures; hence the EF constructs were treated as separable in subsequent models. After accounting for influences of age and fluid intelligence, regression analyses identified a direct relation between working memory and reading passage comprehension. This result implicating working memory in performance of a complex and integrative reading comprehension task is in line with previous literature (Peng et al., 2018). Working memory also exhibited an indirect association with reading passage comprehension by way of text recall/inference, such that the higher one's operation span, the better one is able to read text fluently and make inferences based on its meaning, and subsequently construct accurate text representations.

Part of the novelty of our findings is in showing that working memory may play a lesser role in lower-level literacy skills, such as nonword decoding, than in higher-level skills, such as text recall/inference processes and reading passage comprehension. Our results corroborate Oakhill et al. (2003) in finding a significant direct association between measures of working memory and reading comprehension, but not between working memory and decoding. However, such an association has been reported by others (Christopher et al., 2012; Kieffer et al., 2013). In light of these mixed findings, a meta-analysis may be warranted to ascertain the relation of working memory to decoding.

Unlike working memory, task-switching was significantly associated only with nonword decoding. This is consistent with prior work that found an association between task-switching and word reading (e.g., Cartwright, 2012), and suggests that the ability to shift attention is instrumental for retrieving and applying letter-sound associations. Although the current study focused only on nonword decoding, we expect task-switching to impact decoding more generally. In relation to the dual-route model (Coltheart, 2006), readers must flexibly alternate between reliance on the lexical and nonlexical routes as they encounter both familiar and unfamiliar words. Within the more transparent French orthography, task-switching has been found to correlate with decoding (Colé, Duncan, & Blaye, 2014), suggesting an association independent of orthographic depth.

Inhibitory control was associated with nonword decoding and with text recall/inference abilities. In contrast to working memory, inhibitory control did not show a direct relation to passage comprehension. These findings are consistent with a previous large-scale study of adolescents that also found inhibitory control to be associated with decoding ability, but not with reading comprehension (Arrington, Kulesz, Francis, Fletcher, & Barnes, 2014). Thus, as in the current study, the effect of inhibitory control on reading comprehension appeared to be indirect and mediated by decoding ability.

Limitations

The simple view distinguishes decoding ability and linguistic comprehension as factors underlying reading comprehension. However, as we did not assess linguistic comprehension (e.g., receptive vocabulary and grammar) independently of text, it is difficult to apply the current findings to this framework. We also recognize that some cognitive assessments may be poorly suited for individual differences research (Hedge, Powell, & Sumner, 2017); hence future work should not rely on single measures to assess underlying EF constructs (see Denckla, 1994).

Conclusions

Our findings indicate that different components of EF have distinct relations with literacy skills in adolescents, which were evident after accounting for a number of control variables previously shown to influence reading abilities. We did not find evidence in support of unity across EF constructs. Given the complexity inherent to both reading and EF, it is perhaps not surprising that the relation between these cognitive processes is multifaceted. Our findings suggest that problems with a number of different EF skills may underlie reading difficulties in adolescents. Prior research has found a paucity of evidence that EF may be targeted to improve overall academic skills such as reading (Jacob, & Parkinson, 2015), and that it has limited potential in identifying responsiveness to targeted academic skills interventions (Miciak, Cirino, Ahmed, Reid, & Vaughn, 2019). Nevertheless, as the current study indicates, there is evidence of associations between EF and reading skills. Translating these findings into interventions to support reading comprehension will require further work.

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