Cognitive and Linguistic Predictors of Mathematical Word Problems With and Without Irrelevant Information

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Abstract

The purpose of this study was to identify cognitive and linguistic predictors of word problems with versus without irrelevant information. The sample was 701 2nd-grade students who received no specialized intervention on word problems. In the fall, they were assessed on initial arithmetic and word-problem skill as well as language ability, working memory capacity, and processing speed; in the spring, they were tested on a word-problem measure that included items with versus without irrelevant information. Significant predictors common to both forms of word problems were initial arithmetic and word problem-solving skill as well as language and working memory. Nonverbal reasoning predicted word problems with irrelevant information, but not word problems without irrelevant information. Findings are discussed in terms of implications for intervention and future research.

Keywords: cognitive predictors, linguistic predictors, problem solving, word problems, irrelevant information

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1. Introduction

Word problems (WPs) represent a major component of the mathematics curriculum across kindergarten through high school, and many high-stakes standardized tests, such as the National Assessment of Educational Progress (NAEP; National Assessment Governing Board, 2009), place heavy emphasis on mathematical word-problem solving. This makes sense because among school-age math measures, WPs are the best predictor of adult employment and wages (Every Child a Chance Trust, 2009; Murnane et al., 2001; Parsons & Bynner, 1997; Rivera-Batiz, 1992). Therefore, improving word-problem solving is critical for school and occupational success.

Not surprisingly, students at risk for or with mathematics learning disabilities struggle with word-problem solving (Parmar, Cawley, & Frazita, 1996). More surprising is that this struggle often occurs in the presence of adequate arithmetic skill (Fuchs et al., 2008; Swanson, Jerman, & Zheng, 2008). Some research indicates that arithmetic and word-problem solving are distinct components of mathematical competence. For example, studies demonstrate that the cognitive and linguistic processes underlying word-problem solving differ from those involved in arithmetic (e.g., Swanson & Beebe-Frankenberger, 2004; Fuchs et al, 2005; Fuchs et al., 2006; Geary et al., 2012).

For these reasons, early screening and intervention procedures for preventing WP difficultly likely require a different approach than is needed for arithmetic. Toward this end, understanding the WP features that create challenge is critical. In the present study, we focused on one potentially critical WP feature: the presence of irrelevant information. Specifically, we examined whether the cognitive and linguistic student characteristics that predict WP solution accuracy differ for WPs with versus without irrelevant information. We focused on second grade because individual differences in word-problem solving are established at this time (Fuchs et al., 2013) and because second grade is often when identification of learning disability begins (Fletcher, Lyon, Fuchs, & Barnes, 2006).

In this introduction, we begin by providing background information on word-problem solving, including a brief discussion about why word-problem solving may represent challenge in the presence of adequate arithmetic skill and about which cognitive and linguistic factors distinguish between word-problem solving and arithmetic skill. We then turn our attention to complex WPs, specifically those with irrelevant information, and provide a rationale for the present study's focus.

1.1 Word-problem solving: A distinct area of mathematical competence

A major distinction between word-problem solving and arithmetic is the addition of linguistic information, which requires students to decipher a WP narrative in order to build a problem model, identify the missing information, construct a number sentence to find the missing information, and (only then) perform calculation procedures to find the missing number. By contrast, arithmetic problems are already set up for calculation.

Four large-scale studies have examined whether arithmetic and word-problem solving skills constitute a single ability or are distinct areas of mathematical competence, by examining whether the cognitive and linguistic factors underlying word-problem solving and arithmetic differ. In these studies, simple WPs were defined as linguistically presented one-step problems that required arithmetic solutions. Studying 353 first, second, and third graders, Swanson and Beebe-Frankenberger (2004) found that short-term memory and fluid intelligence were unique to simple WPs, whereas phonological processing was unique to arithmetic. Working memory contributed strongly to both areas. Fuchs et al. (2005) measured cognitive abilities at the beginning of first grade to predict the development of arithmetic and simple WP skill among 272 children. Common predictors were teacher ratings of attentive behavior and working memory. Nonverbal problem solving was unique to simple WPs and phonological processing was unique to arithmetic. With 312 third graders, Fuchs, Fuchs, Compton, et al. (2006) examined the cognitive correlates of arithmetic versus simple WPs while controlling for the role of arithmetic skill in simple WPs. For simple WPs, nonverbal problem solving, sight word efficiency, language, and concept formation were unique, whereas for arithmetic, processing speed and phonological decoding were unique. Only teacher ratings of attentive behavior were common to both word-problem solving and arithmetic.

With a representative sample of 924 third graders classified as having difficulty with arithmetic, word-problem solving, both domains, or neither, Fuchs, Fuchs, Stuebing et al. (2008) explored patterns of difficulty in arithmetic and word-problem solving. Students were assessed on three measures of word-problem solving and three measures of arithmetic skill, as well as nine cognitive/linguistic dimensions. Using multivariate profile analyses, Fuchs et al. found that specific arithmetic difficulty was associated with deficits in processing speed and attentive behavior and strengths in language. By contrast, word-problem solving was associated with deficits in language. Across these studies, results suggest that individual differences in word-problem solving are associated with a distinctive set of cognitive and linguistic abilities.

1.2 Sources of WP difficulty

As mentioned, the most transparent distinction between word-problem solving and arithmetic is inclusion of linguistic information. The presentation of linguistic information, or the manner in which WPs are worded, influences the difficulty of a problem (e.g., Helwig, Rosek-Toedesco, Tindal, Heath, & Almond, 1999). It is important, however, to consider the type and extent of linguistic complexity embedded in a WP and to identify the sources of difficulty that make WPs especially challenging. These sources of WP difficulty may not necessarily distinguish word-problem solving and arithmetic, but instead create differential challenge within word-problem solving, as a function of WP features.

WP features that increase complexity include the following. First, the need to analyze other data sources, such as graphs or signage, to find the relevant information required for problem solving can increase challenge (Fuchs & Fuchs, 2007), by taxing working memory capacity. Second, the inclusion of irrelevant information decreases WP accuracy and causes differential challenge for students with mathematics learning disabilities (Parmar et al., 1996). In this paper, we refer to WPs that have one or more of these features as *complex WPs.* These features create problems that more accurately reflect real-world word-problem solving situations than simple WPs (i.e., WPs without these complicating features). To date, no studies have examined the cognitive predictors of complex versus simple WPs.

Complex WPs, such as those containing irrelevant information, often make problems for which solution strategies have been learned appear novel and confusing. In the present study, we focus on three problem types: (a) combine WPs (two quantities are combined to form a total), (b) compare WPs (two quantities are compared to find a difference), and (c) change WPs (an action triggers an increase or decrease in a starting amount). Now consider this simple combine WP: *Emma has two cats. Molly has three dogs. How many animals do the girls have altogether?* Next, consider this complex combine WP, with the same cover story except for the addition of irrelevant information: *Emma has two cats. Molly has three dogs. Molly walks her dogs four* *times a week. How many animals do the girls have altogether?* Although this irrelevant information (i.e., *Molly walks her dogs four times a week*) does not alter the problem type or the required solution method, it does make it harder for the student to identify the problem as belonging to the combine problem type. This is because most students expect combine problems to incorporate two given numbers along with one missing number. To make this situation more problematic, many students approach WPs without thinking deeply about how irrelevant information detracts them from recognizing a novel problem as belonging to a known, or previously taught, problem type. Furthermore, students may encounter irrelevant information presented within tables and graphs. For example, on many high-stakes assessments, irrelevant information is not frequently presented within problem text. In many cases, students have to negotiate irrelevant information provided within tables and graphs.

Because school instruction does little to vary the complexity of WPs, students often have difficulty deciphering problems that incorporate the kinds of complexity reflected in the real world. In other words, much instruction fails to link complex WPs to simple WPs by providing students with explicit strategies to connect complex problems with the problems used for instruction. One approach for promoting word-problem solving in school-age children that targets complex WPs is schema-broadening instruction (e.g., Fuchs et al., 2003a). Students are taught to transfer their knowledge of problem types to recognize complex problems as belonging to a problem type for which they have learned a solution strategy.

Cooper and Sweller (1987) identified three variables contributing to word-problem solving transfer. Students must (a) master problem solution rules, (b) develop categories, or *schemas,* for classifying problems that require similar solution methods, and (c) connect novel (or complex) problems to previously solved problems. Schemas facilitate transfer because students are able to connect novel problems with taught problems and apply learned problem-solution methods. In our previous example (i.e., *Emma has two cats. Molly has three dogs. How many animals do the girls have altogether?*), students learn to categorize this WP as a *combine* problem type, or schema, and then to apply a set combine solution strategies. Next, complex WP statements are introduced (i.e., *Emma has two cats. Molly has three dogs. Molly walks her dogs four times a week. How many animals do the girls have altogether?*), and intervention focuses on strategies for recognizing complex WP features, such as irrelevant information or combinations of problem types or finding relevant information in sources other than the WP statement. Students learn to connect this problem with the previous WP. They learn that while some sources of complexity make a problem appear different from what is expected, the underlying structure (i.e., problem-type) and problem solution method remain the same. The broader the schema, the greater the probability the student will recognize the connection between complex and previously solved problems.

Salomon and Perkins (1989) provided a framework for understanding how to broaden schemas and distinguished between two forms of transfer. Low-road transfer, accomplished through varied and extensive practice, involves the automatic triggering of well-learned, stimulus-controlled behavior in a new context (Fuchs et al., 2003a; Salomon & Perkins, 1989). In contrast, word-problem solving represents high-road transfer, which requires individuals to abstract connections (i.e., word-problem solving schemas) between familiar and novel tasks (Fuchs et al., 2003a; Salomon & Perkins, 1989). Salomon and Perkins posited that the hallmark of high-road transfer is “mindful abstraction,” or metacognition (Fuchs et al., 2003a). With metacognition, an individual withholds an initial response and intentionally examines how the novel problem at hand connects with familiar problems.

1.3 Cognitive and linguistic demands of word-problem solving

Although a variety of cognitive and academic skills have been theoretically and empirically related to word-problem solving, in this study we focus on working memory, nonverbal reasoning, and language.

The process of solving a WP—interpreting text, identifying a schema, and applying a solution strategy—not only requires metacognition, but also makes strong demands on reasoning and working memory. Here, we highlight a model of word-problem solving, which is based on the seminal work of Kintsch and colleagues (e.g., Cummins et al., 1988; Kintsch & Greeno, 1985; Nathan et al., 1992) and theories of text comprehension and discourse processing (e.g., Graesser, Millis, & Zwaan, 1997; Van Dijk & Kintsch, 1983). This model (Fuchs et al., 2015) posits that word-problem solving involves problem-solving strategies that rely on working memory, reasoning, and language and assumes that general features of text comprehension apply across WP statements.

This model assumes memory representations of word-problem solving have three components. First, when processing a problem narrative, a student must construct a coherent structure to capture the text's essential ideas (i.e., the propositional text structure). Next, the student supplements the text with inferences based on his background knowledge to develop a situation model. Then, the student coordinates this information with the third component, a problem model or schema. It is at this stage that a student formalizes conceptual relations among quantities and uses the schema to guide the application of problem solution strategies. At this stage, nonverbal reasoning is the process through which a student targets and organizes essential information, infers information not evident within the problem, and excludes irrelevant information (Tolar et al., 2012). Overall, this process of constructing a propositional text structure, inferencing, identifying a schema, and applying a solution strategy involves coordination of information from memory and the world and requires the storing of multiple steps that must be manipulated in working memory (Kintsch & Greeno, 1985; LeFevre et al., 2010).

In summary, working memory is the process through which a student translates text to a mathematical equation; as a student builds a problem model, multiple pieces of information must be stored and manipulated in memory. Nonverbal reasoning is not only the process through which students organize information, but also the process through which students identify and exclude irrelevant information. Thus, word-problem solving places strong demands on working memory and reasoning.

1.3.1 Working memory Working memory, the ability to hold a mental representation of information in mind while simultaneously engaged with other mental processes, consists of a central executive, which coordinates and controls the three subsystems of working memory (i.e., visuo-spatial sketchpad, phonological loop, episodic buffer) (Baddeley & Hitch, 1974; Baddeley, 2000) and is often considered the most important component of working memory. The central executive controls which information is attended to; its role is in attentional processes, such as the inhibition of information. Therefore, in the presence of irrelevant information within WPs, it is expected that working memory would significantly contribute to WP performance.

Working memory features prominently in theories of mathematical word-problem solving. According to Kintsch and Greeno (1985), as a student solves a WP, new sets are formed on-line as the text is processed. As a student processes text, a proposition activates a set-building strategy. When a proposition is completed, an appropriate set is formed and the proposition is assigned a place in the schema. As new sets are formed, previous sets once active in the memory buffer are displaced. Thus, working memory represents the representational and attentional systems needed for effective execution of procedures (Ackerman, 1988) to reach a correct solution.

Previous studies on individual differences have demonstrated the critical role of working memory in integrating information during problem solving (e.g., LeBlanc & Weber-Russell, 1996; Swanson & Beebe-Frankenberger, 2004; Swanson & Sachse-Lee, 2001). For example, Swanson and Beebe-Frankenberger (2004) found that working memory contributes unique variance to problem solving beyond what phonological processes (e.g., short-term memory, phonological knowledge), reading skill, calculation, inhibition, processing speed, and semantic processing contribute. Overall, results across studies indicate that working memory is an important predictor of mathematical word-problem solving. Furthermore, prior work has also demonstrated individual differences in working memory for numbers versus words.

Of the working memory tasks, counting span is relevant to understanding the underlying processes used to solve arithmetic problems (Hitch & McAuley, 1991; Siegel & Ryan, 1989). During this task, a student must maintain one or a series of numbers in working memory while performing the act of counting. Another working memory task, listening span, involves words and sentences as opposed to numbers. In a study by Fuchs et al. (2010), counting span was uniquely predictive of procedural calculations, but not for WPs. In contrast, for WPs, listening span was uniquely predictive, whereas counting span was not. These findings support earlier work (e.g., Dark & Benbow, 1981; Siegel & Ryan, 1989). Fuchs et al. suggest the possibility that some individuals' word or number representations are more highly active in working memory. They state, "Strong activation of Arabic numerals and corresponding magnitudes in working memory may facilitate execution of procedural calculations, whereas strong activation of verbal information may aid in one or several component processes (e.g., building problem models) involved in solving word problems" (p. 1744).

1.3.2 Reasoning Another potentially important factor to consider is nonverbal reasoning, which refers to the ability to infer and implement rules, as well as to identify patterns and relations (Nutley et al., 2011). Previous research has identified nonverbal reasoning as a significant predictor of WP performance (e.g., Fuchs et al., 2006; Fuchs et al., 2015). When solving WPs with irrelevant information, nonverbal reasoning is likely an important factor for several reasons. First, as conceptualized by Cooper and Sweller (1987), students must (a) master problem-solution strategies, (b) categorize problems into problem-types or schemas, and (c) recognize how novel problems relate to taught problems. Students learn to categorize a WP as a specific problem type, or schema, once they master the problem solution rules. Overall, the recognition of a schema guides the solution-strategy used. This process of schema identification and application of a viable solution strategy makes strong demands on reasoning ability.

1.3.3 Language The role of language comprehension is also important to consider, given the obvious need to process linguistic information when building a problem model of a WP. In Fuchs et al. (2015), second-grade students were assessed on general and WP-specific language comprehension. Path analytic mediation results showed that the effects of general language comprehension on informational text comprehension were entirely direct. Effects of general language comprehension on WPs, however, were partially mediated by WP-specific language. Results suggest that WPs differ from other forms of text comprehension by requiring WP-specific language comprehension in addition to general language comprehension.

As described above, language, working memory, and nonverbal reasoning have been demonstrated to underlie word-problem solving, but while each of the three cognitive resources are well studied for WPs generally, it remains unknown whether the cognitive and linguistic predictors of complex problems (i.e., with irrelevant information) differ from those associated with simple problems (i.e., without irrelevant information). Understanding the cognitive resources that support complex WP development can lead to theoretically-driven intervention procedures to improve the timing and efficacy of word-problem solving intervention.

1.4 Purpose of present study

In the present study, we targeted irrelevant information as a source of WP complexity and considered the effects of cognitive and linguistic abilities, as hypothesized by Kintsch et al. (1985) and for which the literature indicates a role in word-problem solving: language comprehension (i.e., a composite of listening comprehension and vocabulary), reasoning (i.e., nonverbal concept formation), and working memory (i.e., sentence and counting span tasks). We measured these abilities at the start of second grade. In our quantitative models, we controlled for start-of-the-year WP (without irrelevant information) and arithmetic skill. We also included processing speed (i.e., a speeded cross out task), which refers to the efficiency with which cognitive tasks are performed (Bull & Johnston, 1997), as a control variable because of its demonstrated role in arithmetic, which is required to solve WPs. In the spring of second grade, we measured WPs with and without irrelevant information. Across our WP measures, the focus was on combine, change, and compare problem types, which are the three WP schemas that dominate second-grade word-problem solving (Riley & Greeno, 1988; Riley, Greeno, & Heller, 1983).

The purpose of the present study was to explore the cognitive and linguistic predictors of second-grade mathematical WP performance on WPs with irrelevant information and how those are similar to and different from the predictors of WPs without irrelevant information. Although previous studies have demonstrated language comprehension, reasoning, and working memory as important predictors of word-problem solving, available research has not focused on WPs with versus without irrelevant information. First, we tested the difference between student performance on WPs with and without irrelevant information. Then, we analyzed the relation between cognitive/linguistic predictors and outcomes for WPs with and without irrelevant information within the same model, allowing for direct comparisons across the two outcomes. Simultaneously examining important cognitive and linguistic predictors offers the advantage of providing a more accurate and stringent analysis of each ability's contribution because each variable competes for variance against other constructs.

2. Method

2.1 Participants

Data in this study were collected with all cohorts in a four-cohort study (2008-2012) assessing the effects of calculations versus word-problem intervention (Fuchs et al., 2014). Participants included in this study were randomly sampled from 79 second-grade classrooms across public elementary schools in a large metropolitan school district in the United States. Classrooms were randomly assigned to one of three conditions: word-problem solving intervention, calculations intervention, and business-as-usual (i.e., control). The present analysis relied on data only from the control group (n = 303) and the non-WP intervention group (n = 398). We excluded word-problem intervention students because word-problem intervention was designed to alter the typical trajectories of development and decrease the role of cognitive and linguistic predictors in WP development. Also as shown in Fuchs et al. (2014), calculations intervention did not improve or alter the trajectory of WP development; thus, we combined the calculation intervention and control groups for analysis (N = 701).

Student demographics were as follows: 53% female; 40% African American, 26% Caucasian, 25% Hispanic, < 3% Asian, and 6% other; < 3% identified with a speech and language impairment, < 2% identified with a learning disability, and < 2% identified with a comorbid speech and learning disability; and 84% free/reduced lunch. On the Wide Range Achievement Test (WRAT)-Arithmetic (Wilkinson & Robertson, 2006), mean performance was 94.10 (*SD* = 12.73); on WRAT-Reading, 100.08 (*SD* = 15.88); and on Wechsler Abbreviated Scale of Intelligence (*WASI*; Wechsler, 1999), 92.78 (*SD* = 12.91).

2.2 Cognitive and linguistic predictor measures

2.2.1 Language comprehension We used two tests of language ($r = 0.61$, $p < 0.001$), from which we created a unit-weighted composite variable using a principal components factor analysis. Because the principal components factor analysis yielded only one factor, no rotation was necessary. The *Woodcock Diagnostic Reading Battery* (*WDRB)—Listening Comprehension* (Woodcock, 1997), which consists of 38 items, measures the ability to understand sentences or passages. Students supply the word missing at the end of sentences or passages that progress from simple verbal analogies and associations to discerning implications. Reliability is 0.80. *WASI Vocabulary* (Wechsler, 1999) measures expressive vocabulary knowledge with 42 items. Students name pictures and define words. Responses are awarded scores of 0, 1, or 2 based on quality. Testing discontinues after five consecutives scores of 0. According to the publishers, average reliability is 0.89.

2.2.2 Nonverbal reasoning With *Woodcock Johnson-III Tests of Cognitive Abilities* (WJ-III; Woodcock, McGrew, & Mather, 2001)-*Concept Formation*, students identify the rules for concepts when shown illustrations of instances and non-instances of the concept. Students earn credit by correctly identifying the rule that governs each concept. Cut-off points determine the ceiling. The score is the number of correct responses. Reliability is 0.93.

2.2.3 Central executive working memory We used two subtests from the *Working Memory Test Battery for Children* (WMTB-C; Pickering & Gathercole, 2001)—*Listening Recall* and *Counting Recall*. We included both subtests rather than creating a composite variable of working memory based on prior work showing that listening recall taps into the verbal demands of word problems, whereas counting recall taps into the ability to handle numbers within working memory when calculating numbers (Fuchs et al., 2010). Each subtest includes six dual-task items at span levels from 1-6 to 1-9. At each span level, the number of items to be recalled increases by one. Passing four items within a span moves the student to the next level. Failing three items terminates the subtest. We used the trials correct score. Test-retest reliability ranges from 0.84-0.93. For *Listening Recall*, the student determines if each sentence in a series is true and then recalls the last word in each sentence in the correct order. For *Counting Recall*, the student counts a set of 4, 5, 6, or 7 dots, each on a separate card. After the last card within an item, the student recalls the number of dots on each of the cards in the correct order.

2.2.4 Processing speed With the *WJ-III* (Woodcock et al., 2001) *Cross Out*, students locate and cross out five identical pictures matching a stimulus picture at the beginning of each row. Students have 3 min to complete 30 rows and earn credit by correctly crossing out matching items in each row. Reliability is 0.91.

2.3 Academic Control Variables

2.3.1 Simple WPs To control for initial word-problem solving skill, we used a measure of simple WPs (Jordan & Hanich, 2000; adapted from Carpenter & Moser, 1984; Riley et al., 1983), with 14 WPs involving sums or minuends of nine or less and no irrelevant information.

Each problem reflects a combine, compare, or change relationship. The tester reads each item aloud; students have 30 s to respond and can ask for re-reading(s) as needed. The score is the number of correct answers. Coefficient alpha on this sample was 0.83.

2.3.2 Arithmetic To control for initial arithmetic skill, we used *Math Fact Fluency* (Fuchs, Hamlett, & Powell, 2003b), with four subtests: 25 single-digit addition problems with sums from 6 to 12; 25 single-digit subtraction problems with minuends from 6 to 12; 25 single-digit addition problems with sums from 5 to 18; 25 single-digit subtraction problems with minuends from 5 to 18. Students have 1 min to write answers for each subtest. The score is the number of correct answers across subtests. Alpha on this sample was 0.93.

2.4 Outcomes

2.4.1 WPs To assess WP performance, with and without irrelevant information, we used Second-Grade Vanderbilt Story Problems (Fuchs & Seethaler, 2008). This measure comprises 18 word problems representing combine, compare, or change problem types. Credit is earned for correct math and labels in answers. For the purposes of our analyses, we split Story Problems into two subtests: (a) VSP—No Irrelevant Information (VSP) and (b) VSP—Irrelevant Information (VSP-I). Irrelevant information was embedded in the problem statement or in pictographs. We removed all two-step WPs (which required combinations across problem types). VSP and VSP-I each included seven problems. Alpha on this sample was 0.74 for VSP and 0.68 for VSP-I.

2.5 Procedure

Tests were administered by trained examiners, each of whom had reached criterion during mock administrations. Students were pretested in September-October on simple WPs, arithmetic in large groups and on the cognitive and linguistic predictor measures individually.

They were posttested in April on VSP and VSP-I. Participants did not receive WP intervention. All individual sessions were audiotaped. From the larger study (Fuchs et al., 2014), 20% of tapes were selected randomly, stratifying by tester, for accuracy checks by an independent scorer and then re-scored by a second scorer. Agreement was 98%. All data were double entered/verified.

3. Data Analysis and Results

See Table 1 for means and standard deviations (raw scores and standard scores for nationally normed tests) and correlations (all $p < 0.01$). Preliminary analyses of univariate plots indicated normal distributions of variables and plots of residuals suggest multivariate normality. We conducted a dependent samples *t* test to compare performance on WPs with and without irrelevant information. There was a significant difference in scores for WPs without irrelevant information ($M = 5.58$, $SD = 2.47$) and WPs with irrelevant information ($M = 4.03$, $SD = 2.58$); $t(700)=19.41$, $p < 0.001$), with an effect size of 0.73. This suggests that when WPs contain irrelevant information, students have more difficulty solving them correctly.

Next, we conducted multivariate multiple regression to determine which predictor variables significantly predicted WPs with and without irrelevant information. For analyses, raw scores were transformed to sample-based *z*-scores. We used multivariate multiple regression because it allows for the joint analysis of our two outcome measures with a single set of predictor variables and accounts for the correlation between our outcomes. See Table 2 for the summary of the results.

The total variance explained for WPs without irrelevant information was $R^2 = .28$, $F(7, 693) = 37.69$, $p < 0.001$. Significant predictors were initial WP skill ($p < 0.001$), arithmetic ($p < 0.001$), listening recall ($p < 0.001$), and language ($p < 0.01$). For WPs with irrelevant information, the total variance explained was $R^2 = .37$, $F(7, 693) = 56.92$, $p < 0.001$. The significant predictors were initial WP skill ($p < 0.001$), arithmetic ($p < 0.001$), listening recall ($p < 0.01$), language ($p < 0.001$), and nonverbal reasoning ($p < 0.05$). Neither processing speed nor counting recall was significant in either analysis. To reiterate, language was a significant predictor of both outcomes, whereas nonverbal reasoning only predicted WPs with irrelevant information (refer to Table 2)

To extend our analysis, we tested for significant differences in standardized coefficients between our outcome measures. Using Stata, we tested the null hypothesis that the effect of nonverbal reasoning on WPs with irrelevant information is equal to effect of nonverbal reasoning on WPs without irrelevant information. Results indicated the coefficients for nonverbal reasoning on the outcomes were significantly different at $\alpha = 0.05$, $F(1, 693) = 3.93$, $p = 0.048$. Next, we tested the null hypothesis that the effect of language on WPs with irrelevant information is equal to the effect of language on WPs without irrelevant information. Results indicated that the coefficients for language on WPs with versus WPs without irrelevant information were not significantly different, $F(1, 693) = 0.71$, $p = 0.398$. Remaining analyses indicated that the coefficients for initial WP skill ($F(1, 693) = 0.47$, $p = 0.49$), arithmetic ($F(1, 693) = 0.07$, $p = 0.79$), listening recall ($F(1, 693) = 0.55$, $p = 0.46$), counting recall ($F(1, 693) = 0.14$, $p = 0.71$), and processing speed ($F(1, 693) = 0.63$, $p = 0.43$) were not significantly different between outcomes.

4. Discussion

Prior research has examined the cognitive and linguistic predictors of word-problem solving versus arithmetic skills but has not focused on distinctions between simple versus complex WPs by isolating features of complexity. We extended this line of research by examining the cognitive and linguistic predictors of word-problem solving with and without an important source of complexity: irrelevant information. Our goal was to deepen understanding of complex word-problem solving to gain insight for developing efficient and effective intervention procedures targeting the needs of students with or at risk for developing word-problem solving difficulty.

Irrelevant information appears to increase the complexity of a WP. A WP statement without irrelevant information requires students to decipher the narrative to build a problem model, identify the missing information, construct a number sentence to find the missing information, and then perform calculations to find the missing number. As Kinstch et al. (1985) hypothesized, this appears to require problem-solving skills that tax working memory and reasoning ability, as well as language comprehension. But beyond this, a WP statement that also includes irrelevant information increases the challenge of recognizing the WP as belonging to a familiar problem type, as it further presses working memory, reasoning, and language comprehension resources. In line with expectations, results indicated that students experienced greater difficulty when solving WPs with irrelevant information, and the effect size was 0.73 with students performing better on WPs without irrelevant information than on those with irrelevant information.

At the same time, however, findings indicated many similarities in the cognitive predictors of WPs with and without irrelevant information with respect to academic and cognitive factors that support performance. We found that pretest simple WP skill, arithmetic, working memory for words and sentences, and language were engaged to a comparable extent for WPs with and without irrelevant information. For each one standard deviation increase in initial simple WP skill, word-problem solving accuracy increased by 0.30 and 0.27 for WPs with and without irrelevant information, respectively. For initial arithmetic, accuracy increased by

0.17 for WPs with irrelevant information and 0.16 for WPs without irrelevant information for each one standard deviation increase. For each one standard deviation increase in initial working memory for words and sentences, accuracy increased by 0.11 and 0.14 for WPs with and without irrelevant information, respectively; for initial language, accuracy increased by 0.14 and 0.11.

It is not surprising that beginning word-problem solving and arithmetic supported both forms of WPs. Foundational mathematics skill, in the form of arithmetic, is an established pathway to word-problem solving competence (e.g., Fuchs et al., 2006, 2012) and though insufficient, is a necessary foundation for WP performance (Fuchs et al., 2015). Our WP performance measures were specifically designed to represent combine, compare, and change problem types. Fluency with addition and subtraction supports these types of WPs, particularly at the last stage of word-problem solving when a student applies a solution strategy to obtain an answer. At this stage, arithmetic is the medium through which numerical information is manipulated to generate a solution. It is important to note, however, that the relations between numbers in WPs are conveyed via language. Thus, increasing arithmetic skill alone is insufficient for improving WP performance, as demonstrated in Fuchs et al.'s randomized control trial (2015).

Working memory for words and sentences (i.e., *Listening Recall* task) also predicted both forms of WPs with statistically comparable coefficients. While counting recall working memory failed to achieve significance for both forms of WPs, working memory for words and sentences did achieve significance, with standardized coefficients of 0.14 (*SE* = 0.04) for WPs without irrelevant information and 0.12 (*SE* = 0.04) for WPs with irrelevant information (throughout discussion, we report standardized coefficients). These findings support previous studies on the role of working memory in WPs. Good versus poor WP solvers differ on working memory (e.g., LeBlanc & Weber-Russell, 1996; Passolunghi & Siegel, 2001, 2004). When controlling for other cognitive factors, individual differences in working memory account for variance in WPs (e.g., LeBlanc & Weber-Russell, 1996; Swanson & Beebe-Frankenberger, 2004). In a study by Fuchs et al. (2010), listening recall predicted WPs, while counting recall predicted procedural calculations and not WPs, thereby suggesting individual differences in working memory in words versus numbers. In theories of word-problem solving, working memory features prominently. According to Kintsch and Greeno (1985), as a student solves a WP, new sets are formed on-line as the text is processed. As a student processes text, a proposition activates a set-building strategy. When a proposition is completed, an appropriate set is formed and the proposition is assigned a place in the schema. As new sets are formed, previous sets once active in the memory buffer are displaced.

For word-problem solving, we also expected language (i.e., vocabulary and listening comprehension) to play a key role. We found that language was a significant predictor of WPs with irrelevant information (0.11) and without irrelevant information (0.14). It is not surprising that language supports WP learning for both types of WPs, given the need to process linguistic information when building WP models. Our findings support previous work demonstrating the importance of a language in word-problem solving (e.g., Fuchs et al., 2006; Fuchs et al., 2008).

At the same time, it is interesting that language did not discriminate between WPs with and without irrelevant information. Yet, our findings support prior work. In a study by Tolar et al. (2012), language predicted performance on both WPs with low- and high-complexity. In the present study, we had expected a difference because irrelevant information adds linguistic information and linguistic challenge to a WP.

The lack of distinction for the role of language in problems with and without irrelevant information may have occurred for two reasons. First, the language challenge in our WPs may have been sufficiently demanding that the addition of irrelevant information did not further press demands. For example, consider the following compare WP without irrelevant information: *Charles is 5 years older than his sister Jill. Jill is 2 years old. How old is Charles?* Next, consider another compare WP, this time with irrelevant information (refer to Figure 1): *The picture shows how much money Ms. Taylor spent. She spent $3 less on bread than on milk. She also bought 2 bags of apples. How much did Ms. Taylor spend on milk?* This WP includes irrelevant information contained within a picture and text. Focusing on text, the above WPs place similar language demands. Both are compare problems with the missing number at the first position in the overarching equation (i.e., bigger quantity minus smaller quantity equals difference) and each include complicated language constructions in sets (i.e., *older than, less on bread than on milk*) that are WP-specific. In the second WP presented above, textual irrelevant information is presented in the third sentence (i.e., *She also bought 2 bags of apples*). Sentence 3, however, does not contain WP-specific language.

Thus, the addition of irrelevant information may not have further taxed language. The second reason why language failed to discriminate between the two types of WPs may be due that our more complex problems often incorporated irrelevant information within graphs, pictographs, or pictures. Irrelevant information contained in a graph, picture, or pictograph softens the language demands created by the irrelevant information. This is because linguistic information contained in graphs, pictographs, or pictures generally consist of simple words or sentences and do not add WP-specific language or complicated constructions involving sets.

It is possible our WP measures failed to capture a broad range of language demands across problems with and without irrelevant information. Irrelevant information generally increases the complexity of WPs by increasing the length of text students must navigate to identify key information. Yet, our WP measure with irrelevant information contained irrelevant information within graphs, pictographs, pictures, and text. While the format of these WPs paralleled those found in some standardized mathematics tests, our WP measure with irrelevant information did not allow for a perfect isolation of only one format presentation of irrelevant information. Thus, the manner in which irrelevant information was presented in each WP may not have challenged language as much as the WP components that were shared across the problems with and without irrelevant information. Irrelevant information contained within graphs, pictures, or pictographs may place different demands than irrelevant information contained in text. In addition, our WP measures contained three types of problems (i.e., combine, compare, change). It is worth considering whether language demands differ among these problem types and in future work, discriminate which problem types for which irrelevant information is not important.

Only one measure emerged as a predictor of word-problem solving with irrelevant information but not word-problem solving without irrelevant information: nonverbal reasoning. For each one standard deviation increase in initial nonverbal reasoning, accuracy increased by 0.08 and 0.01 for WPs with and without irrelevant information, respectively. Previous research has identified nonverbal reasoning as a significant predictor of WP performance (e.g., Fuchs et al, 2006; Fuchs et al., 2015) and growth for high-complexity WPs (e.g., Tolar et al., 2012), but prior work has not specifically examined differences in predictors of WPs with versus without irrelevant information.

In the present study, we operationalized nonverbal reasoning with the *WJ-III: Concept Formation*, a task that requires students to identify the rules for concepts when shown illustrations of instances and non-instances of the concept. To formulate a rule, the student must distinguish relevant from irrelevant features of that class. Therefore, this type of reasoning reflects an individual's categorical reasoning ability. It is not surprising then that individual differences in nonverbal reasoning helped explain the development of WPs with irrelevant information but not on WPs without irrelevant information. This suggests that the ability to reason analytically and make categorical judgments in distinguishing relevant from irrelevant features of classes of objects is an important foundation for success with complex WPs.

When solving a WP, a student maps components of the WP onto a problem model that represents quantities and their relations. The resulting problem model is strictly a mathematical representation of a WP's text. While this process requires some degree of reasoning and is an important component of word-problem solving, some patterns of WP performance cannot be fully explained by a mathematical representation of a WP (Staub & Reusser, 1995). When solving WPs, students often have difficulties with problems that differ from taught problems. They must learn to connect a novel problem with previously taught WPs and recognize that novel problems differ only in terms of superficial features (e.g., irrelevant information, new cover story, vocabulary). While superficial features make a problem novel, they do not alter the underlying mathematical structure or the problem-solution method. The addition of features, however, increases WP complexity and thereby makes greater demands on reasoning ability. For example, the ability to reason analytically and make categorical judgments in distinguishing relevant from irrelevant features of classes of object, as measured by our nonverbal reasoning measure, applies to complex WPs with and without irrelevant information.

Furthermore, as a WP becomes increasingly complex, a student may rely less on a WP's problem model and more on the *situation model* (i.e., the mental simulation, or qualitative representation, of a WP's text). This may be especially relevant for those individuals who are less experienced with solving WPs and for whom the connection between a WP's text and problem model is not salient (Tolar et al., 2012). Because a situation model is a function of the wording of a WP and includes inferences based on real-world learning and experiences, situation models may be advantageous for less experienced problem solvers because they may elicit informal, albeit effective, solution strategies that are more accessible than computational models or methods. As a result, less experienced problem solvers who rely on situation models based on real-world learning are more likely to need stronger general reasoning ability to solve increasingly complex WPs.

This was suggested by Tolar et al. (2012), who assessed predictors of the development of word-problem solving from the beginning of third grade to the end of fifth grade. Nonverbal reasoning predicted initial WP performance and growth for low-complexity WPs (i.e., problems conforming to one problem type and requiring one to four steps to reach solution), but only growth for high-complexity problems (i.e., problems that simultaneously assess four problem types within a single narrative). Moreover, nonverbal reasoning was the only predictor of growth for high-complexity WPs. Working memory, however, was not included as predictor of initial WP performance or growth. Because nonverbal reasoning relies on working memory, it is important to control for working memory; the present study does this.

Tolar et al. (2012) would have deemed our WPs with and without irrelevant information as low-complexity. It is important, however, to consider that students in the present study were in the second grade and thus have had less experience with solving WPs than students in the Tolar et al. study. Thus, students in the present study needed stronger reasoning ability to solve WPs with irrelevant information, even when controlling for working memory. Further, Tolar et al. did not isolate the effect of irrelevant information within WPs, whereas the present study does. Therefore, nonverbal reasoning ability is likely a critical factor, over and beyond language and working memory, for solving complex WPs, particularly those with irrelevant information. Our present findings support this.

The present study’s findings have several implications for instruction. First, results support current word-problem solving interventions designed to compensate for students’ weaknesses in reasoning, as well as the need for explicit transfer instruction designed to promote students’ awareness of the connections between familiar and novel WPs. For example, in schema-based instruction with explicit transfer instruction, students learn efficient reasoning strategies for connecting longer narratives, which may contain irrelevant information, to familiar WP types. Next, results suggest that a focus on nonverbal reasoning may represent a productive strategy for screening students for early word-problem solving intervention. Furthermore, it seems potentially instructive to examine nonverbal reasoning, and other underlying cognitive features supporting complex word-problem solving, in the context of word-problem solving instruction. Such research allows for the examination of the cognitive factors associated with poor response to otherwise effective word-problem solving instruction.

At the same time, it is important to consider our findings with study limitations in mind. Our WP measure included irrelevant information found within text or pictographs, graphs, and pictures. Because irrelevant information found within text versus irrelevant information found only in graphs or pictures may operate differentially, mixing the format presentation of irrelevant information may have masked the importance of some predictors. Also, we operationalized each domain-general cognitive construct with a particular measure. Changes in measures can alter patterns of performance and study findings. Thus, replication with other measures for each predictor is warranted. Moreover, our method are correlational and only useful for formulating hypothesis about causality. Experimental research is needed to test our implications for instructional design and to examine the predictive utility of a screening battery that includes measures of WPs with and without irrelevant information. Another limitation is that other cognitive abilities related to word-problem solving were not examined in this study. For example, attentive behavior has been theoretically and empirically related to word-problem solving and should be investigated in future research, as attentive behavior is strongly linked to working memory (Kofler, Rapport, Bolden, Sarver, & Raiker, 2010). Limitations aside, the present study suggests the need to consider nonverbal reasoning ability in the development of word-problem solving interventions targeting complex WPs. Future research should continue to examine the differential predictors of WP-types, including WPs with multiple steps and/or other forms of superficial features.

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Table 1

Means and Standard Deviations (SDs) for Raw Scores and Nationally Norm-Referenced Standard Scores and Correlations (N = 701)

	Raw Scores		Standard Scores		Correlations								
Variables	Mean	(*SD*)	Mean	(*SD*)	VSP	VSP-I	A	P	L	CF	PS	LR	CR
Story Problems-*No Irrelevant Information* (VSP)	5.58	*(2.47)*	-	-	1								
Story Problems-*Irrelevant Information* (VSP-I)	4.03	*(2.59)*	-	-	0.65	1							
Arithmetic (A)	21.92	*(11.34)*	-	-	0.36	0.40	1						
Single-digit Story Problems (P)	6.79	*(3.62)*	-	-	0.47	0.55	0.50	1					
Language Composite (L)	-	-	-		0.36	0.43	0.19	0.50	1				
Concept Formation (CF)	11.77	*(5.81)*	92.13	*(12.14)*	0.30	0.40	0.32	0.52	0.48	1			
Processing Speed (PS)	11.49	*(2.75)*	95.30	*(14.57)*	0.23	0.23	0.35	0.32	0.20	0.27	1		
Listening Recall (LR)	7.02	*(3.56)*	83.82	*(17.33)*	0.35	0.38	0.24	0.46	0.45	0.38	0.30	1	
Counting Recall (CR)	14.42	*(4.49)*	84.31	*(14.89)*	0.18	0.22	0.28	0.32	0.22	0.27	0.23	0.36	1

Notes. All correlations are significant at $p < 0.01$. VSP and VSP-I are from Fuchs and Seethaler (2008). Arithmetic is from *Math Fact Fluency* (Fuchs et al., 2003b). Single-Digit Story Problems is from Jordan and Hanich (2000); adapted from Carpenter and Moser (1984), Riley et al. (1983). Language is a composite of *Listening Comprehension* (Woodcock, 1997) and *WASI Vocabulary* (Wechsler, 1999). Concept Formation is *WJ-III Concept Formation* (Woodcock, McGrew, & Mather, 2001). Processing Speed is *WJ-III Cross Out* (Woodcock et al., 2001). LR is *Listening Recall* from WMTB-C (Pickering & Gathercole, 2001). CR is *Counting Recall* from WMTB-C.

Table 2

Multivariate Multiple Regression Results for Cognitive and Linguistic Predictors of WPs with and without Irrelevant Information

	B	*SE*	*t*	95% CI
VSP				
(Constant)	(0.01)	0.03	0.28	-0.01-0.07
Arithmetic	0.16	0.04	4.09***	0.08-0.24
Single-digit Story Problems	0.27	0.05	6.02***	0.18-0.36
Language Composite	0.11	0.04	2.77**	0.03-0.19
Concept Formation	0.01	0.04	0.15	-0.07-0.08
Processing Speed	0.02	0.04	0.68	-0.05-0.10
Listening Recall	0.14	0.04	3.61***	0.07-0.22
Counting Recall	-0.04	0.04	-0.97	-0.11-0.04
VSP-I				
(Constant)	(0.01)	0.03	0.19	-0.05-0.07
Arithmetic	0.17	0.04	4.64***	0.10-0.24
Single-digit Story Problems	0.30	0.04	7.14***	0.22-0.38
Language Composite	0.14	0.04	3.83***	0.00-0.22
Concept Formation	0.08	0.04	2.21*	0.01-0.16
Processing Speed	-0.00	0.03	-0.10	-0.07-0.06
Listening Recall	0.12	0.04	3.08**	0.04-0.19
Counting Recall	-0.02	0.03	-0.65	-0.08-0.04

Notes. *$p < 0.05$, ** $p < 0.01$, ***$p < 0.001$.

Figure 1

Ms. Taylor

Bread: $1
Milk: ?
Crackers: $3
Apples: $6