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The relationship between linguistic skills and arithmetic knowledge

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ABSTRACT

Although language is implicated in children's mathematical development, few studies have focused specifically on how different linguistic skills relate to children's mathematical performance. Building on the model proposed by LeFevre et al. (2010), this study examined how general verbal ability and phonological skills were differentially related to children's arithmetic knowledge. Third grade children ($N=287$) were assessed on verbal analogies, phonological decoding, symbolic number skill, procedural arithmetic, and arithmetic word problems. Using mediation analyses, the results indicated that verbal analogies were indirectly related to arithmetic knowledge through symbolic number skill, whereas phonological decoding had a direct relationship with arithmetic performance. These results suggest that general verbal ability influences how children understand and reason with numbers, whereas phonological skills are involved in executing conventional arithmetic problems.

1. Introduction

Much like reading, learning and doing mathematics are steeped in oral and written language (Adams, 2003; Adams & Lowery, 2007; Schleppegrell, 2007). For instance, mathematics instruction in classrooms depends primarily on oral explanations and interactions, and the delivery of mathematics curriculum often occurs via written text (Bielenberg & Wong Fillmore, 2004/2005; Schleppegrell, 2007). Furthermore, mathematics consists of a specialized vocabulary: words such as volume, ruler, plot, and product, have different meanings in mathematics than when used in everyday language (Adams, 2003). In turn, to be mathematically proficient, children must develop a language that allows them to participate not only during mathematics instruction, but also to engage quantitatively with the world outside the classroom.

Other than the obvious example of word problems, however, the significant language demands of mathematics have until recently been overlooked by researchers and practitioners. A growing body of studies indicate that the same underlying processes that are important for reading, particularly phonological processing, are important for mathematics (e.g., Hecht, Torgesen, Wagner, & Rashotte, 2001; Jordan, Kaplan, & Hanich, 2002; Simmons & Singleton, 2008). Indeed, it has even been suggested that children's mathematical difficulties might actually reflect deficient linguistic processes as opposed to deficits in quantitative processes (LeFevre et al., 2010; Vukovic, 2012). This supposition is in part supported by neuropsychological evidence showing that in addition to a specialized quantitative circuit in the parietal lobe, a linguistic circuit in the left angular gyrus supports the manipulation of numbers in verbal form (Dehaene, Piazza, Pinel, & Cohen, 2003), suggesting that there is a linguistic basis for some aspects of mathematics. Furthermore, children tend to have more difficulty with language-based mathematical tasks (e.g., number facts, word problems) than with tasks that have fewer language demands (e.g., nonverbal calculation, number sense) (Jordan & Levine, 2009; Jordan, Mulhern, & Wylie, 2009; Locuniak & Jordan, 2008). Taken together, these findings suggest an inextricable link between linguistic skills and mathematical performance.

The nature of this relationship, however, remains underspecified. More specifically, although linguistic skills are implicated in mathematical cognition, few studies have systematically examined how different linguistic skills are related to children's mathematical performance. A deeper understanding of the relationship between linguistic skills and children's mathematical performance is necessary to provide theoretical insight and practical guidance into how to best support children's mathematical development. To begin to increase the specificity of our understanding of the role of linguistic skills in mathematical cognition, this study examined how general verbal ability and phonological skills were differentially related to children's arithmetic knowledge. We focused specifically on arithmetic because of its foundational role for the more complex mathematics children encounter in middle and high school.

1.1. Linguistic skills and arithmetic knowledge

The bulk of studies investigating the relationship between linguistic skills and children's arithmetic knowledge have focused on phonological processes, because completing simple arithmetic problems requires the retrieval of phonological codes, as well as encoding and

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maintaining phonological representations in immediate awareness (Geary, 1993; Simmons & Singleton, 2008). Weaknesses in phonological processing are therefore thought to hinder the development of tasks that rely on the manipulation and storage of verbal codes, such as counting and solving simple arithmetic problems. Studies show that phonological processes are indeed important for children's arithmetic development (e.g., Fuchs et al., 2005; Hecht et al., 2001; Simmons & Singleton, 2008). This *phonological representation* hypothesis also helps explain the finding that many children with reading difficulties also have difficulty with arithmetic (e.g., Dirks, Spyer, van Lieshout, & de Sonneville, 2008; Rubinsten, 2009; Simmons & Singleton, 2008).

Although an important starting point, the phonological representation hypothesis does not fully account for the link between linguistic skills and arithmetic performance. For instance, there exist children with arithmetic difficulties who are nonetheless good word readers (and therefore tend to have age-appropriate phonological skills) and vice versa (e.g., Fuchs, Fuchs, & Prentice, 2004; Landerl, Fussenegger, Moll, & Willburger, 2009), suggesting that phonological skills are not the sole influential factor. Moreover, Jordan and colleagues have found that good readers with arithmetic difficulties use their strengths in verbal reasoning to complete arithmetic problems, suggesting that linguistic skills beyond phonological processing are involved in arithmetic performance (e.g., Jordan & Hanich, 2003). Indeed, there is evidence that more than just an issue of vocabulary, the language used in arithmetic word problems influences how children represent and solve these problems (e.g., Abedi & Lord, 2001; Brissiaud & Sander, 2010). Together, these findings suggest that general verbal ability plays a different role in children's arithmetic performance than phonological skills.

Few studies, however, have specifically contrasted the unique effects of general verbal ability and phonological skills on children's arithmetic performance. In a relevant study, LeFevre et al. (2010) proposed a theoretical model whereby linguistic skills influence mathematical cognition indirectly through symbolic number skill—the number and quantitative skills that depend on the formal number system but do not require knowledge of formal mathematics (see also Jordan, Glutting, & Ramineni, 2010). Examples of symbolic number skill include number identification and numerical reasoning. In their analyses, LeFevre et al. (2010) examined how a linguistic composite that tapped vocabulary, phonological skills, and symbolic number skill (i.e., number identification) directly predicted mathematical outcomes. The authors found that the linguistic composite measured in children at 4.5-years old explained unique variance in procedural arithmetic, numeration, geometry, and measurement at 7.5-years old. That the linguistic composite included general verbal ability, phonological skills, and symbolic number skills, however, makes it difficult to disentangle how different linguistic skills relate to symbolic number skill, as well as the direct and indirect effects of general verbal ability and phonological skills on mathematical cognition. As such, the model proposed by LeFevre et al. provides the basis for investigating the unique role of general verbal ability and phonological skills in children's arithmetic knowledge.

1.2. Present study

Building on previous research, we tested the mediation model proposed by LeFevre et al. (2010; see Fig. 1), which makes three predictions. First, children's linguistic skills should be related to children's symbolic number skill (path *a*). Second, symbolic number skill should be related to arithmetic knowledge (path *b*). Finally, linguistic skills should have an indirect effect on arithmetic knowledge through symbolic number skill (path *ab*). We expected this model to hold for general verbal ability, consistent with the predictions of LeFevre et al. By contrast, we hypothesized that phonological skills would maintain a direct effect on arithmetic knowledge (path c^1), given that phonological processes are involved in the storage and retrieval of numbers from long-term memory (e.g., Geary, 1993; Simmons & Singleton, 2008).

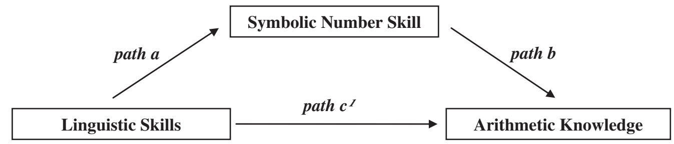

Fig. 1. Predicted relationships among linguistic skills, symbolic number skill, and arithmetic knowledge.

2. Method

2.1. Participants

The participants were 287 (134 girls) third graders (mean age = 8.60 years, *SD* = 4 months). The children attended five elementary schools located primarily in working class neighborhoods in an urban Canadian city. The mathematics curriculum was the same across the five schools and emphasized a balanced approach between conceptual understanding and procedural skills. The children were 53.0% majority culture (n = 152), 14.3% Canadian indigenous persons (n = 41), 13.9% Middle Eastern (n = 40), 7.7% Asian (n = 22), and 11.1% other (n = 32). There were no differences by demographic group on the study measures. These participants have been reported on previously (Author).

2.2. Materials

2.2.1. Control variables

In each set of analyses, we included control variables to provide for a more stringent test of our models. LeFevre et al. (2010) hypothesized visual–spatial working memory as a distinct pathway to mathematics separate from a linguistic pathway. Although we did not have a measure of visual–spatial working memory, we controlled for working memory using backwards digit span (Wechsler, 1991) and we controlled for visual–spatial thinking with the Block Rotation test of the *Woodcock–Johnson Third Edition* (*WJ-III*; Woodcock, McGrew, & Mather, 2001).

2.2.2. Linguistic skill

LeFevre et al. (2010) hypothesized that the linguistic basis of mathematics stems from a general language system as opposed to a mathematics-specific language system. As such, we also used domain-general linguistic measures.

2.2.2.1. General verbal ability. Consistent with LeFevre et al. (2010), we hypothesized that general verbal ability also reflects children's ability to acquire language-based number skills. Verbal analogies reflect acquired knowledge and skill associated with language and its everyday use and is thus considered a good proxy for overall verbal ability (e.g., Flanagan, Ortiz, Alfonso, & Mascolo, 2002; Primrose, Fuller, & Littledyke, 2001). We used the Analogy subtest of the *WJ-III* Reading Vocabulary test (Woodcock et al., 2001) as a measure of general verbal ability. With this task, children solve an analogy read aloud by an examiner (e.g., *pencil* is to *lead* as *pen* is to …). The publisher reports reliability between .88 and .90.

2.2.2.2. Phonological skills. Consistent with others (Geary, 1993; LeFevre et al., 2010; Simmons & Singleton, 2008), we also hypothesized that encoding and manipulating numerical symbols are similar to the processes used when encoding and manipulating lexical symbols. We used the Word Attack test of the *WJ-III* (Woodcock et al., 2001) to assess phonological processing—phonological decoding specifically.