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Digging deeper: Shared deep structures of early literacy and mathematics involve symbolic mapping and relational reasoning☆

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ABSTRACT

This study was based on the hypothesis that symbolic mapping and relational reasoning are part of the deep structure of both early literacy and mathematics. Eighty-six preschool children completed a range of symbolic, relational, literacy, and mathematics measures, as well as a measure of their receptive vocabulary. Results were consistent with the study's hypothesis. Symbolic and relational scores were related to performance in both literacy and mathematics. Literacy and mathematics tasks grouped together in factor analyses according to hypothesized symbolic and relational demands. Further, the resulting cross-domain factor scores were related to symbolic and relational factor scores as predicted. Thus, symbolic mapping and relational reasoning were found to be cognitive processes related to both early literacy and mathematics, suggesting potential target areas for future intervention research. Findings are discussed in terms of their implications for better understanding the relation between literacy and mathematics and for early childhood instruction.

As early as kindergarten, children show marked individual differences in literacy and mathematics. These early individual differences predict children's later academic achievement (e.g., Duncan et al., 2007; Romano, Babchishin, Pagani, & Kohen, 2010) and employment (Geary, Hoard, Nugent, & Bailey, 2013; Ritchie & Bates, 2013). Moreover, individual children's literacy and mathematics knowledge are highly related, both concurrently and longitudinally (Claessens & Engel, 2013; La Paro & Pianta, 2000; Lerkkanen, Rasku-Puttonen, Aunola, & Nurmi, 2005; Neumann, Hood, Ford, & Neumann, 2013; Purpura, Hume, Sims, & Lonigan, 2011; Purpura & Napoli, 2015; Watts, Duncan, Siegler, & Davis-Kean, 2014). These phenomena suggest that a better understanding of the processes that contribute to early literacy and math knowledge could indicate levers for simultaneously increasing children's achievement in both domains. Thus, the goal of the present study was to investigate whether two factors – symbolic mapping and relational reasoning – may partially explain relations between early literacy and mathematics.

Current explanations for the relation between early literacy and mathematics involve factors that are broad-reaching and influence numerous aspects of development. Some focus on the role of socio-environmental features, such as socioeconomic level and home learning environment (Jordan, Kaplan, Ramineni, & Locuniak, 2009; LeFevre et al., 2009; Levine, Suriyakham, Rowe, Huttenlocher, & Gunderson, 2010; Snow, Burns, & Griffin, 1998). Other explanations focus on the role of general cognitive skills, such as intelligence and working memory (Alloway & Alloway, 2010; De Smedt, Taylor, Archibald, & Ansari, 2010; Deary, Strand, Smith, & Fernandes, 2007). For example, children's IQ in elementary school has been found to account for about half of the variance in the same children's performance on mathematics and English standardized achievement tests in high school (Deary et al., 2007). A final set of explanations focus on the role of general language ability as being vital for memory and verbal analysis in both domains (Bleses, Makransky, Dale, Hojen, & Ari, 2016; Donlan, Cowan, Newton, & Lloyd, 2007). For instance, phonological awareness, while undeniably essential to reading, also has been shown to be predictive of mathematics performance (De Smedt et al., 2010; Hecht, Torgesen, Wagner, & Rashotte, 2001).

While identifying general factors related to both literacy and mathematics achievement provides a starting point for

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understanding connections across the domains, identifying the *mechanisms* through which these broad factors influence performance requires further investigation. Consider socioeconomic level as an example. It does not directly influence literacy and mathematics, but is instead mediated through a number of processes, such as family stress and investment (Gennetian & Miller, 2002; McLoyd, 1998). With regard to intelligence, the question remains: how do particular processes within this construct enable students to more effectively or efficiently engage in early literacy and mathematics? Measures of children's intelligence comprise various constructs, such as spatial reasoning, processing speed, relational reasoning, and symbol recognition and mapping (Wechsler, 2012a). Understanding the contributions of these individual processes could provide a more nuanced understanding of how to support early literacy and mathematics, and perhaps identify more specific processes that may be more malleable or targetable than general intelligence. The present study was based on the premise that a careful analysis of the commonalities of early literacy and mathematics knowledge would suggest specific cognitive processes involved in both domains.

1.1. Surface features versus deep structures in early literacy and mathematics

Academic tasks involve both surface features and deep structures (Chi & VanLehn, 2012). Surface features relate to the literal objects or entities of a task. In literacy, surface features include letters and words, whereas in mathematics, they include numbers and operational symbols. Deep structures relate to the rules, schema, or principles involved in a task. We hypothesized that while early literacy and mathematics skills differ in surface features, they share some deep structural features, which rely on common processes that may, in part, explain the relations between the domains.

To explore this hypothesis, we conducted a rational task analysis of specific skills within each domain that are associated with literacy and mathematics during preschool. We included skills that have been either theorized or empirically shown to be related to later achievement within their respective domains. As shown in Table 1, the analysis suggested that early skills in both literacy and mathematics may share at least two deep structures – (1) *symbolic mapping*, shared by letter identification, numeral identification, letter-sound knowledge, and numeral-quantity knowledge and (2) *relational reasoning*, shared by rhyme awareness, magnitude comparison, phonological operations, and non-symbolic arithmetic.

1.2. Symbolic mapping in early literacy and mathematics

Literacy and mathematics are based on systems of symbols: letters and numerals. Children must learn several associations for each symbol, including its visual shape, its name, and its referent (i.e., sounds for letters and quantities for numerals). They must then coordinate their knowledge of individual symbols to accomplish more complex tasks in each domain (e.g., word reading, arithmetic problems). Thus, symbolic mapping, which we define as fluently accessing the name and meaning of symbols, is foundational in both domains. The present study conceptualized symbolic mapping as encompassing two main parts: mapping symbols to labels and mapping symbols to referents.

Research supports this conceptualization of symbol learning in the two domains. Symbolic knowledge in the two domains is correlated (Matthews, Ponitz, & Morrison, 2009; Neumann et al., 2013; Piasta, Purpura, & Wagner, 2010; Purpura & Napoli, 2015; Purpura et al., 2011; Scanlon & Vellutino, 1996), and the processes of acquiring this symbolic knowledge in each domain are parallel (Benoit, Lehalle, Molina, Tijus, & Jouen, 2013; Bialystok, 2000; Bialystok & Martin, 2003; Hurst, Anderson, & Cordes, 2017; McBride-Chang, 1999). Further, the facility, which children can retrieve associations between visual and verbal information from memory, predicts both their word reading and their single digit arithmetic (Koponen, Aunola, Ahonen, & Nurmi, 2007). These findings likely reflect both the general relation between processing speed and achievement (Kail & Hall, 1994), and the ability to fluently map symbols to labels and referents in each domain.

1.2.1. Mapping symbols to labels

Fluently labeling symbols with their names is a critical early skill in both literacy and mathematics. The ability to rapidly and accurately attach letter names to letter symbols (i.e., letter identification) is one of the strongest predictors of reading performance (Foulin, 2005; Hammill, 2004; Hiebert, Cioffi, & Antonak, 1984; Schatschneider, Fletcher, Francis, Carlson, & Foorman, 2004; Snow et al., 1998). One *meta*-analysis found that letter identification before formal schooling and later reading abilities was moderately to highly correlated, with the mean correlation across studies being $r = .52$ ($SD = .14$) (Snow et al., 1998). Another study found a correlation as high as $r = .83$ (Stuart, 1995). In many cases, the number of randomly presented letters a kindergartner successfully names is nearly as good of a predictor of future reading achievement as an entire standardized assessment (Snow et al., 1998).

Research on numeral identification is less prevalent but has begun to receive more attention in the past decade. Available research suggests that numeral identification is correlated with other measures of mathematical knowledge, such as numerical magnitude estimation (Berteletti, Lucangeli, Piazza, Dehaene, & Zorzi, 2010; Kolkman, Kroesbergen, & Leseman, 2013), and that the speed with which children are able to name Arabic numerals predicts math achievement (Swanson & Kim, 2007). Indeed, some have argued that children's facility with numeral identification in kindergarten and first grade can be a screening tool for future mathematics difficulties (Chard et al., 2005; Lembke & Foegen, 2009).

1.2.2. Mapping symbols to referents

Though mapping symbols with symbol names is an important first step in discerning between different symbols, symbols only become meaningful when children understand their relation to their referents. In early literacy, this skill entails knowing the sound(s) represented by each letter. Letter–sound knowledge is widely regarded as foundational to understanding the alphabetic principle (Byrne, 1998; Foulin, 2005; Stuart & Coltheart, 1988). Indeed, mastery of letter–sound knowledge is predictive of reading success (Schatschneider et al., 2004).

In early math, mapping symbols to referents entails understanding the quantity represented by the symbol. Children's ability to link symbols with quantities in early childhood predicts their future mathematics performance (Brankaer, Ghesquière, & De Smedt, 2014; Krajewski & Schneider, 2009; Krajewski, Schneider, & Niedling, 2008). The more quickly children access the magnitude of numerals and compare them, the more quickly and accurately they provide the sum for simple arithmetic problems (Holloway & Ansari, 2009). It has been argued that numerals mediate the relation between informal mathematical knowledge and formal mathematical knowledge, but only when knowledge of both numeral name and numeral quantity is present (Purpura, Baroody, & Lonigan, 2013).

1.3. Relational reasoning in early literacy and mathematics

Relational reasoning is broadly defined as "the ability to discern meaningful patterns within otherwise unconnected information" (Dumas, Alexander, & Grossnickle, 2013). It entails making comparisons and recognizing similarities and differences between sets of information to discern meaningful relationships, structures, and

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