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The roles of patterning and spatial skills in early mathematics development☆

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ABSTRACT

Because math knowledge begins to develop at a young age to varying degrees, it is important to identify foundational cognitive and academic skills that might contribute to its development. The current study focused on two important, but often overlooked skills that recent evidence suggests are important contributors to early math development: patterning and spatial skills. We assessed preschool children's repeating patterning skills, spatial skills, general cognitive skills and math knowledge at the beginning of the pre-kindergarten year. We re-assessed their math knowledge near the end of the school year, with complete data for 73 children. Children's repeating patterning and spatial skills were related and were each unique predictors of children's math knowledge at the same time point and seven months later. Further, repeating patterning skills predicted later math knowledge even after controlling for prior math knowledge. Thus, although repeating patterning and spatial skills are related, repeating patterning skills are a unique predictor of math knowledge and growth. Both theories of early math development and early math standards should be expanded to incorporate a role for repeating patterning and spatial skills.

Proficiency in mathematics is important for academic, economic, and life success. For example, greater academic achievement in math is related to college completion, higher earnings, and better health decisions (Adelman, 2006; Reyna, Nelson, Han, & Dieckmann, 2009; Ritchie & Bates, 2013). Individual differences in math knowledge emerge in preschool and are fairly stable. For example, general math knowledge in the final year of preschool (pre-kindergarten year, or prek) and kindergarten predict math achievement across primary and secondary school (Duncan et al., 2007; Jordan, Kaplan, Ramineni, & Locuniak, 2009; Nguyen et al., 2016; Watts, Duncan, Siegler, & Davis-Kean, 2014). Further, weak math knowledge at school entry among low-income children largely explains their weak math knowledge later in elementary school (Jordan et al., 2009). Such findings have led to increased attention to math instruction in preschool. For example, recent observations in U.S. preschools indicate that math accounted for 25% of instructional time (Piasta, Pelatti, & Lynnine, 2014), which is substantially more time than the 14% of instructional time spent on math in first-grade classrooms in the 1990s (NICHD Early Child Care Research Network, 2002).

Because math knowledge begins to develop at a young age to varying degrees, it is imperative that we identify foundational cognitive and academic skills that contribute to this development and explain its variation. The goal of the current study was to focus on two important, but often overlooked, skills that recent evidence suggests are important contributors to early math development: repeating patterning and spatial skills. We begin with background on current math education standards, which give minimal attention to the role of each skill in early math development. Then, we review empirical evidence for the importance of spatial and repeating patterning skills for math knowledge, considering each in turn. Finally, we explore how spatial and repeating patterning skills may be related to each other.

1. Math education standards

The Common Core State Standards (2010), or local variations of them, are currently being implemented in schools across the country. However, these standards give minimal attention to patterning or spatial skills in the early grades. Patterning skills encompass the ability to notice and use predicable sequences, such as a predictable array of shapes or sounds or functional relations between two

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variables (Burgoyne, Witteveen, Tolan, Malone, & Hulme, 2017). With young children, the focus is on skills with repeating patterns (i.e., linear patterns that have a unit that repeats, such as circle–circle–square–circle–circle–square). Thus, the current paper focuses on repeating patterning skills.

The importance of patterning skills for math achievement is currently under debate. Previously, patterning skills were included in national and state math standards for prek and kindergarten under the algebra strand (National Association for the Education of Young Children, 2014; National Council of Teachers of Mathematics, 2006). However, in 2008, the National Mathematics Advisory Panel (2008) concluded: "In the Major Topics of School Algebra set forth in this report, patterns are not a topic of major importance. The prominence given to patterns in PreK-8 is not supported by comparative analyses of curricula or mathematical considerations" (p. 59). The only evidence cited in the report was a curriculum analysis indicating that only one of the six highest performing countries on an international assessment emphasized patterns in the early grades (Schmidt & Houang, 2007). In part, the recommendation of the panel reflects the paucity of evidence that existed at the time on the value of patterning skills. The Common Core State Standards (2010) followed this recommendation, not including patterns as a math content standard at any grade level. Anecdotal evidence suggests that teachers may not welcome this change. One kindergarten teacher recently complained to a colleague: "They took patterns away from us! Kids actually liked to do patterns."

Spatial skills also receive minimal attention in the Common Core State Standards (2010) for math. Spatial skills encompass cognitive skills related to visual imagery and mental manipulation of spatial information (Uttal et al., 2013). Such skills are only mentioned once in the early grades, as part of a content standard for Kindergarten. Spatial skills also received minimal attention in past national and state math standards for prek and kindergarten (National Association for the Education of Young Children, 2014; National Council of Teachers of Mathematics, 2006). However, there is a growing advocacy for more attention to spatial skills from early in education (Newcombe, 2010; Verdine, Golinkoff, Hirsh-Pasek, & Newcombe, 2014). Thus, research on the potential roles of spatial and patterning skills for early math knowledge development is urgently needed. Next, we review past research on each skill and its relations to math knowledge.

2. Spatial skills

First consider spatial skills. Young children regularly engage their spatial skills as they play with blocks, puzzles, and videogames (Jirout & Newcombe, 2015; Levine, Ratliff, Huttenlocher, & Cannon, 2012; Newcombe, 2010; Verdine, Golinkoff, Hirsh-Pasek, Newcombe, et al., 2014). In one large, representative sample, 75% of 4- to 7-year old children were reported to play with blocks, puzzles and board games at least sometimes (i.e., three to five times per week), and 25% were reported to play with these toys often (i.e., six times or more per week) (Jirout & Newcombe, 2015). Further, children in this study who played with these toys more often also had higher spatial skills. Some young children also hear many spatial words when talking with their parents, and frequency of hearing spatial words is also linked to spatial skills (Pruden, Levine, & Huttenlocher, 2011).

Spatial skills are core cognitive skills such as spatial visualization (the ability to imagine and mentally transform spatial information), form perception (the ability to copy and distinguish shapes from other shapes, including symbols), and visual–spatial working memory (i.e., *visual–spatial WM*, the ability to hold the locations of different objects, landmarks etc. in working memory) (Mix & Cheng, 2012; Mix et al., 2016; Uttal et al., 2013). Spatial skills are present in infancy and continue to develop through childhood (Newcombe, 2010; Uttal et al., 2013). For example, children's ability to represent and transform spatial information improves with age (Levine, Huttenlocher, Taylor, & Langrock, 1999), and their visual–spatial WM capacity increases over development as well (Isaacs & Vargha-Khadem, 1989; Li & Geary, 2013).

3. Links between spatial skills and math knowledge

How might spatial skills influence math knowledge? The most common theoretical perspective is that mathematical thinking is supported by spatial representations (Mix & Cheng, 2012). From mental number lines to geometric figures, information about locations in space are often processed when solving math problems. For example, some people generate schematic representations of math problems that include the spatial relations described in the problems, and these people are more likely to solve the problems correctly (Hegarty & Kozhevnikov, 1999). Further, visual–spatial WM is needed to solve some types of math problems, such as addition problems that involve carrying (Caviola, Mammarella, Cornoldi, & Lucangeli, 2012). Additionally, mathematical ideas are often grounded in experiences moving through space, such as moving objects to combine or separate sets (addition and subtraction), and stepping along a path as an experience supporting the link from a number line to magnitudes (Griffin, 2004). Although most theory and research is with school-age children and adults, one theory of early math development has incorporated spatial skill, specifically visual–spatial WM, as a foundational cognitive skill for supporting early numeracy knowledge, which subsequently supports later math achievement (LeFevre et al., 2010).

There is robust evidence that spatial skills are linked to individual differences in math knowledge. Children and adults with better spatial skills relative to their peers also have better math skills (see Mix & Cheng, 2012 for a review). For example, visual–spatial WM is predictive of math knowledge in school-age children (Bull, Espy, & Wiebe, 2008; Meyer, Salimpoor, Wu, Geary, & Menon, 2010; Raghubar, Barnes, & Hecht, 2010), as is form perception (Lachance & Mazzocco, 2006; Zhang & Lin, 2015) and spatial visualization (Guay & McDaniel, 1977; Kyttälä, Aunio, Lehto, Van Luit, & Hautamäki, 2003). A few of these studies have confirmed a link between spatial skills and later math knowledge, controlling for earlier math knowledge or examining growth in math knowledge (Bull et al., 2008; Lachance & Mazzocco, 2006). Although most longitudinal evidence comes from school-age children and adults, recent evidence indicates this association is present before school entry. Spatial assembly skill at age 3 was predictive of math knowledge concurrently and two years later, controlling for earlier math knowledge and executive function skills (Verdine, Golinkoff, Hirsh-Pasek, & Newcombe, 2017), and visual–spatial WM at age 4.5 predicted math achievement through Grade 3, controlling for reading achievement and executive function skills (Bull et al., 2008). Further, spatial skill in infancy may be predictive of math knowledge at age 4 (Lauer & Lourenco, 2016). After reviewing the literature, Mix and Cheng (2012) concluded: "the connection between space and math may be one of the most robust and well-established findings in cognitive psychology" (p. 198).

Despite the robust longitudinal relations, causal evidence that improving spatial skills leads to improvements in math knowledge is mixed, especially for children. Three studies have reported that improving children's spatial skills also improved their performance on math assessments (Cheng & Mix, 2013; Hawes, Moss, Caswell, Naqvi, & MacKinnon, 2017; Lowrie, Logan, & Ramful, 2017). However, two other studies failed to find an effect (Hawes, Moss, Caswell, & Poliszczuk, 2015; Xu & LeFevre, 2016), and there are