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A longitudinal analysis of early spatial skills compared to arithmetic and verbal skills as predictors of fifth-grade girls' math reasoning☆

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ABSTRACT

This study was designed to examine early predictors of later math reasoning in girls. Specifically, girls' first-grade spatial skills were compared with first-grade verbal and arithmetic skills as predictors of spatial and verbal–analytical math reasoning in fifth grade (N = 79). The first-grade girls were given assessments measuring: (1) spatial skills (WISC-IV Block-Design subtest, and 2-d and 3-d mental-rotation tasks), (2) verbal skills (Peabody Picture Vocabulary Test), and (3) arithmetic skills (addition/subtraction). In fifth grade, girls were given a math-reasoning test, assessing both math reasoning-spatial (geometry/measurement items) and math reasoning-analytical (number/algebra items). The estimated path model accounted for approximately half the variance in math reasoning. First-grade spatial skills were the strongest predictors of both types of fifth-grade math reasoning. First-grade arithmetic skills significantly predicted math reasoning-analytical. Early verbal skills were not directly related to fifth-grade math reasoning, although there was an indirect pathway connecting them through early spatial skills. Thus, spatial skills, assessed by first grade, already function as key long-term predictors of analytical as well as spatial math-reasoning skills as late as fifth grade.

1. Introduction

1.1. Rationale and purpose

The present study was designed to understand how girls' initial spatial skills at the outset of math learning in first grade might be predictive of their later math problem-solving skills 4 years later in fifth grade. In order to put any evidence for a long-term spatial/math association in perspective, it is also important to directly compare early spatial predictors with both early arithmetic and verbal predictors. Thus, a major contribution of the present study is to examine the long-term predictive effects of early spatial skills on girls' later math reasoning, relative to the predictive effects of early verbal and arithmetic skills.

Understanding the relevance of girls' early spatial skills to later math reasoning is particularly critical because of the extensive research across all ages showing that, overall, girls are disadvantaged compared to boys when solving types of spatial problems that relate to math performance (Casey, Nuttall, Pezaris, & Benbow, 1995; Ehrlich, Levine, & Goldin-Meadow, 2006; Johnson & Meade, 1987; Levine, Huttenlocher, Taylor, & Langrock, 1999; Uttal et al., 2013; Voyer, Voyer, & Bryden, 1995). Gender differences in spatial skills favoring boys emerge as early as 4 years of age (Levine et al., 1999). In addition, longitudinal research has shown that girls' disadvantages in mathematics emerge by fifth grade and are associated with increased math complexity at this grade level (Gibbs, 2010).

Large-scale studies have shown math reasoning skills to be the most predictive of later performance in higher-level mathematics in middle school, high school, and beyond (Benbow, Lubinski, Shea, & Eftekhari-Sanjani, 2000; Hedges & Nowell, 1995). Yet, prior research investigating spatial skills as predictors of mathematics has not specifically addressed math reasoning, but instead has typically examined standardized measures of math achievement or specific content areas (Mix & Cheng, 2012). Because lower spatial skills may have particular long-term consequences for girls' opportunities in math-related fields (Webb, Lubinski, & Benbow, 2007), it is critical that we have a better understanding of girls' *early* spatial skills, and their relation to math reasoning at around fifth grade when gender differences in mathematics start to emerge. This is the rationale in the present study for focusing specifically on math reasoning at fifth grade rather than assessing general math achievement.

1.2. Spatial predictors of math performance

In a 2012 review, Mix and Cheng (2012) reported that connections between space and math are one of the most robust and well-

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established findings in cognitive psychology. Recently, short-term spatial/arithmetic relationships have been found at the early childhood level as well (see review by Verdine et al., 2014). However, little is known about the long-term effects of early spatial skills on later math performance (Mix & Cheng, 2012), and addressing this question is one of the major goals of the present study.

Two key spatial skills found to relate to mathematics performance across ages include: mental rotation and spatial visualization (Mix & Cheng, 2012). Mental rotation consists of ability to look at an object or picture of an object and visualize what it might look like when rotated in 2-d/3-d space. Spatial visualization consists of multi-step processing of spatial information, such as ability to examine a group of shapes and mentally combine them to create a new design. Both spatial skills serve as key components for a range of spatial tasks in which the child has to solve a series of multi-step problems, and rotate spatial elements to solve the task (including puzzles, block-design, mental-rotation tasks).

1.3. Rationale for investigating spatial/math relations in girls

Researchers have found that associations between spatial skills and math performance are substantially stronger in females than males (Battista, 1990; Casey et al., 1995; Friedman, 1995). A major longitudinal study, following 400,000 students, found that spatial reasoning in high school was predictive of choice of majors and careers in science, technology, engineering, and math (STEM), (Wai, Lubinski, & Benbow, 2009). These researchers also found girls to have lower spatial skills than boys (Webb et al., 2007). Thus, a relationship has been established between spatial skills and relative success and failure in math and science, and these skills are related to employment in a wide range of STEM careers in which women are underrepresented.

1.4. Predictors of two types of math reasoning

Research in cognitive psychology, cognitive neuroscience, and mathematics support differences in verbal–analytical vs. visual–spatial cognitive processes when solving math problems (Battista, 1990; Kosslyn & Thompson, 2003; Krutetskii, 1976; Presmeg, 1986; Repovs & Baddeley, 1986). Therefore, an additional purpose of this study was to investigate girls' early spatial skills as predictors of two types of math reasoning in upper-elementary grades. Mathematics content-analysis across grade-levels has shown that the largest advantage for males compared to females is found for mathematical reasoning in which spatial visualizations have been shown to be beneficial (e.g., geometry, measurement, proportional thinking, estimation) (Gallagher et al., 2000; Lummis & Stevenson, 1990; Marshall & Smith, 1987). Consequently, we were interested in whether a strong longitudinal spatial/math relation in girls would occur only for math content that focused on spatial reasoning, or whether it would generalize to types of math-reasoning problems that involve verbal–analytical reasoning. This question has not been addressed previously in the literature.

It might be expected that spatial skills would primarily predict spatial math reasoning as indicated by the substantial number of geometry/measurement items on standardized math tests that are heavily based on spatial reasoning. However, it has also been proposed that spatial–visualization processes may come into play when solving complex verbal–analytical math problems as well. Specifically, it has been argued that spatial reasoning would be involved when problems are novel or ill-defined, while verbal processes may take over when math problems are well-defined and familiar (Mix & Cheng, 2012). For example, strong spatial skills may be an advantage on verbal–analytical word problems when the task requires being able to effectively translate words and numbers into the spatial-array of a math equation, or to construct a mental-model of a problem and plan the solution, based on that model (Hegarty, Mayer, & Monk, 1995).

In summary, the present study contributes uniquely to the literature in several ways. First, we address the role of spatial skills as an early predictor of girls' later *math reasoning* skills (4 years later—at the point at which gender differences in mathematics start to emerge in fifth grade). Secondly, we examine math reasoning in depth, investigating the effect of early spatial skills on *different types of math reasoning*. Thus, a major purpose of this study was to follow a group of girls, starting at school-outset, and compare their early spatial skills to other key early cognitive factors as predictors of both spatial and analytical math reasoning by fifth grade.

1.5. Design of the present research

A path-analytical approach was used in this study to investigate the relation between girls' spatial, arithmetic, and verbal skills in first grade and two different types of fifth-grade math reasoning. The early spatial tasks assessed spatial visualization and mental rotation; arithmetic measures assessed addition and subtraction; the verbal measure assessed vocabulary skills.

1.5.1. A partial replication of a study on first-grade girls

This study is a longitudinal follow-up of a prior study of first-grade girls (names of authors deleted). It is only a partial replication, because measures of early [1]home learning environment and early spatial/math home activities were not included. Instead, this longitudinal study addresses pathways in the prior study relating specifically to first-grade girls' early cognitive skills in order to compare them as predictors of girls' math reasoning 4 years later. Socioeconomic status (SES) and maternal spatial skills were included as control variables.

1.5.2. Fifth-grade math reasoning

Fifth-grade students who were administered a math-reasoning test in this study consisted of girls from the first-grade study who remained within the schools. In order to systematically address math-reasoning skills in fifth grade, we developed a math-reasoning test (mainly drawn from released-items from standardized math achievement tests) in consultation with a group of researchers (educational-psychologists, school-psychologists, measurement-specialists, mathematics-educators). The Math Reasoning-Analytical subtest included number/algebra items specifically selected to tap higher verbal–analytical reasoning (in addition to math-facts and procedural-knowledge). The Math Reasoning-Spatial subtest included geometry/measurement items taken directly from standardized math assessments that were specifically designed to tap spatial reasoning involving visualization and manipulation of images. (See sample items in Appendices A and B.)

1.5.3. Rationale for hypothesized model

There is a paucity of longitudinal research directly comparing effects of early spatial, language, and arithmetic skills on later math performance, and this research has primarily examined math achievement only up to third grade (LeFevre et al., 2010; Zhang et al., 2014). Furthermore, this research has focused on predictors of later arithmetic or general math achievement, rather than focusing in depth on later math reasoning, as in the present study. The literature is further complicated by diverse measures used to assess these skills (e.g., LeFevre et al., 2010; Zhang et al., 2014). For example, several studies (e.g., LeFevre et al., 2010; Vukovic & Lesaux, 2013) used the same measure of verbal processing (PPVT) as in the present study for one of their measures of language skills. However, they chose visual–spatial working memory as

[1] A supplemental analysis including the Home Learning Environment measure (HLE) from the original first grade study (Dearing et al., 2012) was conducted, and it showed that the key relations between first grade and fifth grade variables addressed in the present study still held within that context.