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.

Keywords: spatial skills; arithmetic; gender; longitudinal; math reasoning

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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 four 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 four 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 (Hedges & Nowell, 1995; Benbow, Lubinski, Shea, & Eftekhari-Sanjani, 2000). 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). 4) 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-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, 2006). 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 (four 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 ¹home 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 four 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 Appendix 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., 2012; Zhang et al., 2013). Further, 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., 2013). 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 their measure of spatial processing, making it difficult to compare their findings to other spatial-skills literature assessing spatial visualization and mental rotation.

LeFevre and her associates found that preschool and kindergarten spatial working memory, numerical, and linguistic skills all independently predicted math achievement performance two years later. Vukovic and Lesaux (2013) found language measures to be

the best predictor of later math achievement, but over half their students were non-native English speakers. Zhang et al. (2013) recently found that *both* verbal and spatial skills (letter knowledge vs. spatial visualization) in kindergarteners predicted level of arithmetic in first grade, and later arithmetic growth through third grade.

Based on the literature, we reasoned that our longitudinal study would show early spatial skills predicting later math performance in girls. However, we did not make precise predictions on the relative predictive power for the different pathways estimated within our models. Specifically, neither the theoretical or empirical knowledge base, at this point, is sufficient to guide whether the predictive effects of early spatial skills are likely to be stronger than the predictive effects of early arithmetic and verbal skills on girls' later upper-elementary math-reasoning abilities. All three types of early cognitive measures have been found to predict later math achievement (Duncan et al., 2007; LeFevre et al., 2010; Mix & Cheng, 2012; Zhang et al., 2013).

1.5.4 Hypothesized model. The hypothesized model was based in part on findings of our first-grade study. Following these prior findings, SES should predict first-grade arithmetic and verbal skills, while the SES/spatial skills relation should be indirect (through direct effects of SES on verbal skills). We also expected that mothers' spatial skills would predict both first-grade spatial and arithmetic skills. Our overall hypothesized pattern of associations is displayed in Figure 1. Lighter solid lines in the hypothesized model show pathways obtained previously in the first-grade study. Darker solid lines represent new hypothesized pathways for the longitudinal predictors of fifth-grade math reasoning. As shown in the model, all possible pathways between the three types of early cognitive skills and the two types of math-reasoning skills were included in

the hypothesized model. This is based on prior research supporting each of these early cognitive skills as possible predictors of later math achievement (Duncan et al., 2007; LeFevre et al., 2010; Mix & Cheng, 2012; Zhang et al., 2013), and the small amount of research directly comparing them.

2. Methods

2.1 Participants

First-grade participants included 127 first-grade girls – mean age of 6.72 years ($SD = .34$) – and their mothers. Girls were recruited from 27 regular education classrooms in two Northeastern public-school districts. About 40% of the sample had incomes less than 200% of the federal poverty threshold and about 40% had incomes greater than 450%. The sample was approximately 63% European American, 12% Asian, 10% Hispanic, 3% African American, 12% multi-race or “other.”

The longitudinal follow-up included all of the first-grade girls from the prior research who had remained within the two school systems by fifth grade. Out of the 127 girls tested at first grade, 91 remained in the school system, and 79 were tested on the math-reasoning assessment measure in spring (a 62% retention rate over four years). In order to examine possible attrition effects, the group of first-grade girls participating in the longitudinal study was compared to the first-grade girls not available for testing in fifth grade. The two groups did not differ significantly on any variables used in the study. Only students who had received prior parent permission and assented to testing were assessed. All procedures and forms had prior approval from the University IRB.

2.2 First-Grade Data Collection from the Maternal Phone Interviews

2.2.1 Telephone interviews. Phone interviews with the mothers were used to collect data on SES and maternal spatial skills. Mothers were asked to follow along in

packets previously mailed to them. To collect SES information, mothers reported on number of years of education and annual family income.

2.2.2 Maternal spatial skills. A brief mental rotation test (consisting of five items), adapted from the *Vandenberg Mental Rotation Test* (Vandenberg & Kuse, 1978), was given to the mothers. They reported their choices on the mental rotation task to the interviewer. The task is to select the two objects out of four that are identical to, albeit rotated versions of, the target object. On each of the five items, mothers were given two points for selecting both of the correct objects, one point if they selected one correct and one incorrect object, and zero points if both choices were incorrect; average score per trial was reported. Cronbach's inter-item reliability was high ($\alpha = .80$) in the present sample.

2.3 First-Grade Data Collection from the Student Assessments

To assess first-grade girls' arithmetic, verbal, and spatial skills, we conducted three in-school individual assessments. During the first and second sessions in the fall, girls completed the 3-d and 2-d mental rotation tasks, the WISC-IV Block Design subtest, and the Peabody Picture Vocabulary Test (PPVT). During the third session in spring, girls completed addition and subtraction problems.

2.3.1 Verbal skills. The *Peabody Picture Vocabulary Test-Fourth Edition* (PPVT-IV; Dunn & Dunn, 2007) was used to assess girls' verbal skills. This is a norm-referenced measure of receptive vocabulary, and is administered by presenting a stimulus word (spoken by tester) and asking children to identify a pictorial representation of that word from four choices. This measure has demonstrated excellent reliability and validity

in socioeconomically diverse samples (Dunn & Dunn, 2007), and our Cronbach's inter-item reliability was high ($\alpha = .90$).

2.3.2 Arithmetic performance. Girls solved 10 addition problems and 10 subtraction problems, with problem-order counterbalanced across individuals. Problems included either two 1-digit numbers, or one 2-digit number and one 1-digit number. The problems used integers between 2-9 and 12-19, with the constraint that the same two integers (e.g., 3 + 3 or 6 - 6) were never used in the same problem. The range of sums was 9-24; the range of differences was 3-15. Each problem was presented, written horizontally on a card (e.g., 7 + 3) and read aloud (e.g., "What is seven plus three?"). The problems were presented visually and the children gave their answers verbally. One point was given for each item solved correctly. Both 10-item scales had fine inter-item reliabilities ($\alpha = .76$, addition; $\alpha = .79$, subtraction).

2.3.3 Spatial Performance. To investigate spatial skills, three measures were used. All three spatial measures included ability to mentally visualize, manipulate, and rotate objects in space, and two involved spatial visualization skills.

The *Block Design* subtest of the *Wechsler Intelligence Scale for Children-Fourth Edition* (WISC-IV) (Wechsler, 2003), one of the most frequently used instruments for assessing children's spatial skills, was selected as a measure. This subtest is designed to measure ability of 6- to 12-year-olds to solve part-whole relations tasks, while they rotate the small blocks to reproduce the correct pattern. Test-retest reliability and validity have been repeatedly established in socioeconomically diverse samples (Novak et al., 1991; Wechsler, 2003). The pre-kindergarten Block Design score was one of the best predictors of later school achievement in grades one and two (Novak et al., 1991). Our Cronbach's

inter-item reliability was $\alpha = .75$.

The second spatial task included a subset of 16 items from the *Mental Transformation Task* (Levine et al., 1999) for 4- to 6-year-olds. These items require children to match a target – a picture of two halves of a shape rotated in 2-d space – to four choices of possible completed figures; only one of the four figures was formed by the two rotated-halves. All of the items required mental rotation of the shape halves in order to match the whole figure, and involve part-whole relations matching (see Levine et al., 1999 for details on this task). Our Cronbach's inter-item reliability was $\alpha = .72$.

The third spatial task consisted of the 14-item *3-d Mental Rotation task* that was adapted from a similar 10-item task developed for kindergarten-age children (see Casey, Andrews et al., 2008 for details on this task). The task consisted of 14 identical pairs of 3-d figures. Children had to both flip and turn one of the identical figures so that it was placed in the same orientation as the other figure, thereby, physically rotating objects in 3-d space. Participants were given 10 seconds to solve each problem, with the item scored as correct if the first figure was in the same orientation as the second figure, or incorrect if the second figure was not oriented correctly. Our Cronbach's inter-item reliability was $\alpha = .69$.

2.4 Fifth-grade Mathematics Reasoning Assessment

2.4.1 Fifth-grade math test design, construction, and pilot testing. In designing a systematic math assessment tool, we developed items that covered a wide range of skills. We designed the math-reasoning assessment tool by selecting and adapting released standardized math items that tapped higher-level problem solving skills (including Trends in International Mathematics and Science Study (TIMSS), National

Assessment of Educational Progress (NAEP), and Massachusetts Comprehensive Assessment System (MCAS)). We selected items that required students to make decisions about how to approach a problem as well as requiring recall of information or performing simple algorithms. As needed, we modified the items in order to increase variability and cover the desired range of concepts. The items varied based on content area: (1) 14 items addressing content areas of number and algebra (and tapping verbal-analytical reasoning), and (2) 13 items addressing content areas of geometry and measurement (and tapping spatial reasoning). (See sample items in Appendix A and B.) For math reasoning- spatial items, Cronbach's inter-item reliability was $\alpha = .70$; for math reasoning-analytical items, Cronbach's inter-item reliability was $\alpha = .75$.

In this assessment tool, the goal was to maximize the number of geometry and measurement items that addressed spatial math reasoning and the number of numerical and algebra items that addressed analytical reasoning. Measurement problems involved use of spatial manipulations rather than formulas for problem solving. Geometry problems involved mental manipulations and part-whole relations rather than applying particular geometry rules or propositions. Algebra problems involved searching for the correct rule for solving a problem or numerical patterns in a chart. Number problems involved multi-step word problems. Number/algebra and geometry/measurement items were of approximately equal difficulty level. The 27-item test followed a multiple-choice format, where students selected 1 correct answer out of 4 choices.

2.4.2 Assessment procedures. The students were given the math-reasoning test in school in spring semester of fifth grade. Students were tested in groups; the assessment

took approximately 35 min., 1 min. allowed per-item. Questions were read aloud as students read along.

2.5 Statistical Analyses

To examine the direct and indirect relations between girls' background characteristics, their first-grade spatial, arithmetic, and verbal skills, and their fifth-grade math-reasoning skills, the data were examined using path analysis (Kline, 2005). This method of analysis was selected as the best approach for our longitudinal study, as the sample-size was not sufficient to fit a full structural equation model (i.e., one with measurement and structural paths). It also allowed us to examine the effects of the predictor variables simultaneously on two dependent measures while adjusting for correlation between these two measures.

As a first step, we fit the hypothesized model to the data (see Figure 1). The hypothesized model also included error covariances among all exogenous predictors as well as an error covariance between the fifth-grade math reasoning-spatial and math reasoning-analytical subtests (for simplicity, not pictured in Figure 1). We allowed this error covariance to be free because each outcome was comprised of different items from the same math assessment. Using a data driven approach, all non-significant paths were trimmed from this initial model, except for a borderline significant path ($p < 0.10$) between first-grade arithmetic and fifth-grade math reasoning-spatial.

There are several ways that the prior first-grade study and the present longitudinal study differ from one another. First, we did not include a measurement model in these analyses in order to accommodate the smaller sample size in our longitudinal data. Secondly, in the current set of analyses we omitted several variables (see section 1.4.1).

The reason for these omissions is twofold: (1) the questions we hoped to address revolved specifically around early skills predicting later math skills, and (2) given the smaller sample size, we only included necessary control variables and predictor variables that were closely aligned with our current research questions. Note that our composite measure of SES combined together income level and mothers' educational level.

2.6 Missing Data

Out of the original 127 participants in the first-grade study, 79 were participants in both first- and fifth-grade studies. Of those 79, 94% of the data were complete across all variables. Participants were most likely to be missing data on family-background and parent measures. Student achievement data were more complete, with only 2.5% ($n = 2$) missing data for first-grade arithmetic and fifth-grade math-reasoning measures. In order to account for missing data, models were estimated using full information maximum likelihood (FIML).

3. Results and Discussion

3.1 Zero-Order Correlations

Raw descriptive statistics for all variables are provided in Table 1; zero-order correlations among the predictor variables are presented in Table 2. Table 3 includes zero-order correlations between predictor variables and dependent variables.

3.2 Composite Variables

In the present longitudinal study, the major composite variables created here are based on the measurement model reported in the initial first-grade study, which was shown to have strong psychometric properties. In the initial first-grade study, the resulting factor loadings and global fit indices for the measurement model indicated good

fit to the data (e.g., Full Information ML $\chi^2(6) = 2.93$, $p = 0.82$; RMSEA value less than .05, 90% CI = .00-.05). Therefore, prior to analyzing the data, composite measures were created for all variables for which there were multiple indicators by converting values to z scores and averaging over them. Variables in the analyses that included only one indicator (e.g., maternal spatial ability and child verbal skills) were left in their natural metric. Composite variables included socio-economic status (SES), which combined income level with mothers' educational level, the arithmetic composite measure, which included addition and subtraction scores, and the spatial composite measure, which combined Block Design, 2-d mental rotation, and 3-d mental rotation.

3.3 Primary Analyses

In the first step of the analysis, a hypothesized path model was fit to the data (see Figure 1). This hypothesized model for the subset of first-graders who remained in the fifth-grade sample was based, in part, on results for the full 127 participants in the prior first-grade study. Specifically, the partial replication component of the model included: (1) paths between mother's spatial skills and their daughters' first-grade spatial and arithmetic skills; (2) a path between SES and first-grade verbal skills and first-grade arithmetic skills; and (3) a path between first-grade verbal skills and first-grade spatial skills (see Figure 1).

In addition, for the longitudinal predictors of the fifth-grade math-reasoning measures, an initial general assumption was made that direct pathways would be found between SES and fifth-grade math-reasoning measures, as well as direct pathways between all three cognitive measures assessed in first grade (spatial, verbal, and arithmetic) and the two fifth-grade math-reasoning measures. The model also tested for

any indirect relations between mothers' spatial skills and fifth-grade outcomes through either first-grade spatial or arithmetic. Because the fifth-grade outcomes were two categories of multiple-choice questions from the same assessment, we allowed for error variances of these variables to co-vary in the model.

The hypothesized model was a good fit to the data (Full Information ML χ^2 (6)=2.93, $p = 0.82$; RMSEA < 0.01; 90% confidence interval <0.01; 0.09). In the next step, using a data driven approach to the analysis, all non-significant paths were trimmed from this initial model, except for a borderline significant path ($p < 0.10$) between first-grade arithmetic and fifth-grade spatial math reasoning. This trimmed model (Full Information ML χ^2 (8)=1.88, $p = 0.98$; RMSEA < 0.01; 90% confidence interval <0.01; 0.07) had the advantage of parsimony while not significantly differing from the fuller model in terms of overall fit (see Figure 2).

3.4 Findings for Partial Replication of First-Grade Study

Patterns of findings from the larger first-grade study were generally reproduced in our final reduced model (see Figure 2) using the subsample of participants who were available at both grades: (1) Girls from higher-SES families tended to have higher first-grade arithmetic and verbal scores. (2) The SES/first-grade spatial relation was an indirect one -- though the direct relation between SES and first-grade verbal, and the direct relation between first-grade verbal and first-grade spatial. (3) Mother's spatial skills predicted girls' first-grade spatial skills. The only difference in findings between the larger first-grade study and this longitudinal subsample of 79 was that maternal spatial ability did not significantly predict first-grade arithmetic performance here.

3.5 New Longitudinal Findings

In total, the estimated path model accounted for approximately half of the variance in girls' math reasoning-spatial ($r^2 = 55\%$) and math reasoning-analytical ($r^2 = 44\%$). In the hypothesized model (see Figure 1), we made the general assumption that all three types of cognitive functioning in first grade might predict both types of fifth-grade math reasoning.

3.5.1 Early spatial skills as a predictor of fifth-grade math reasoning-spatial and math reasoning-analytical. One set of hypotheses was strongly supported -- there were direct relationships between the first-grade spatial composite score and both fifth-grade math reasoning-spatial and fifth-grade math reasoning-analytical. In fact, paths between girls' first-grade spatial skills and the two types of fifth-grade math-reasoning subtests showed the strongest associations (standardized coefficients for spatial and analytical math reasoning were 0.44 and 0.37 respectively).

3.5.2 Early arithmetic skills as a predictor of fifth-grade math reasoning-analytical. For the second set of hypotheses -- the first-grade arithmetic composite score was significantly related to fifth-grade math reasoning-analytical, and marginally related to fifth-grade math reasoning-spatial (see Table 5). The early arithmetic/late math reasoning-analytical relation would be expected because the analytical reasoning items involved solving numerical and algebraic word problems, which clearly draw on arithmetical concepts.

3.5.3 Comparison of early spatial to early arithmetic predictors. In order to compare early spatial skills to early arithmetic skills in terms the strength of their associations with the two fifth-grade math-reasoning measures, we used the Wald test for nested (dependent) coefficients from the same structural model to compare the difference

between two regression coefficients (Kodde & Palm, 1986). We found that the difference between direct effects of first-grade spatial and first-grade arithmetic on math reasoning-*spatial* was significant, $\chi^2(1) = 5.61$, $p = .02$. Differences between the direct effects of first-grade spatial (standardized coefficient, 0.37) and first-grade arithmetic (standardized coefficient, 0.22) on math reasoning-*analytical* were not significant.

3.5.4 No direct relation was found between early verbal skills and later math reasoning. The hypothesized pathway assuming that the first-grade verbal score would directly predict fifth-grade spatial and analytical math-reasoning scores was not supported by the data. Instead, there were significant indirect effects between this language measure and the fifth-grade outcomes. The association occurred first through the pathway from early verbal to early spatial skills, which had been found in the earlier first-grade study. It may be due in part to the shared variance of these two cognitive measures in tapping different components of general intelligence (Johnson & Bouchard, 2005). Next, this verbal pathway only connected to types of later math reasoning indirectly through early spatial skills. Thus, early spatial skills predicted fifth-grade math reasoning, even controlling for the shared variance between verbal and spatial abilities, while verbal skills did not.

3.5.5 Relation between control variables and math reasoning. As expected, we found both direct and indirect relationships between SES factors (measured in first and fifth grade) and spatial and analytical math-reasoning scores. The relationship between SES and both fifth-grade outcomes was mediated by two separate indirect pathways: (1) from first-grade verbal skills to first-grade spatial skills, and then to both types of math reasoning, and (2) from arithmetic skills to the two types of math reasoning. For fifth-

grade math reasoning-spatial skills, approximately 31% of the total effect of SES was mediated through the three first-grade skill measures. For fifth-grade math reasoning-analytical skills, approximately 36% of the total effect of SES was mediated through the three first-grade skill measures. Note that the maternal spatial skills variable only predicted math reasoning indirectly. Girls' first-grade spatial skills served as an indirect pathway between maternal spatial skills and their daughters' fifth-grade math reasoning-spatial performance.

3.6 Major Implications

The present findings indicate that by first grade, young girls' ability to solve spatial problems already are predictive of their ability four-years later to capitalize on this type of thinking when solving spatially-related math-reasoning problems. Most importantly, this study clearly establishes an association between early spatial skills in girls and their later skill at solving *analytically based* math-reasoning problems as well – a new finding in the literature.

These spatial/math findings are quite consistent with the extensive literature showing a strong relation between spatial skills and math achievement (Mix & Cheng, 2012). What has been newly established here is that this association can be found in girls starting at the outset of schooling and extending to the end of their elementary schooling in fifth grade. Other research has shown an association between early spatial skills and later math achievement through grade 3 (LeFevre et al., 2010; Zhang et al., 2013). What is also unique about the present study is that we separated math reasoning into two different subtypes, and found early spatial skills in girls to predict not only spatially-related math reasoning, but also analytically-related math reasoning. By comparing early

spatial skills with early arithmetic skills, we also were able to show that this longitudinal association with analytical reasoning is as strong for early spatial skills as it is for early arithmetic skills.

One would expect that early arithmetic skills would be important for later use of these computational skills when solving higher-level number and algebra problems. But why would early spatial skills predict stronger analytical math reasoning? One factor may relate to the advantage of those with strong spatial skills in being able to effectively generate mental representations in order to spatially structure and organize mathematical problems. For example, in number and algebra word problems, students are required to translate a complex series of numbers and words and convert them into an equation-based spatial array. They must mentally visualize on which side of the equation various numbers need to be placed, in which order, and where, in relation to which numerical symbols, and this may involve a series of mental manipulations and/or transformations (Mix & Cheng, 2012). Hegarty, Mayer, and Monk (1995) propose that with analytical word problems, spatial problem solving is involved when constructing a mental-model of a problem and planning the solution based on that model. For example, Hegarty and Kozhevnikov (1999) found that in sixth graders, students who used schematic spatial representations such as diagrams had better mathematical problem solving. Note that the use of the schematic representations also correlated strongly with scores on the Block Design subtest from the WISC-IV (one of the measures of first-grade spatial skills used in the present study).

For applied math reasoning problems involving novel, ill-defined problems in particular, spatial reasoning may facilitate the ability to translate complex verbal and

number problems into an appropriate spatial array representing the equation. In contrast, for simpler problems with known algorithms, students do not have to make this translation, as they already have the previously known repertoire of behaviors available to them in relation to the memorized series of steps and procedures necessary to solve the problem.

The importance of spatial layouts in children's number concepts has been shown in ability to accurately represent the mental number line. Gunderson and her associates (Gunderson et al., 2012) used 2-d mental rotation and transformation task involving flips, slides, and turns to assess early spatial skills (the same 2-d mental rotation task used in the present study). They found that performance on the spatial task predicted the quality of young children's mental number line representations. Further, the relation between young children's early spatial skills and their later mathematics achievement was mediated by the children's early skill at number line representations.

Cheng and Mix (2012) conducted 2-d mental rotation training with first and second graders (again using the same 2-d mental rotation task as in the present study), and found that practice solving these spatial problems directly improved children's arithmetic performance. This success was largely due to their dramatic improvement on missing terms problems, such as $4 + __ = 12$. Cheng and Mix (2012) concluded that the mental rotation problems improved the cognitive processes needed to mentally manipulate these symbols into a more conventional spatial format (e.g., $12 - 4 = __$). Thus, there are a variety of ways that effective spatial skills could benefit children's ability to understand the spatial layout of numerical and arithmetic problems. These early skills would likely benefit older students as they utilize these skills when solving higher-level number and

algebra problems (Mix & Cheng, 2012).

3.7 Limitations

One limitation is the sample size of girls remaining in the fifth-grade sample. Although we retained 87% of first-grade girls who remained within the schools, we only had 62% of the original first-grade sample. Thus, it would be useful to conduct a replication, with a new and larger sample. Secondly, our focus on girls does not allow us to speak to whether the evident patterns of association generalize to boys. There is some evidence that the spatial/math relationship is stronger for girls (Casey et al., 1995; Friedman, 1995). Given the time-intensive nature of longitudinal research, and our special interest in girls, we maximized statistical power for detecting individual differences by sampling only this gender. Based on the understudied nature of within-gender questions, our study is a useful step in advancing the knowledge base.

Furthermore, it is important to note our inferences based on path analysis are limited to considerations of whether or not our results are *consistent* with causal hypotheses. There remains potential for omitted variable bias. Characteristics of girls or their environments that were not observed in this study could be the true cause of variations in later math-reasoning skills. As a descriptive study, however, we believe this work should help to identify strategies for designing effective spatial intervention studies. One psychometric problem is that the arithmetic composite measure was more negatively skewed than the spatial composite measure. Consequently, the spatial composite measure may do a better job of capturing high performance. It is worth noting also that our comparison of the effect sizes for spatial skills versus arithmetic and verbal skills on later math reasoning were relatively exploratory (and final model choice was driven

empirically rather than theoretically to some extent); thus, these results should help guide future hypothesis testing.

3.8 Conclusions

The importance of spatial reasoning as an alternate route to success in STEM has become clear to policy makers at the national level, along with recognition that spatial ability plays a critical role in structuring students' educational and occupational choices and outcomes – either towards or away from STEM fields (National Science Board, 2010). There is extensive evidence that spatial skills can be improved through training (see meta-analysis by Uttal et al., 2013). Unfortunately, spatial skills are not systematically taught as a key component of the mathematics curriculum. Instead, those with effective spatial skills simply rise to the top in math and science, and those with lower spatial skills do not receive the training they need (National Science Board, 2010).

Given our increasingly technological world, all members of our society will need to have progressively more sophisticated skill at interpreting information presented in spatial abstractions, such as computer graphics, diagrams, and 3-d virtual images (Terlecki, Newcombe, & Little, 2008). It has been found that more highly developed and technological societies actually have *wider gender-gaps* in spatial skills than countries with less gender equity and less development (Lippa, Collaer, & Peters, 2010). In order to intervene and reduce this gender disparity, we first need to have a better understanding of how girls vary in their early development of spatial problem solving. In addition, it is important to understand how this variability in spatial skills factors into their acquisition of different types of math-reasoning skills as mathematics becomes more complex at the later grades. Both goals were major objectives of our present research.

References

- Battista, M. T. (1990). Spatial visualization and gender differences in high school geometry. *Journal for Research in Mathematics Education*, 21(1), 47-60.
doi:10.2307/749456
- Benbow, C. P., Lubinski, D., Shea, D. L. & Eftekhari-Sanjani, H. (2000). Sex differences in mathematical reasoning ability: Their status 20 years later. *Psychological Science*, 11(6), 474-480.
- Casey, M. B., Andrews, N., Schindler, H., Kersh, J., Samper, A., & Copley, J. (2008). The development of spatial skills through interventions involving block-building activities. *Cognition and Instruction*, 26(3), 269-309.
doi:10.1080/07370000802177177
- Casey, M. B., Nuttall, R., Pezaris, E., & Benbow, C. P. (1995). The influence of spatial ability on gender differences in mathematics college entrance test scores across diverse samples. *Developmental Psychology*, 31(4), 697-705. doi:10.1037/0012-1649.31.4.697
- Cheng, Y. L., & Mix, K. S. (2014). Spatial training improves children's mathematics ability. *Journal of Cognition and Development*, 15(1), 2-11. doi: 10.1080/15248372.2012.725186
- Duncan, G. J., Dowsett, C.J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P.,...Japel, C. (2007). School readiness and later achievement. *Developmental Psychology*, 43(6), 1428-1446. doi:10.1037/0012-1649.43.6.1428
- Dunn, L. M., & Dunn, D. M. (2007). Peabody Picture Vocabulary Test (4th ed.). San Antonio, TX: Pearson.

- Ehrlich, S., Levine, S., & Goldin-Meadow, S. (2006). The importance of gestures in children's spatial reasoning. *Developmental Psychology*, 42, 1259 – 1268.
- Friedman, L. (1995). The space factor in mathematics: Gender differences. *Review of Educational Research*, 65(1), 22-50. doi:10.2307/1170477
- Geary, D. C., Saults, S. J., Liu, F., & Hoard, M. K. (2000). Sex differences in spatial cognition, computational fluency, and arithmetical reasoning. *Journal of Experimental Child Psychology. Special Issue: Sex and Gender Development*, 77(4), 337-353. doi:10.1006/jecp.2000.2594
- Gibbs, B. G. (2010). Reversing fortunes or content change? Gender gaps in math-related skill throughout childhood. *Social Science Research*, 39(4), 540–569. doi:10.1016/j.ssresearch.2010.02.005
- Gunderson, E.A., Ramirez, G., Beilock, S. L., & Levine, S. C. (2012). The relation between spatial skill and early number knowledge: The role of the linear number line. *Developmental Psychology*, 48(5), 1229-1241. doi: 10.1037/a0027433
- Hedges, L. V., & Nowell, A. (1995). Sex differences in mental test scores, variability, and numbers of high-scoring individuals. *Science*, 269(5220), 41-45. doi: 10.1126/science.7604277
- Hegarty, M., & Kozhevnikov, M. (1999). Types of visual-spatial representations and mathematical problem solving. *Journal of Educational Psychology*, 91(4), 684-689.
- Hegarty, M., Mayer, R. E., Monk, C. A. (1995). Comprehension of arithmetic word problems: A comparison of successful and unsuccessful problem solvers. *Journal of Educational Psychology*, 87(1), 18-32. doi: 10.1037/0022/0663.87.1.18

- Johnson, W., & Bouchard, T. J., Jr. (2005). The structure of human intelligence: It is verbal, perceptual and image rotation (VPR), not fluid and crystallized. *Intelligence*, 33(4), 393-416. doi: 10.1016/j.intell.2004.12.002
- Johnson, E. S., & Meade, A. C. (1987). Developmental patterns of spatial ability: An early sex difference. *Child Development*, 58(3), 725-740. doi:10.2307/1130210
- Kline, R. B. (2005). *Principles and Practice of Structural Equation Modeling* (2nd ed.). New York, NY: Guilford Press.
- Kodde, D. A., & Palm, F. C. (1986). Notes and comments: Wald criteria for jointly testing equality and inequality restrictions. *Econometrica*, 54(5), 1243-1248.
- Kosslyn, S. M., & Thompson, W. L. (2003). When is early visual cortex activated during visual mental imagery? *Psychological Bulletin*, 129(5), 723–746. doi: 10.1037/0033-2909.129.5.723
- Krutetskii, V. A. (1976). The psychology of mathematical abilities in schoolchildren. Chicago: University of Chicago Press .
- LeFevre, J., Fast, L., Skwarchuk, S., Smith-Chant, B., Bisanz, J., Kamawar, D., & Penner-Wilger, M. (2010). Pathways to mathematics: Longitudinal predictors of performance. *Child Development*, 81(6), 1753-1767. doi:10.1111/j.1467-8624.2010.01508.x
- Levine, S. C., Huttenlocher, J., Taylor, A., & Langrock, A. (1999). Early sex differences in spatial skill. *Developmental Psychology*, 35(4), 940-949. doi:10.1037/0012-1649.35.4.940
- Levine, S. C., Ratliff, K. R., Huttenlocher, J., & Cannon, J. (2012). Early puzzle play: A predictor of preschoolers' spatial transformation skill. *Developmental Psychology*,

- 48(2), 530–542. doi: 10.1037/a0025913
- Lippa, R. A., Collaer, M. L., & Peters, M. (2010). Sex differences in mental rotation and line angle judgments are positively associated with gender equality and economic development across 53 nations. *Archives of Sexual Behavior*, 39(4), 990-997. doi:10.1007/s10508-008-9460-8
- Lummis, M., & Stevenson, H. W. (1990). Gender differences in beliefs and achievement: A cross-cultural study. *Developmental Psychology*, 26(2), 254-263. doi:10.1037/0012-1649.26.2.254
- Marshall, S. P., & Smith, J. D. (1987). Sex differences in learning mathematics: A longitudinal study with item and error analyses. *Journal of Educational Psychology*, 79(4), 372-383. doi:10.1037/0022-0663.79.4.372
- Mix, K. S., & Cheng, U. L., (2012). The relation between space and math: Developmental and educational implications. In J. B. Benson (Ed.), *Advances in child development and behavior*. (Vol. 42), (pp. 199-243). Waltham, MA: Academic Press.
- National Science Board. (2010). Preparing the next generation of STEM innovators: Identifying and developing our nation's human capital. Arlington, VA: National Science Foundation.
- Novak, P. A., Tsushima, W. T. and Tsushima, M. M. (1991). Predictive validity of two short-forms of the WPPSI: A 3-year follow-up study. *Journal of Clinical Psychology*, 47(5), 698–702. doi:10.1002/1097-4679(199109)47:5<698::AID-JCLP2270470511>3.0.CO;2-Q
- Presmeg, N. C. (1986). Visualization in high school mathematics. *For the Learning of*

- Mathematics*, 63, 42 – 46.
- Repovs, G., & Baddeley, A. (1986). The multi-component model of working memory: Explorations of experimental cognitive psychology. *Neuroscience*, 139, 5-21.
- Terlecki, M. S., Newcombe, N. S., & Little, M. (2008). Durable and generalized effects of spatial experience on mental rotation: Gender differences in growth patterns. *Applied Cognitive Psychology*, 22(7), 996-1013. doi:10.1002/acp.1420
- Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N.S. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin*, 139(2), 352–402. doi: 10.1037/a0028446
- Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills*, 47(2), 599-604. doi:10.2466/pms.1978.47.2.599
- Verdine, B. N., Golinkoff, R. M., Hirsh-Pasek, K., Newcombe, N. S., Filipowicz, A. T., Chang, A. (2014). Deconstructing building blocks: Preschoolers' spatial assembly performance relates to early mathematical skills. *Child Development*, 85(3), 1062-1076. doi:10.1111/cdev.12165
- Vukovic, R. K., & Lesaux, N. K. (2013). The language of mathematics: Investigating the ways language counts for children's mathematical development. *Journal of Experimental Child Psychology*, 115, 227-244.
- Voyer, D., Voyer, S., & Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables. *Psychological Bulletin*, 117(2), 250-270. doi:10.1037//0033-2909.117.2.250

- Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology, 101*(4), 817-835.
doi:10.1037/a0016127
- Webb, R. M., Lubinski, D., & Benbow, C. P. (2007). Spatial ability: A neglected dimension in talent searches for intellectually precocious youth. *Journal of Educational Psychology, 99*, 397-420.
- Wechsler, D. (2003). Wechsler intelligence scale for children—Fourth Edition. San Antonio, TX: Psychological Corporation.
- Zhang, X., Koponen, T., Räsänen, P., Aunola, K., Larkkanen, M., & Nurmi, J. (2014). Linguistic and spatial skills predict early arithmetic development via counting sequence knowledge. *Child Development, 85*(3), 1091-1107.
doi: 10.1111/cdev.12173

Footnotes

¹A supplemental analysis including the Home Learning Environment measure (HLE) from the original first grade study (Dearing et al., 2000) 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.

Figure 1. Hypothesized relationships in the path analysis.

Figure 2. Significant direct effects (standardized coefficients) in the path analysis.

† $p < .10$. * $p < .05$. ** $p < .01$.

Appendix A
Sample Math Reasoning-Analytical Items

1

Bush Height (cm)	Shadow Length (cm)
20	16
40	32
60	48
80	64

The table above shows the shadow lengths of four bushes of different heights. What is the shadow length of a bush that has a height of 50 centimeters?

36 cm

☐

38 cm

☐

42 cm

☐

40 cm

☐

2

Janis, Maija, and their mother were eating a cake. Janis ate $\frac{1}{2}$ of the cake.

Maija ate $\frac{1}{4}$ of the cake. Their mother ate $\frac{1}{8}$ of the cake.

How much of the cake is left?

 $\frac{1}{2}$ ☐ $\frac{5}{8}$ ☐ $\frac{1}{8}$ ☐ $\frac{7}{8}$ ☐

3

The two number sentences shown below are true.

$$\square - \bigcirc = 6$$

$$\bigcirc + \bigcirc = 2$$

Which of the following equations must also be true?

$$\square \times \bigcirc = \square$$

☐

$$\bigcirc \times 2 = \bigcirc$$

☐

$$\square + \bigcirc = \square$$

☐

$$\square - \square = \bigcirc$$

☐

4

In Toshi's garden there are 12 times as many roses as sunflowers.

There are 124 sunflowers in the garden.

What is the total number of roses and sunflowers combined in the garden?

124

☐

2,976

☐

1,488

☐

1,612

☐

Appendix B
Sample Math Reasoning-Spatial Items

1

Ina found the following patterns to make containers.

Which pattern actually makes the container shown beside it?

☐ ☐ ☐ ☐

2

How many small cubes were used to build the figure below?

24

☐

36

☐

33

☐

66

☐

3

Which one of the small shapes below can be copied and put together like a puzzle to form the large square? Use as many copies of the one shape as you need.

4

Ed wrapped a single piece of ribbon around the box. The ribbon crossed all sides of the box. How many inches of ribbon did Ed use?

18 in.

10 in.

12 in.

16 in.

Table 1

Descriptive Statistics

Variable	Mean (SD)	Min	Max	Cronbach's Inter-item Reliability
Socio-Economic Status				
Mothers' Years of Education	11.37 ^a (3.18)	1	14	
Income Level	\$137,173 ^b (\$1,11989)	\$3,570	\$500,000	
Mothers' Spatial Skills				
Vandenberg Mental Rotation Task	1.26 ^c (0.47)	0	2	.80
Arithmetic Performance (1 st Grade)				
Proportion correct addition	0.86 (0.19)	.10	1.00	.76
Proportion correct subtraction	0.74 (0.27)	0	1.00	.79
Verbal Ability (1 st Grade)				
PPVT	108.62 (14.07)	82	138	.90
Spatial Ability (1 st Grade)				
WISC-IV Block Design ^d	10.33 (3.33)	1	22	.75
Proportion correct 2-d MR ^e	0.66 (0.20)	.19	1.00	.72
Proportion correct 3-d MR ^e	0.62 (0.17)	.21	1.00	.69
Math Reasoning-Analytical (5 th Grade)				
Proportion correct items	0.54 (0.24)	.14	1.00	.75
Math Reasoning-Spatial (5 th Grade)				
Proportion correct items	0.60 (0.22)	0	1.00	.70

Note. PPVT = Peabody Picture Vocabulary Test – Fourth Edition; WISC-IV = Wechsler Intelligence Scale for Children – Fourth Edition.

^aMean maternal years of education = 4.37 years post-high school. ^bPrior to calculation of composite scores, income was log-transformed to approximate a normal distribution. ^cMaternal Spatial Ability = *M* correct per trial.

^dWISC-IV Block Design = Standard Score. ^eMR = Mental Rotation task

Table 2

Zero-order Correlation Coefficients for Predictor Variables

	Income Level	Mothers' Years of Ed.	Mothers' Spatial Skills	1 st Grade WISC-IV	1 st Grade 2-d MR	1 st Grade 3-d MR	1 st Grade Addition	1 st Grade Subtraction	1 st Grade PPVT
Income Level	—	.60**	.28*	.24	.16	.12	.34**	.33**	.35**
Mothers' Years of Ed.		—	.36**	.30*	.32**	.26*	.42**	.34**	.56**
Mothers' Spatial Skills			—	.33**	.41**	.18	.18	.18	.14
1 st Grade WISC-IV				—	.35**	.42**	.20	.24*	.31**
1 st Grade 2-d MR					—	.33**	.28*	.29**	.32**
1 st Grade 3-d MR						—	.17	.17	.25*
1 st Grade Addition							—	.66**	.24*
1 st Grade Subtraction								—	.21
1 st Grade PPVT									—

Note. WISC-IV = Wechsler Intelligence Scale for Children – Fourth Edition; MR = Mental Rotation; PPVT = Peabody Picture Vocabulary Test – Fourth Edition.

* $p < .05$. ** $p < .01$.

Table 3

Zero-order Correlation Coefficients Between Predictor Measures and Dependent Measures

	5 th Grade Math Reasoning- Spatial	5 th Grade Math Reasoning- Analytical
Income Level	.47**	.39**
Mothers' Years of Ed.	.54**	.46**
Mothers' Spatial Skills	.32*	.28*
1 st Grade WISC-IV	.42**	.32**
1 st Grade 2-d MR	.49**	.43**
1 st Grade 3-d MR	.49**	.46**
1 st Grade Addition	.50**	.43**
1 st Grade Subtraction	.39**	.42**
1 st Grade PPVT	.43**	.40**

Note. WISC-IV = Wechsler Intelligence Scale for Children – Fourth Edition;
 MR = Mental Rotation; PPVT = Peabody Picture Vocabulary Test – Fourth Edition.
 * $p < .05$. ** $p < .01$.

Table 4

Unstandardized Coefficients in the Path Analysis

Predictor Variable	Outcome Variable									
	1 st Grade Verbal		1 st Grade Spatial		1 st Grade Arithmetic		5 th Grade Math Reasoning-Spatial		5 th Grade Math Reasoning-Analytical	
	Unst.	SE	Unst.	SE	Unst.	SE	Unst.	SE	Unst.	SE
1 st Grade Spatial										
Direct Effect	—	—	—	—	—	—	0.13**	0.02	0.11**	0.03
Indirect Effect	—	—	—	—	—	—	—	—	—	—
Total Effect	—	—	—	—	—	—	0.13**	0.02	0.11**	0.03
1 st Grade Arithmetic										
Direct Effect	—	—	—	—	—	—	0.04 [†]	0.02	0.06*	0.03
Indirect Effect	—	—	—	—	—	—	—	—	—	—
Total Effect	—	—	—	—	—	—	0.04 [†]	0.02	0.06*	0.03
1 st Grade Verbal										
Direct Effect	—	—	0.02*	0.01	—	—	—	—	—	—
Indirect Effect	—	—	—	—	—	—	0.002*	0.001	0.002*	0.001
Total Effect	—	—	0.02*	0.01	—	—	0.002*	0.001	0.002*	0.001
Mothers' Spatial Skills										
Direct Effect	—	—	0.56*	0.17	—	—	—	—	—	—
Indirect Effect	—	—	—	—	—	—	0.07*	0.03	0.06*	0.03
Total Effect	—	—	0.56*	0.17	—	—	0.07*	0.03	0.06*	0.03
SES Composite										
Direct Effect	8.02**	1.54	—	—	0.49**	0.10	0.09**	0.02	0.08*	0.03
Indirect Effect	—	—	0.14*	0.05	—	—	0.04*	0.01	0.04*	0.02
Total Effect	8.02**	1.54	0.14*	0.05	0.49**	0.10	0.12**	0.02	0.12**	0.03

[†] $p < .10$. * $p < .05$. ** $p < .01$.

Table 5

Standardized Coefficients in the Path Analysis

Predictor Variable	Outcome Variable	
	5 th Grade Math Reasoning-Spatial	5 th Grade Math Reasoning-Analytical
	Stand. Coefficient	Stand. Coefficient
1 st Grade Spatial		
Direct Effect	0.44**	0.37**
Indirect Effect	—	—
Total Effect	0.44**	0.37**
1 st Grade Arithmetic		
Direct Effect	0.17 [†]	0.22*
Indirect Effect	—	—
Total Effect	0.17 [†]	0.22*
1 st Grade Verbal		
Direct Effect	—	—
Indirect Effect	0.14*	0.12*
Total Effect	0.14*	0.12*
Mothers' Spatial Skills		
Direct Effect	—	—
Indirect Effect	0.15*	0.13*
Total Effect	0.15*	0.13*
SES Composite		
Direct Effect	0.36**	0.30*
Indirect Effect	0.16*	0.17*
Total Effect	0.52**	0.47**

[†] $p < .10$. * $p < .05$. ** $p < .01$.