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Spatial Skills, but Not Spatial Anxiety, Mediate the Gender Difference in Number Line Estimation

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Recently, there has been increasing evidence showing that males estimate whole numbers more accurately than females on the number line. However, relatively little is known about what factors contribute to this gender gap. The current study explored potential mediators of the gender difference in number line estimation, including spatial skills and spatial anxiety. In the Fall (time-point 1 [T1]), 490 children from kindergarten through fourth grade (274 girls) completed age-appropriate measures of number line estimation, spatial skills (including proportional reasoning, mental rotation, mental transformation, and visuospatial working memory), and spatial anxiety. About 5 month later in the Spring (time-point 2 [T2]), children completed the same measure of number line estimation again. Boys were more accurate on number line estimation, proportional reasoning, and mental rotation than girls, whereas girls showed higher levels of spatial anxiety. Critically, spatial skills (a latent variable constructed from proportional reasoning, mental rotation, mental transformation, and visuospatial working memory) at T1 mediated the gender difference in T2 number line estimation whereas spatial anxiety was not a significant mediator. These relationships held even after controlling for T1 number line estimation, reading achievement, and reading anxiety. Among the four spatial skills, proportional reasoning and mental rotation (but not mental transformation or visuospatial working memory) were mediators of the gender difference in T2 number line estimation. These findings constitute, to our knowledge, the first evidence regarding factors contributing to the gender difference in whole number line estimation.

Keywords: gender difference, number line estimation, proportional reasoning, mental rotation, spatial anxiety

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The issue of gender differences in mathematics ability has received substantial attention as researchers seek to understand the underrepresentation of women in science, technology, engineering, and mathematics fields (Ceci et al., 2009; Griffith, 2010; Halpern et al., 2007). Some studies have reported better math performance among males than females on, for example, standardized tests (Casey et al., 1997; Hilton & Berglund, 1974) and word problems (Geary, 1996; Marshall, 1984). However, recent meta-analyses of United States and international samples suggest that considerable gender differences exist only in specific content areas, and the differences are trivial between males and females when averaging across various math tasks and age groups (Else-Quest et al., 2010; Hyde et al., 1990; Lindberg et al., 2010).

Despite the small gender gap on many math tasks, several recent studies have consistently documented a male advantage on number line estimation (Bull et al., 2013; Gunderson et al., 2012; Hansen et al., 2015; Hutchison et al., 2019; LeFevre et al., 2010; Reinert et al., 2017; Thompson & Opfer, 2008). On a standard number line estimation problem, participants are presented with a blank number line with numbers on both ends (e.g., 0 and 100, 0 and 1000, etc.) and a number that they need to locate on the number line. In one study of first through sixth graders, out of a wide range of numerical tasks (e.g., number comparison, number ordering, counting, arithmetic, etc.), boys outperformed girls only on number line estimation, whereas girls outperformed boys on counting and no gender differences were found any other tasks (Hutchison et al., 2019). The male advantage in number line estimation was also found among younger children (i.e., kindergarteners; Gunderson et al., 2012) and adults (Bull et al., 2013) and using an unbounded version of the task (i.e., on which number lines only had a start point and a unit marked; Reinert et al., 2017). More recently, Geary et al. (2021) reported that sixth and seventh grade boys estimated fractions more accurately than girls on 0–5 number

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lines. A meta-analysis of six studies that included a total of 758 participants (including children in first through fifth grades and adolescents) reported a Hedge's $g = .52$ male advantage in performance on number line estimation tasks involving fractions and whole numbers, a medium effect size (Rivers et al., 2021).

Understanding factors contributing to the male advantage on number line estimation is important because of the critical role of number line estimation skill in mathematics development. Empirically, competence with number line estimation predicts performance on other math tasks and general math achievement, both concurrently and longitudinally (Berteletti et al., 2010; Booth & Siegler, 2006; Friso-van den Bos et al., 2015; Geary, 2011; Hansen et al., 2015; Jordan et al., 2013; Moore & Ashcraft, 2015). Theoretically, progress in number line estimation has been argued to reflect changes in numerical representations, which are fundamental for developing mathematics knowledge (Berteletti et al., 2010; Dehaene et al., 2008; Kim & Opfer, 2017; Opfer & Siegler, 2007).

However, to our knowledge, little is known about factors contributing to the gender gap in number line estimation. To date, the only study that has provided direct evidence on this issue is by Geary et al. (2021), in which the gender difference in fraction number line estimation among sixth and seventh graders was mediated by visuospatial attention. The current study aims to extend these findings by examining how spatial skills as well as spatial anxiety contribute to the gender gap in number line estimation of whole numbers among younger children (i.e., from kindergarteners to fourth graders).

The specific spatial skills we measured were proportional reasoning, mental rotation, mental transformation, and visuospatial working memory. Most prior work has used the terms "mental rotation" and "mental transformation" interchangeably and mental rotation is often referred to as one type of mental transformation. We distinguish between these skills based on recent findings that mental rotation and mental transformation loaded on different spatial ability factors (Frick, 2019). We use mental rotation to refer to the skills measured by tasks that require distinguishing between mirror-reversed rotated images. We use mental transformation to refer to the skills measured by tasks that require mentally transforming images by rotating, translating, and feature matching.

We expected these four spatial skills (i.e., proportional reasoning, mental rotation, mental transformation, and visuospatial working memory) to be recruited during number line estimation. Number line estimation requires translation between numerical and spatial representations of quantities and imposes high-spatial demands (e.g., Siegler & Booth, 2004). To accurately place a number on a number line, individuals need to assess the magnitude of that number, gauge the length of the line, and parse the space accordingly. Prior research showed that children's spatial skills predict both concurrent and later number line estimation performance (Gunderson et al., 2012; Hansen et al., 2015; LeFevre et al., 2013; Simms et al., 2016). For example, Gunderson et al. (2012) showed that children's early mental transformation skills predicted later number line knowledge, controlling for initial number line knowledge. Children's number line estimation performance is also associated with proportional reasoning (Hansen et al., 2015; Möhring et al., 2018) and visuospatial working memory (LeFevre et al., 2013; Simms et al., 2016).

A substantial male advantage has been consistently found on mental rotation and mental transformation tasks (Halpern et al., 2007; Levine et al., 2016, 1999; Linn & Petersen, 1985; Maeda & Yoon, 2013) but not on proportional reasoning or visuospatial working memory. Levine et al. (1999) reported that boys as young as 4.5 years old demonstrated better mental transformation skills than same-aged girls. There is also evidence suggesting that a male advantage on mental rotation might be present in infancy (Quinn & Liben, 2008). A recent meta-analysis on the development of gender differences in mental rotation showed an effect size of Hedge's $g = .20$ at around 6 years old and increased to Hedge's $g = .50$ at around 14 years old (Lauer et al., 2019). In contrast, studies using proportional reasoning tasks and visuospatial working memory tasks frequently report a lack of gender differences (Boyer et al., 2008; Ham & Gunderson, 2019; Hansen et al., 2015; Möhring et al., 2018, 2015; Robert & Savoie, 2006; Vuontela et al., 2003). For example, Vuontela et al. (2003) reported that 6- to 13-year-old boys were faster but less accurate than girls on visuospatial working memory tasks. Therefore, among the four spatial skills, we specifically expected that mental rotation and mental transformation would mediate the gender difference in number line estimation, but that proportional reasoning and visuospatial working memory would not.

Spatial anxiety, which impairs performance on spatial tasks, is often higher among females than males (Lauer, Esposito, & Bauer, 2018; Lawton, 1994; Ramirez et al., 2012). For example, Lauer, Esposito, and Bauer (2018) showed that 6- to 12-year-old girls reported higher spatial anxiety than boys (Cohen's $d = .37$). At the same time, higher spatial anxiety was related to lower performance on mental transformation but not to performance on standardized math assessment (Lauer, Esposito, & Bauer, 2018). Considering that the number line estimation task taxes spatial skills, we expected spatial anxiety to be negatively associated with performance on number line estimation and to mediate the gender difference in it.

To summarize, we expected spatial skills, particularly mental rotation and mental transformation, and spatial anxiety to mediate the gender difference in number line estimation. To test this prediction, we assessed number line estimation skill, spatial skills, and spatial anxiety among children from kindergarten through fourth grade in the fall semester. About 5 months later, in the spring semester, we assessed children's number line estimation skill again. We focused on these grade levels because competence in number line estimation at this age predicts later math achievement (Friso-van den Bos et al., 2015; Hansen et al., 2015; Jordan et al., 2013). To address potential confounding of general cognitive abilities and motivation in estimating the mediation effects, we included measures of children's reading achievement and reading anxiety as additional covariates. Note that given the correlational nature of these data, results from the mediation analyses do not imply causation.

Method

Participants

Our sample included 490 children from kindergarten to fourth grade (kindergarten: $N = 82$, 45 girls; first grade: $N = 112$, 60 girls; second grade: $N = 104$, 58 girls; third grade: $N = 109$, 59 girls; fourth grade: $N = 83$, 52 girls). Participants in this study were part of a larger longitudinal study that included 627 children from Pre-K to fourth grade (see online supplemental materials, Section A for details). Data reported in the current study were from children tested at the third and the fourth of four time-points in the larger longitudinal study (in this article, the third time-point of the larger study is referred to as T1, and the fourth time-point of the larger study is referred to as T2).[1] These time-points were selected because the third time-point was the only time-point at which all of our predictors of interest were assessed, and we wanted to assess later number line estimation at the fourth and final time-point. Children included in our analytic sample ($N = 490$) were those who had data on grade level, did not repeat a grade, and completed at least one of the seven focal measures in the current study (i.e., T1 number line estimation, T1 proportional reasoning, T1 mental rotation, T1 mental transformation, T1 visuospatial working memory, T1 spatial anxiety, and T2 number line estimation). Some children had missing data on some measures due to absence during one of the sessions, experimenter error, computer error, child refusal to complete the task, or reasons described in the Analytic Approach section below. On average, children in our analytic sample missed 16% of the nine measures (SD = 18%; see Table 1 for sample size per task).

Some parents provided family demographic information. Children included in this analytic sample were racially diverse: 51.3% of them were Black/African American, 20.0% were White, 12.3% were Hispanic, 4.9% were Asian/Asian American, .5% were Native Hawaiian/Other Pacific Islander, 10.7% were multiple races/ethnicities, and .2% were other races/ethnicities ($N_{\text{race/ethnicity}} = 431$). The highest education received by either parent in each family averaged 14.66 years (where 14 years is equivalent to an associate's degree; $SD = 2.42$, $N_{\text{education}} = 431$). Family income averaged $47,926 ($SD$ = $31,719, $N_{\text{income}} = 411$). The study procedures were approved under Temple University's Institutional Review Board (IRB) protocol 21935, "Cognitive and Emotional Bases of Math, Reading, and Spatial Development."

Materials

Students completed age-appropriate measures of number line estimation, spatial skills, verbal skills, spatial anxiety, and reading anxiety. All these measures were administered during two one-on-one sessions with a trained experimenter at T1. At T2, children received the same number line estimation measure again. These measures were part of a larger battery of assessments.[2]

Number Line Estimation

In this task, children were asked to estimate where a given number goes on a number line (Fazio et al., 2014; Siegler & Opfer, 2003). At the beginning of the task, children saw a bounded number line ranging from 0 to 100 (for kindergarteners) or 0 to 1,000 (for first through fourth graders; see online supplemental materials, Section B for all items). Children were asked to indicate where the displayed number at the top of the screen should go on the line. Children were also asked not to spend much time on each trial to encourage estimation. Each child finished 18 test trials presented in a random order. No feedback was given.

Children's accuracy on each trial was scored using percent absolute error (PAE = |response—correct answer|/total number range × 100%). Lower PAEs indicated more accurate performance. Note that number line estimation scores were later reverse coded so that higher scores indicated more accurate performance (see Data Aggregation section). Internal consistency was good within most grade levels at both time points (T1, Cronbach's $\alpha_{\text{kindergarten}} = 0.64$, $\alpha_{\text{first}} = 0.76$, $\alpha_{\text{second}} = 0.80$, $\alpha_{\text{third}} = 0.85$, and $\alpha_{\text{fourth}} = 0.86$; T2, $\alpha_{\text{kindergarten}} = 0.77$, $\alpha_{\text{first}} = 0.84$, $\alpha_{\text{second}} = 0.86$, $\alpha_{\text{third}} = 0.88$, and $\alpha_{\text{fourth}} = 0.89$).

Spatial Skills

Proportional Reasoning. All children received a proportional reasoning task that has been used with children ages 4 to 10 (Möhring et al., 2015). In this task, children were asked to help Paul the bear decide how much each drink (mixtures of cherry juice and water) would taste like cherry. On each trial, children saw a vertical rectangle ("cup") divided into a blue segment that represented water and a red segment that represented cherry juice. A horizontal line near the bottom of the screen had one cherry on the left end (representing "tastes not at all like cherries") and many cherries on the right end (representing "tastes a lot like cherries"). Children were asked to indicate on the line how much like cherry the drink would taste (Figure 1A). The height of the rectangle as well as the proportion of red and blue sections varied across trials. Two practice trials with feedback were given before the test trials. Each child completed 16 test trials in a random order without feedback.

Similar to the number line estimation task, children's accuracy on each trial was scored using PAE (PAE = |line length between response point and the left end—line length between the correct response point and the left end|/total line length * 100%). Proportional reasoning scores were later reverse coded so that higher scores indicated more accurate performance (see Data Aggregation section). Internal consistency was good within all grade levels (Cronbach's $\alpha_{\text{kindergarten}} = 0.85$, $\alpha_{\text{first}} = 0.84$, $\alpha_{\text{second}} = 0.84$, $\alpha_{\text{third}} = 0.85$, and $\alpha_{\text{fourth}} = 0.82$).

Mental Rotation. Kindergarteners completed the Ghost Puzzle task (Frick et al., 2013) and first to fourth graders completed the Letter Rotation task (Quaiser-Pohl et al., 2014) to assess their mental rotation skills.

Ghost Puzzle. In this task, children were asked to mentally rotate two "ghosts" and choose the one that would fit into the "hole" (Frick et al., 2013). The "hole" was white in the shape of a ghost in the middle of a dark circle (Figure 1B). On each trial, the incorrect ghost was a mirror-reversed image of the target ghost. Each child completed two practice trials and 22 test trials. On the

[1] There are two other published studies using this longitudinal dataset (Gunderson & Hildebrand, 2021; Ren et al., 2019).

[2] The larger longitudinal study included a number of other measures that varied by grade level and time–point. Measures collected at the third time-point but not included in the current study: analog magnitude system acuity, 0–10 number line estimation, whole number comparison, fraction comparison, linear measurement, approximate symbolic calculation, exact calculation, theory of intelligence, and gender stereotype beliefs. Measures collected at the fourth time-point but not included in the current study: visuospatial working memory, mental rotation, mental transformation, proportional reasoning, analog magnitude system acuity, 0–10 number line estimation, whole number comparison, fraction comparison, linear measurement, approximate symbolic calculation, exact calculation, decimal comparison, self-concept of academic abilities, and enjoyment of academic domains.

Table 1
Number of Participants and Standardized Scores (M and SD) on Each Measure by Child Gender

Measures (time-point)	Girls			Boys			Gender difference effect size (Cohen's *d*)
	N	*M*	*SD*	*N*	*M*	*SD*	
Number line estimation (T1)	237	−0.25	0.88	196	0.31	1.04	0.59
Number line estimation (T2)	221	−0.17	0.93	167	0.22	1.03	0.40
Proportional reasoning (T1)	255	−0.10	1.00	206	0.12	0.98	0.22
Mental rotation (T1)	261	−0.10	0.95	203	0.12	1.04	0.22
Mental transformation (T1)	246	−0.05	0.93	197	0.06	1.07	0.11
Visuospatial working memory (T1)	250	−0.05	0.93	203	0.06	1.07	0.12
Reading achievement (T1)	235	−0.05	0.91	188	0.06	1.09	0.11
Spatial anxiety (T1)	196	0.10	1.03	167	−0.11	0.95	−0.21
Reading anxiety (T1)	164	−0.01	0.98	131	0.01	1.02	0.02

Note. T1 = time-point 1; T2 = time-point 2. PAE (percent absolute error) scores on number line estimation and proportional reasoning were arcsine transformed. Then, scores on all measures were standardized within grade level. On number line estimation and proportional reasoning, standardized scores were then reverse coded so that higher scores indicate more accurate performance. On spatial anxiety and reading anxiety, higher scores indicate higher levels of anxiety. Positive effect sizes indicate higher scores among boys, and negative effect sizes indicate higher scores among girls.

first practice trial, children worked with foam board pieces and fit them into a hole. On the second practice trial, children mentally rotated the same images of the foam pieces. Children received feedback on the practice trials but not the test trials. Children's accuracy was scored by calculating the percentage of items answered correctly. Internal consistency was acceptable (Cronbach's $\alpha_{\text{kindergarten}} = 0.63$).

Letter Rotation. In this task, children were asked to choose which two letters among four rotated letters would match a target letter in a box (Quaiser-Pohl et al., 2014; Figure 1C). Among the four choices, two letters were mirror-reversals of the target letter while the other two matched the target letter. Children first saw two examples with answers filled out and then completed two practice trials with feedback. After practice trials, each child completed 16 test trials without feedback. A response was counted as accurate only when both correct options were chosen. Children's accuracy was scored by calculating the percentage of items answered correctly. Internal consistency was good within all grade levels (Cronbach's $\alpha_{\text{first}} = 0.85$, $\alpha_{\text{second}} = 0.87$, $\alpha_{\text{third}} = 0.81$, and $\alpha_{\text{fourth}} = 0.81$).

Mental Transformation. Kindergarteners completed a shortened version of the Children's Mental Transformation task (CMTT; Levine et al., 1999). First through fourth graders completed the Mental Rotation subtest of the Thurstone's Primary Mental Abilities test (PMA; Thurstone & Thurstone, 1938).

Children's Mental Transformation Task (CMTT). In this task, children were asked to determine which of the four shapes provided would be formed by fitting two pieces together (Levine et al., 1999; Figure 1D). Each child completed 24 items. Half of the items can be solved by mental rotation, and the other half can be solved by mental translation. Children's accuracy was indicated by the percentage of items answered correctly. Internal consistency was acceptable (Cronbach's $\alpha_{\text{kindergarten}} = 0.69$).

Thurstone's Primary Mental Abilities (PMA) Test, Mental Rotation Subtest. Children from first through fourth grade completed the Mental Rotation subtest of Thurstone's PMA Test (Thurstone & Thurstone, 1938; Figure 1E). On each trial, children were asked to choose from four shapes for the one that would form a square with a target shape. At the beginning of the task, the experimenter showed children a square and a rectangle and explained the definition of each shape. Children then completed four practice trials with feedback. Following the practice, children completed 16 test trials without any feedback. Children's accuracy was scored by the percentage of items answered correctly. Internal consistency was low in most grade levels (Cronbach's $\alpha_{\text{first}} = 0.52$, $\alpha_{\text{second}} = 0.63$, $\alpha_{\text{third}} = 0.50$, and $\alpha_{\text{fourth}} = 0.40$).

Visuospatial Working Memory. Visuospatial working memory was assessed at all four time points with the Dot Matrix subtest of Automated Work Memory Assessment (AWMA; Alloway, 2007). On each trial, children were shown a 4 × 4 grid on the computer screen and one or more dots appeared briefly in a sequence of squares (one at a time). Children were then asked to point to the squares in the sequence that the dot(s) appeared in them. Level of difficulty was gradually increased by increasing the number of dots, starting with one dot. Children completed three practice trials with feedback before the test trials. Six test trials at each span length (i.e., number of dots) were then presented. The task ended after children answered incorrectly on three consecutive trials with the same number of dots. Each child received a standardized score normed for ages 5 to 69 years old.

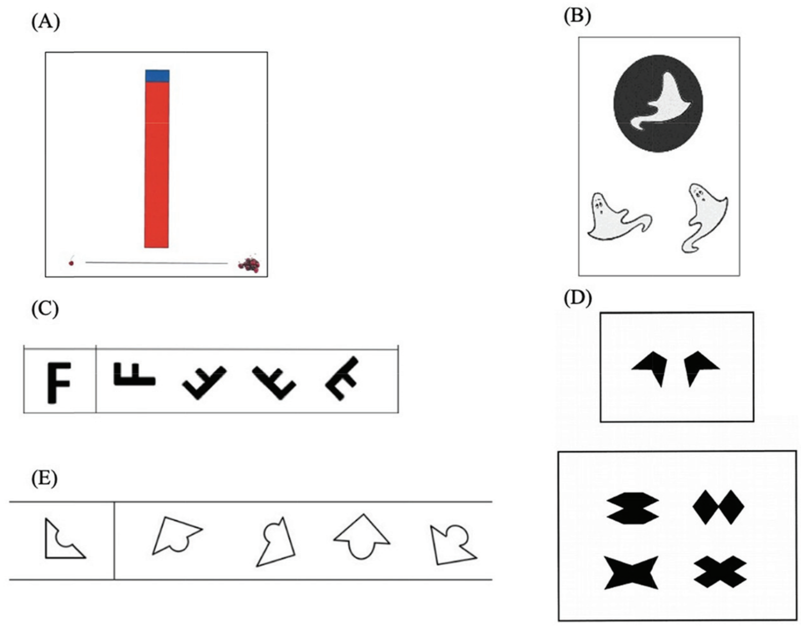
Reading Achievement

Reading achievement was measured with the Woodcock-Johnson IV Letter-Word Identification subtest (Schrank et al., 2014). In this test, children were asked to identify individual letters and read words of increasing difficulty. Basal was met when participants answered correctly on the six lowest-numbered items administered, and ceiling was met when participants answered incorrectly on the six highest-numbered items administered. The test ended when a participant met both basal and ceiling criteria. Children's W scores were used in the analyses.

Spatial Anxiety

Children completed a spatial anxiety questionnaire with eight items (Ramirez et al., 2012; see online supplemental materials, Section C for the full questionnaire). The experimenter asked children questions such as, "How do you feel when a friend asks you how to get from school to your house?" and "How do you feel if your teacher asked you to build this house out of these blocks in 5 minute? [Show child a card with pictures of Legos]" Children were asked to indicate their feelings on a scale with five horizontally presented faces featuring emotions ranging from "not nervous at all, very calm" (on the far left) to "very, very nervous" (on the far right). Children's answers were scored using the numerical value

Figure 1
Example Trials of Spatial Skill Measures



Note. (A) An example of the proportional reasoning task, from "The Relation Between Spatial Thinking and Proportional Reasoning in Preschoolers" by W. Möhring, N. S. Newcombe, and A. Frick, 2015, *Journal of Experimental Child Psychology*, *132*, p. 216. Copyright 2015 by Elsevier. Reprinted with permission. (B) An example of the Ghost Puzzle task, from "Development of Mental Rotation in 3- to 5-Year-Old Children" by A. Frick, M. A. Hansen, and N. S. Newcombe, 2013, *Cognitive Development*, *28*, p. 393. Copyright 2013 by Elsevier. Reprinted with permission. (C) An example of the Letter Rotation task, from "Is the Male Advantage in Mental-Rotation Performance Task Independent? On the Usability of Chronometric Tests and Paper-and-Pencil Tests in Children" by C. Quaiser-Pohl, S. Neuburger, M. Heil, P. Jansen, and A. Schmelter, 2014, *International Journal of Testing*, *14*, p. 129. Copyright 2014 by Taylor & Francis Ltd. Reprinted with permission. (D) An example of the Children's Mental Transformation Task, from "Early Sex Differences in Spatial Skill" by S. C. Levine, J. Huttenlocher, A. Taylor, and A. Langrock, 1999, *Developmental Psychology*, *35*, p. 942. Copyright 1999 by the American Psychological Association. Reprinted with permission. (E) Illustration of the type of items used on the Thurstone mental rotation task, from "The Relation Between Spatial Skill and Early Number Knowledge: The Role of the Linear Number Line" by E. A. Gunderson, G. Ramirez, S. L. Beilock, and S. C. Levine, 2012, *Developmental Psychology*, *48*, p. 1233. Copyright 2012 by American Psychological Association. Reprinted with permission. See the online article for the color version of this figure.

represented by each face (i.e., 1 = *not nervous at all, very calm* [far left] and 5 = *very, very nervous* [far right]). Higher scores indicated higher levels of spatial anxiety. Internal consistency was acceptable in most grade levels (Cronbach's $\alpha_{kindergarten} = 0.57$, $\alpha_{first} = 0.66$, $\alpha_{second} = 0.61$, $\alpha_{third} = 0.39$, and $\alpha_{fourth} = 0.56$).

Reading Anxiety

Children completed an eight-item reading anxiety questionnaire (Ramirez et al., 2019; see online supplemental materials, Section C for the full questionnaire). Children answered questions such as, "How do you feel when seeing all the letters or words in a storybook?" and "How would you feel if you were given these words to read? [Show child a card with "the, at, and."]." Children were asked to indicate their feelings on the same scale as that in the Spatial Anxiety questionnaire. Higher scores indicated higher levels of reading anxiety. Internal consistency was acceptable in most grade levels (Cronbach's $\alpha_{kindergarten} = 0.62$, $\alpha_{first} = 0.67$, $\alpha_{second} = 0.63$, $\alpha_{third} = 0.63$, and $\alpha_{fourth} = 0.72$). This study was not preregistered. Study materials, data, and analysis scripts are available upon request.

Analytic Approach

Data Aggregation

For number line estimation and proportional reasoning, trials on which reaction time (RT) was shorter than 200 ms or beyond 3 *SD* away from that child's mean RT were marked as missing. If a child missed more than half of the items or if 90% of a child's estimates were within 10% of the line length (e.g., the child repeatedly marked the same location for every item), the child's performance on that task was marked as missing (Slusser et al., 2013). Otherwise, children's performance was calculated by averaging the PAEs of available trials on each task. PAEs on both tasks were then arcsine transformed (i.e., two times the arcsine of the square root of the original score) to increase normality.

Scores on each task were standardized within grade level to make all measures comparable in the structural equation modeling (SEM) analyses (see the Analytic Plan section; Kline, 2015). Standardized scores on number line estimation and proportional reasoning were then reverse coded so that higher scores indicate better performance. See online supplemental materials, Section D, Table S1 for descriptive statistics by grade level and gender on the original task scores (before transformation, standardization, and reverse coding).

Analytic Plan

Two-sample *t* tests were used to examine whether there were gender differences in number line estimation, proportional reasoning, mental rotation, mental transformation, visuospatial working memory, and spatial anxiety. To examine whether the magnitude of these gender differences changed with grade level, we conducted linear regressions with gender, grade level and the interaction between gender and grade as predictors. Gender was dummy coded with girls being the reference level, and grade level was entered as a continuous variable. In each *t* test and regression, all children with data available for that analysis were included.

SEM was used to test the effects of potential mediators on the gender difference in T2 number line estimation. We conducted two sets of SEM analyses with the four spatial skill measures (i.e., proportional reasoning, mental rotation, mental transformation, and visuospatial working memory) as a spatial skill latent variable or as separate mediators. In these analyses, we first examined the effects of spatial skills and spatial anxiety simultaneously; then, we added T1 number line estimation as a covariate; and finally, we added T1 reading achievement and reading anxiety as covariates. Given the wide range of grade levels in our sample, we explored whether the indirect effects of gender on number line estimation via the mediators differed depending on grade level by fitting moderated mediation models with grade level as a continuous moderator. In the moderated mediation models, we did not include the covariates to reduce the complexity of the models.

In the SEM analyses, we entered covariates as additional mediators. Mediators of cognitive skills (i.e., spatial skill measures, reading achievement, and T1 number line estimation) were set to correlate with each other, and mediators of motivation (i.e., spatial anxiety and reading anxiety) were set to correlate with each other. Model fit was considered good when the comparative fit index (CFI) and the Tucker-Lewis index (TLI) were above .90 and the root mean square error of approximation (RMSEA) was below .08; and model fit was considered as excellent when the CFI and TLI were above .95 and the RMSEA was below .06 (Hu & Bentler, 1999; Kline, 2015). When model fit did not reach the criteria of good, we referred to the modification indices (MI) and set additional correlations between mediators and covariates of which MI was greater than 3.84 (indicating a significant, at the 0.05 level, chi-square decrease by adding the parameter). Full information maximum likelihood (FIML) estimation was used to handle missing data (Enders & Bandalos, 2001), and 95% confidence intervals (CI) of model parameters were estimated using bias-corrected bootstrap with 5,000 iterations (Bollen & Stine, 1990). Parameters with CIs excluding zero were considered significant. Data analyses were conducted using R (R Core Team, 2018) and Mplus Version 8.4 (for SEM; Muthén & Muthén, 1998–2017).

Results

Gender Differences

Table 1 shows descriptive statistics of each measure by gender, and Table 2 shows correlations among the measures. As expected, boys were more accurate than girls on number line estimation at both time points: T1, $t(383.69) = -5.99$, $p < .001$, Cohen's d = .59; T2, $t(336.70) = -3.84$, $p < .001$, Cohen's $d = .40$. Furthermore, compared with girls, boys were more accurate on proportional reasoning, $t(440.77) = -2.34$, $p = .020$, Cohen's $d = .22$; and mental rotation, $t(415.92) = -2.32$, $p = .021$, Cohen's $d = .22$; and showed lower levels of spatial anxiety, $t(359) = 2.02$, p = .044, Cohen's $d = .21$. No gender difference was found on mental transformation, $t(389.43) = -1.16$, $p = .25$, Cohen's $d = .11$, visuospatial working memory, $t(404.34) = -1.20$, $p = .23$, Cohen's d =

Table 2
Correlations Among All Measures

Measures (time-point)	*N*	1	2	3	4	5	6	7	8	9
1. Gender (0 = girls, 1 = boys)	490	—								
2. Number line estimation (T1)	433	.28***	—							
3. Number line estimation (T2)	388	.19***	.66***	—						
4. Proportional reasoning	461	.11*	.33***	.33***	—					
5. Mental rotation	464	.11*	.20***	.26***	.15**	—				
6. Mental transformation	443	.06	.26***	.30***	.20***	.36***	—			
7. Visuospatial working memory	453	.06	.34***	.38***	.20***	.16***	.30***	—		
8. Reading achievement	423	.06	.45***	.48***	.28***	.21***	.29***	.34***	—	
9. Spatial anxiety	363	−.11*	−.08	−.04	.04	−.03	−.07	.02	.03	—
10. Reading anxiety	295	.01	−.24***	−.20**	−.06	−.09	−.11	−.06	−.36***	.46***

Note. T1 = time-point 1; time-point 2. PAE (percent absolute error) scores on number line estimation and proportional reasoning were arcsine transformed. Then, scores on all measures were standardized within grade level. On number line estimation and proportional reasoning, standardized scores were then reverse coded so that higher scores indicate more accurate performance. On spatial anxiety and reading anxiety, higher scores indicate higher levels of anxiety.
* $p < .05$. ** $p < .01$. *** $p < .001$.

.12, reading achievement, $t(365.27) = -1.12$, $p = .27$, Cohen's d = .11, or reading anxiety, $t(273.50) = -.17$, $p = .86$, Cohen's $d = .02$.

The magnitude of the gender differences did not significantly change with grade level on number line estimation, proportional reasoning, or spatial anxiety ($ps > .067$). The gender difference in mental rotation was significantly moderated by grade level, $\beta = -.19$, $SE = .09$, $p = .44$, such that the gender difference was larger at younger ages. However, the interaction between gender and grade level on mental rotation was no longer significant when we excluded kindergarteners (the only grade level who completed the Ghost Puzzle rather than the Letter Rotation task as the measure for mental rotation), $\beta = -.13$, $SE = .10$, $p = .191$.

Mediators of Gender Differences in Number Line Estimation

Spatial Skill Measures as a Latent Variable

We first used confirmatory factor analyses to evaluate a measurement model of a spatial skill latent variable represented by proportional reasoning, mental rotation, mental transformation, and visuospatial working memory. The model achieved an excellent fit, $\chi^2(2) = 4.26$, $p = .119$ (CFI = .98, TLI = .95, and RMSEA = .05). We then proceeded to fit a structural model with the spatial skill latent variable and spatial anxiety as mediators of the gender difference in T2 number line estimation (Model 1). Model fit was acceptable, $\chi^2(12) = 27.56$, $p = .006$ (CFI = .94, TLI = .89, and RMSEA = .05). Because allowing the correlation between spatial skill and spatial anxiety to be freely estimated did not improve model fit, we proceeded with the model not including the correlation between the two.

Table 3 shows standardized estimates of the factor loadings and path coefficients for the models with the spatial latent factor as mediator. The total effect of gender on T2 number line estimation was β = .41, 95% CI [.22, .60]. Spatial skill significantly mediated this effect (indirect effect $\beta = .21$, 95% CI [.05, .41]), leaving the direct effect of gender on T2 number line estimation no longer significant (β = .19, 95% CI [−.02, .39]). Spatial anxiety was not a significant mediator (indirect effect $\beta = .01$, 95% CI [−.01, .05]).

We then examined whether spatial skill and spatial anxiety mediated the gender difference in T2 number line estimation, above and beyond number line estimation at T1 (Model 2). Adding T1 number line estimation as a covariate, the model fit was good, $\chi^2(16) = 37.59$, $p = .002$ (CFI = .96, TLI = .92, and RMSEA = .05; see Table 3 for parameter estimates). T1 number line estimation was a significant mediator of this effect, indirect effect $\beta = .21$, 95% CI [.11, .34]. Spatial skill remained a significant mediator, indirect effect $\beta = .14$, 95% CI [.03, .31] whereas spatial anxiety was not, indirect effect $\beta = .004$, 95% CI [−.01, .03]. The direct effect of gender on T2 number line estimation was no longer significant, $\beta = .05$, 95% CI [−.11, .22].

Finally, we added reading achievement and reading anxiety as additional covariates (Model 3; Figure 2). Model fit was excellent with CFI = .98, TLI = .95, and RMSEA = .04; $\chi^2(22) = 40.47$, p = .010; see Table 3 for parameter estimates.[3] Spatial skill (indirect effect $\beta = .13$, 95% CI [.03, .33]) and T1 number line estimation (indirect effect $\beta = .20$, 95% CI [.10, .33]) remained significant mediators after accounting for reading achievement and reading anxiety, whereas spatial anxiety was not a significant mediator (indirect effect $\beta = .01$, 95% CI [−.01, .05]).

Spatial Skill Measures as Separate Mediators

To understand which specific spatial skills individually mediated the gender difference in number line estimation, we fit a path model with proportional reasoning, mental rotation, mental transformation, visuospatial working memory, and spatial anxiety as separate mediators of the effect of gender on T2 number line estimation performance (Model 4). The overall fit of the model was excellent, CFI = 1.00, TLI = 1.00, RMSEA = .00. The chi-square test was not significant, $\chi^2(4) = 2.91$, $p = .574$.

Table 4 shows the standardized estimates of path coefficients. The total effect of gender on T2 number line estimation was $\beta = .41$ (95% CI [.22, .60]). Estimates of the indirect effects showed that proportional reasoning ($\beta = .04$, 95% CI [.01, .09]) and mental rotation ($\beta = .03$, 95% CI [.01, .08]) significantly mediated the gender difference in T2 number line estimation, but mental transformation (β = .01, 95% CI [−.01, .05]), visuospatial working memory ($\beta = .03$, 95% CI [−.02, .09]), and spatial anxiety did not ($\beta = .02$, 95% CI [−.003, .05]). After accounting for the mediators, the direct effect of gender on number line estimation performance (path c') remained significant ($\beta = .27$, 95% CI [.10, .45]). Thus, the effect of gender on number line estimation was mediated via proportional reasoning and mental rotation but not mental transformation, visuospatial working memory, or spatial anxiety.

We then added T1 number line estimation as a covariate (Model 5). The overall fit of the model was ideal, CFI = 1.00, TLI = 1.00, RMSEA = .00. The chi-square test was not significant, $\chi^2(5)$ = 4.93, $p = .424$ (see Table 4 for standardized estimates of path coefficients). Unsurprisingly, T1 number line estimation significantly mediated the gender difference in T2 number line estimation (indirect effect $\beta = .29$, 95% CI [.19, .41]). Critically, after controlling for T1 number line estimation, proportional reasoning (indirect effect β = .02, 95% CI [.002, .06]) and mental rotation (indirect effect $\beta = .02$, 95% CI [.004, .06]) were still significant mediators of the gender gap in T2 number line estimation. Again, mental transformation (indirect effect $\beta = .004$, 95% CI [−.003, .03]), visual spatial working memory (indirect effect $\beta = .02$, 95% CI [−.01, .06], and spatial anxiety (indirect effect $\beta = .01$, 95% CI [−.01, .04]) were not. The direct effect of gender on T2 number line estimation was not significant ($\beta = .04$, 95% CI [−.11, .20]).

Finally, we added reading achievement and reading anxiety as covariates (Model 6; Figure 3). The model fit was excellent with CFI = .99, TLI = .96, and RMSEA = .04.[4] The chi-square test was not significant, $\chi^2(9) = 14.70$, $p = .100$ (see Table 4 for estimates of path coefficients). Again, T1 number line estimation (indirect effect β = .26, 95% CI [.17, .37]), proportional reasoning (indirect effect β = .02, 95% CI [.001, .05]), and mental rotation (indirect effect $\beta = .02$, 95% CI [.003, .06]) served as significant mediators whereas the

[3] In addition to correlations among cognitive skills and among motivation, the following correlations between mediators and covariates were set to be estimated in the model to improve model fit: reading achievement with reading anxiety, reading achievement with spatial anxiety, T1 number line estimation with reading anxiety, and spatial skill with reading anxiety.

[4] In addition to correlations among cognitive skills and among motivation measures, the following correlations between mediators and covariates were set to be estimated in the model to improve model fit: reading achievement with spatial anxiety, reading achievement with reading anxiety, and T1 number line estimation with reading anxiety.

Table 3
Standardized Estimates (and 95% Confidence Intervals) of Parameters and Indirect Effects in SEM Models With Spatial Skill Latent Variable

Parameters	Model 1 Parameter estimate [95% CI]	Model 2 Parameter estimate [95% CI]	Model 3 Parameter estimate [95% CI]
Spatial skill (factor loadings)			
Proportional reasoning	**0.41 [0.31. 0.52]**	**0.44 [0.34, 0.54]**	**0.45 [0.35, 0.54]**
Mental rotation	**0.44 [0.33, 0.55]**	**0.40 [0.29, 0.52]**	**0.39 [0.28, 0.50]**
Mental transformation	**0.54 [0.40, 0.68]**	**0.52 [0.37, 0.66]**	**0.51 [0.36, 0.65]**
Visuospatial working memory	**0.52 [0.41, 0.63]**	**0.54 [0.43, 0.64]**	**0.55 [0.45, 0.65]**
On gender (*a* paths)			
Spatial skill	**0.31 [0.06, 0.57]**	**0.31 [0.06, 0.57]**	**0.31 [0.06, 0.56]**
Spatial anxiety	−0.21 [−0.41, 0.004]	−0.21 [−0.41, 0.004]	−0.21 [−0.41, 0.01]
T1 number line estimation		**0.55 [0.37, 0.72]**	**0.55 [0.37, 0.73]**
Reading achievement			0.09 [−0.11, 0.28]
Reading anxiety			−0.03 [−0.26, 0.19]
T2 number line estimation on (*b* paths)			
Spatial skill	**0.66 [0.50, 0.80]**	**0.43 [0.25, 0.64]**	**0.41 [0.20, 0.70]**
Spatial anxiety	−0.06 [−0.16, 0.04]	−0.02 [−0.10, 0.07]	−0.03 [−0.15, 0.07]
T1 number line estimation		**0.38 [0.19, 0.53]**	**0.37 [0.19, 0.51]**
Reading achievement			0.08 [−0.13, 0.23]
Reading anxiety			0.04 [−0.09, 0.10]
T2 number line estimation on gender (*c'*)	0.19 [−0.02, 0.39]	0.05 [−0.11, 0.22]	0.06 [−0.10, 0.20]
Indirect effect via			
Spatial skill	**0.21 [0.05, 0.41]**	**0.14 [0.03, 0.31]**	**0.13 [0.03, 0.33]**
Spatial anxiety	0.01 [−0.01, 0.05]	0.004 [−0.01, 0.03]	0.01 [−0.01, 0.05]
T1 number line estimation		**0.21 [0.11, 0.34]**	**0.20 [0.10, 0.33]**
Reading achievement			0.01 [−0.01, 0.0]
Reading anxiety			−0.001 [−0.03, 0.01]

Note. T1 = time-point 1; T2 = time-point 2; SEM = structural equation modeling. Parameter estimates and indirect effects that significantly differed from zero were bolded.

mental transformation, visuospatial working memory, and spatial anxiety did not. The direct effect of gender on T2 number line estimation was not significant ($\beta = .06$, 95% CI [−.10, .21]).

Robustness Checks

We conducted several robustness checks to examine whether the results were attributable to idiosyncrasies of how certain skills were measured or how certain variables were treated in the analyses. We conducted these robustness checks by adjusting Models 3 and 6, which included all covariates. We present model results in online supplemental materials Section E, Figures S1–S6, and summarize them briefly here.

First, to address the issue of grade level adjustment, we reran Models 3 and 6 by excluding kindergarteners (who completed different tasks), using the unstandardized task scores (with PAEs on the number line arcsine transformed and reverse coded), and controlling for grade level (instead of standardizing task scores within each grade). We found that the spatial skill latent variable significantly mediated the gender difference in T2 number line estimation. However, the model with individual spatial skills did not yield any significant mediators (see online supplemental materials, Section E, Figures S1 and S2).

Second, to address the issue that proportional reasoning was measured by a task with a similar response format as number line estimation, we reran Models 3 and 6 while excluding proportional reasoning. The results showed that the spatial skill latent variable significantly mediated the gender difference in T2 number line estimation, and mental rotation was a significant mediator in the model with individual spatial skills (see online supplemental materials, Section E, Figures S3 and S4).

Finally, to address the issue of the scoring of proportional reasoning and number line estimation, we reran Models 3 and 6 using the untransformed PAE scores (not arcsine transformed PAE but standardized and reverse coded) for these two tasks. The results showed that the spatial skill latent variable significantly mediated the gender difference in T2 number line estimation. In the model with individual spatial skills, mental rotation, but not proportional reasoning, was a significant mediator (see online supplemental materials, Section E, Figures S5 and S6).

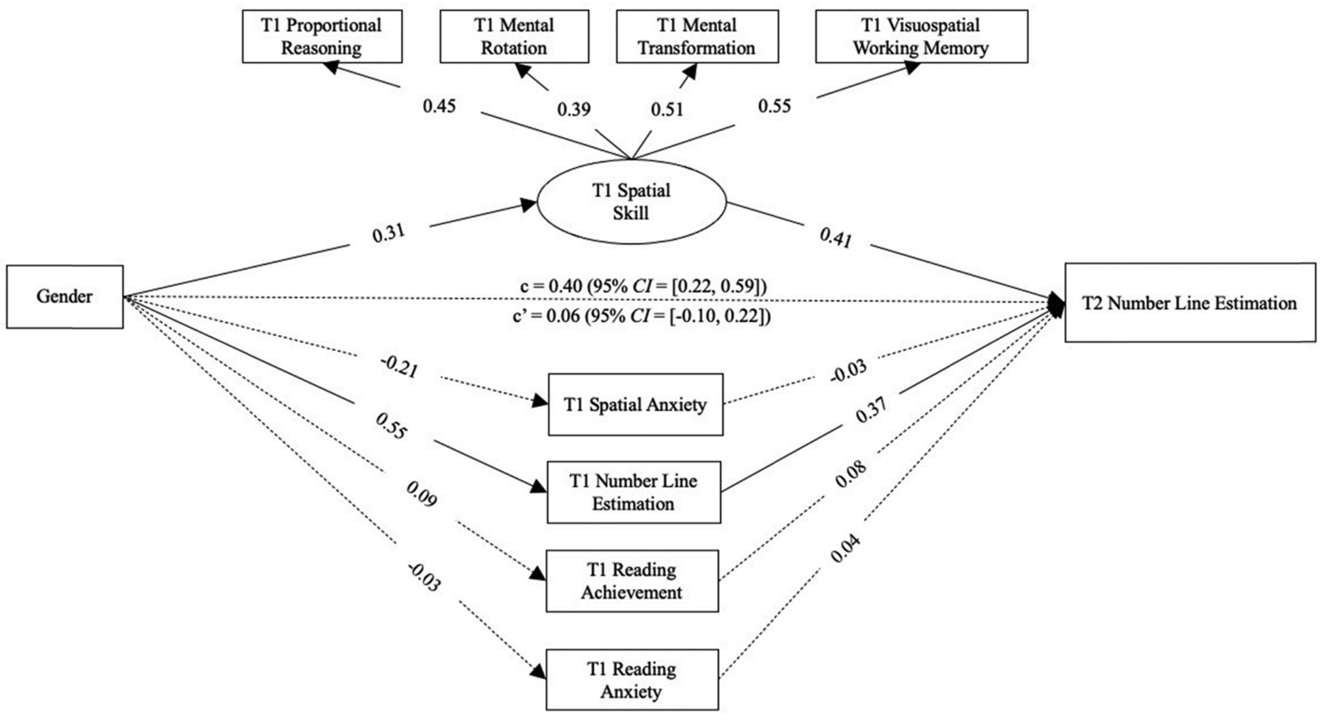
Exploratory Analyses—The Moderating Role of Grade Level

To explore whether the indirect effects of gender on number line estimation via spatial skill and spatial anxiety differed depending on grade level, we fit moderated mediation models with grade level as a continuous moderator. The moderated mediation model involving the spatial skill latent variable did not converge. Given that modification of the model was not of theoretical interest, we did not modify it.

The moderated mediation model with the four spatial skills and spatial anxiety as separate mediators achieved good fit, CFI = .96, TLI = .94, and RMSEA = .08; $\chi^2(39) = 151.33$, $p < .001$. Results showed that grade significantly moderated the path from gender to mental rotation and the direct path from gender to number line estimation; no other moderating effects of grade were significant (see online supplemental materials, Section F, Table S2 for details of the moderated mediation model).

To further explore how grade level moderated the effect of gender on mental rotation and the direct path from gender to T2 number line estimation, we fit Model 4 in Table 4 separately for each grade level. Results showed that the gender effect on mental

Figure 2
Model 3, Gender Difference in Number Line Estimation With Spatial Skill as a Latent Variable



Note. Gender was treated as a binary variable with girls = 0 and boys = 1. Solid lines indicate significant paths, and dashed lines indicate nonsignificant paths. Correlations are omitted in the figure for simplicity. Paths are labeled with standardized parameter estimates. T1 = time-point 1; T2 = time-point 2.

rotation was stronger in early grades and was only significant among kindergartners (kindergartners, β = .52, 95% CI [.07, .96]; first graders, β = .34, 95% CI [−.02, .71]; second graders, β = .10, 95% CI [−.34, .50]; third graders, β = .21, 95% CI [−.19, .58]; and fourth graders, β = −.18, 95% CI [−.69, .30]). These results were consistent with those of our primary analyses of gender differences by grade level on each task separately, which also showed a Gender × Grade interaction only on mental rotation.

Path models for each grade level also revealed that the direct effect of gender on T2 number line estimation was smaller in earlier grades. The effect was not significant among kindergartners and first graders but was significant among second through fourth graders (kindergartners, β = −.27, 95% CI [−.77, .30]; first graders, β = .19, 95% CI [−.14, .55]; second graders, β = .47, 95% CI [.09, .88]; third graders, β = .38, 95% CI [.01, .76]; and fourth graders, β = .50, 95% CI [.07, 1.04]). See online supplemental materials, Section F, Figures S7–S11 for details of these grade-level-specific mediation models.

Discussion

Recently, several studies have documented that males estimated whole numbers more accurately on number lines than females (Bull et al., 2013; Gunderson et al., 2012; Hutchison et al., 2019; Reinert et al., 2017; Thompson & Opfer, 2008). The current study provides, to our knowledge, the first direct evidence regarding factors contributing to the gender difference in number line estimation involving whole numbers and also to the development of this gender difference over time (i.e., over roughly a 5-month period in the current study). We found that among children from kindergarten through fourth grade, spatial skills, particularly proportional reasoning, and mental rotation (measured at T1), mediated boys' advantage in number line estimation measured 5 months later (T2), whereas T1 spatial anxiety did not. These results remained even after controlling for T1 number line estimation, reading achievement, and reading anxiety.

An important finding of the current study is that among children from kindergarten to fourth grade, boys were more accurate on number line estimation than girls. This finding adds to the increasing evidence on this matter with a racially diverse sample. Moreover, the magnitude of this gender difference did not change with grade level. This contradicts Hutchison et al.'s (2019) finding that boys' advantage on number line estimation decreased between Grades 1 and 6. One reason for the discrepancy between the two studies might be that boys are more likely to show superior performance than girls when the number line estimation task is challenging. Although the two studies used the same number line estimation tasks (i.e., 0–100 and 0–1000), these tasks were likely to be less challenging for the participants in Hutchison et al. (2019), who were older than those in the current study (Grades 1–6 vs. kindergarten–fourth grade). This view is also supported by the findings that among adults, men outperformed women on a 0–1,000 number line estimation task (Bull et al., 2013) but not with a presumably less challenging 0–50 number line estimation (Reinert et al., 2017).

More importantly, we found that the spatial skill latent variable (T1) mediated the gender difference in later number line estimation (T2) and

Table 4
Standardized Estimates (and 95% Confidence Intervals) of Parameters in SEM Models With Spatial Skills as Separate Mediators

Parameters	Model 4 Parameter estimate [95% CI]	Model 5 Parameter estimate [95% CI]	Model 6 Parameter estimate [95% CI]
On gender (*a* paths)			
Proportional reasoning	**0.21 [0.02, 0.38]**	**0.21 [0.02, 0.38]**	**0.21 [0.02, 0.38]**
Mental rotation	**0.21 [0.03, 0.40]**	**0.21 [0.03, 0.40]**	**0.21 [0.03, 0.40]**
Mental transformation	0.11 [−0.08, 0.30]	0.11 [−0.08, 0.30]	0.11 [−0.07, 0.30]
Visuospatial working memory	0.11 [−0.07, 0.30]	0.12 [−0.07, 0.30]	0.12 [−0.07, 0.30]
Spatial anxiety	−0.21 [−0.41, 0.002]	−0.21 [−0.41, 0.004]	−0.21 [−0.41, 0.01]
T1 number line estimation		**0.55 [0.37, 0.72]**	**0.55 [0.37, 0.73]**
Reading achievement			0.09 [−0.11, 0.28]
Reading anxiety			−0.02 [−0.25, 0.20]
T2 number line estimation on (*b* paths)			
Proportional reasoning	**0.21 [0.13, 0.31]**	**0.10 [0.02, 0.19]**	**0.09 [0.004, 0.17]**
Mental rotation	**0.15 [0.06, 0.24]**	**0.11 [0.04, 0.19]**	**0.10 [0.03, 0.18]**
Mental transformation	**0.11 [0.02, 0.20]**	0.03 [−0.04, 0.11]	0.02 [−0.06, 0.09]
Visuospatial working memory	**0.29 [0.19, 0.38]**	**0.16 [0.08, 0.24]**	**0.13 [0.05, 0.21]**
Spatial anxiety	−0.07 [−0.17, 0.03]	−0.02 [−0.11, 0.06]	−0.06 [−0.17, 0.05]
T1 number line estimation		**0.53 [0.44, 0.62]**	**0.48, [0.38, 0.58]**
Reading achievement			**0.18 [0.06, 0.30]**
Reading anxiety			0.06 [−0.06, 0.18]
T2 number line estimation on gender (*c'*)	**0.27 [0.10, 0.45]**	0.04 [−0.11, 0.20]	0.06 [−0.10, 0.21]
Indirect effect via			
Proportional reasoning	**0.04 [0.01. 0.09]**	**0.02 [0.002, 0.06]**	**0.02 [0.001, 0.05]**
Mental rotation	**0.03 [0.01, 0.0]**	**0.02 [0.004, 0.06]**	**0.02 [0.003, 0.06]**
Mental transformation	0.01 [−0.01, 0.05]	0.004 [−0.003, 0.03]	0.002 [−0.01, 0.02]
Visuospatial working memory	0.03 [−0.02, 0.09]	0.02 [−0.01, 0.06]	0.02 [−0.01, 0.05]
Spatial anxiety	0.02 [−0.003, 0.05]	0.01 [−0.01, 0.04]	0.01 [−0.01, 0.05]
T1 number line estimation		**0.29 [0.19, 0.41]**	**0.26 [0.17, 0.37]**
Reading achievement			0.02 [−0.02, 0.07]
Reading anxiety			−0.001 [−0.03, 0.01]

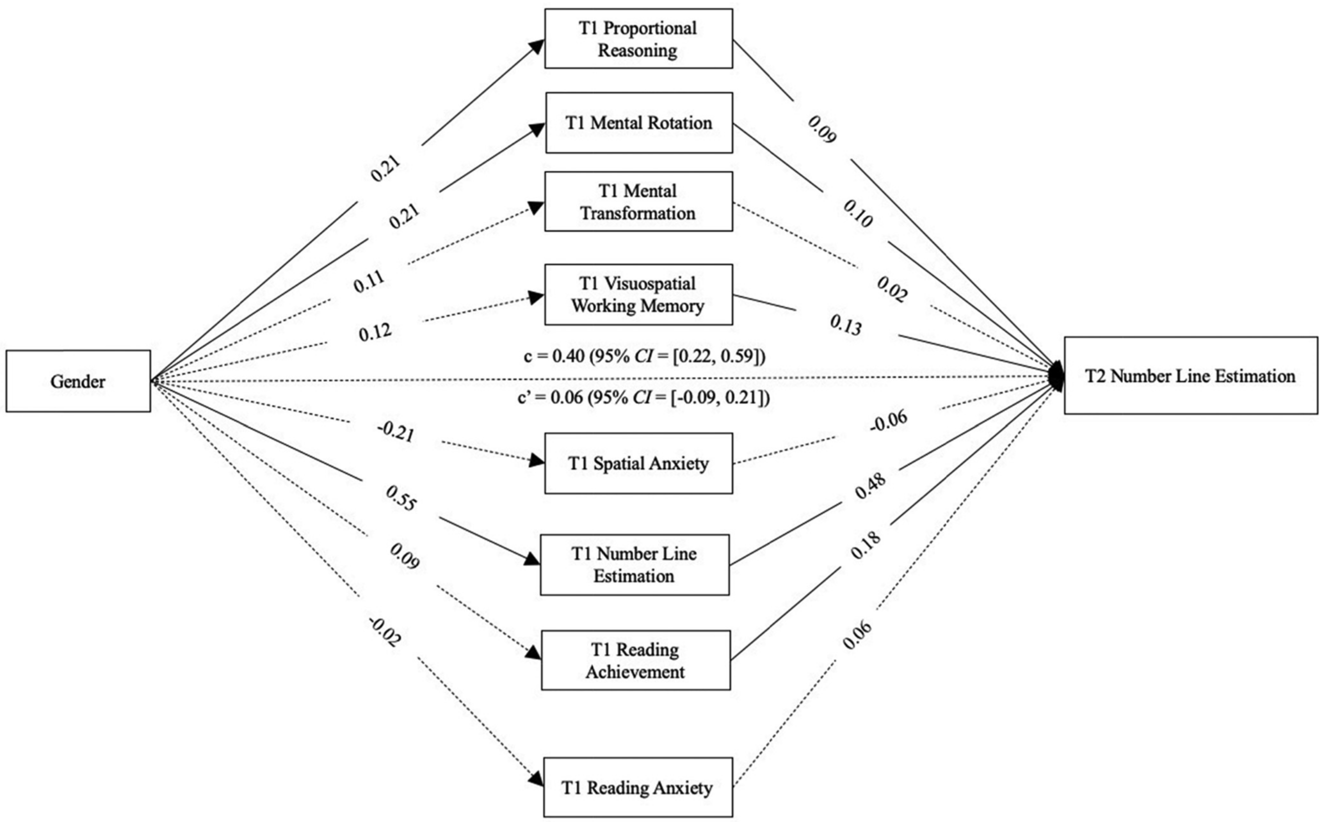
Note. T1 = time-point 1; T2 = time-point 2; SEM = structural equation modeling. Parameter estimates and indirect effects that significantly differed from zero were bolded.

remained a significant mediator even after controlling for T1 number line estimation, reading achievement, and reading anxiety. In previous research, proportional reasoning and mental rotation both correlated with number line estimation performance among children, suggesting that number line estimation recruits these spatial skills (Gunderson et al., 2012; Hansen et al., 2015; Simms et al., 2016). The reliable gender difference in spatial skills favoring boys has led many researchers to predict that the male advantage on number line estimation arises from males' greater spatial skills (Bull et al., 2013; Hutchison et al., 2019). The current findings provided the first direct evidence for this prediction on number line estimation involving whole numbers (see Geary et al., 2021, for similar findings on fraction number line estimation). Moreover, spatial skill remained a significant predictor after controlling for concurrent number line estimation, suggesting that spatial skills not only contribute to the gender gap in number line estimation, but also to the development of that gap over time (i.e., over roughly a 5-month period in the current study).

Among the four spatial skills, we found that proportional reasoning and mental rotation were mediators of the gender difference in number line estimation, but mental transformation and visuospatial working memory were not. These results were not entirely as expected. Although we expected all four types of spatial skills to be involved in number line estimation, we predicted mental rotation and mental transformation to mediate the gender difference in number line estimation given the substantial prior evidence for a male advantage in these skills (Halpern et al., 2007; Levine et al., 2016, 1999; Linn & Petersen, 1985; Maeda & Yoon, 2013). In the current study, children's performance on all four spatial skills correlated with their performance on number line estimation as expected. However, gender differences were found on mental rotation and proportional reasoning and not on mental transformation or visuospatial working memory. We did not expect to find a gender difference in proportional reasoning because several prior studies with children of similar ages to those in the current study reported a lack of gender difference (Boyer et al., 2008; Ham & Gunderson, 2019; Hansen et al., 2015; Möhring et al., 2018, 2015). This discrepancy might be attributable to the specific tasks used to measure proportional reasoning, given that most prior studies assessed proportional reasoning with a matching task, in which children were asked which of two proportions matched a target proportion (Boyer et al., 2008; Ham & Gunderson, 2019; Hansen et al., 2015), whereas we used an estimation task. Moreover, some studies using different proportional reasoning tasks and with older students have found better proportional reasoning among boys than girls (Linn & Pulos, 1983; Sophian & Wood, 1997). Additionally, we did not find any evidence for the expected gender differences in mental transformation, which might be attributable to the low internal consistency of this measure in the current study (Cronbach's α ranged from .40 to .69 across the five grade levels).

Our mediation analyses within each grade level suggest that the gender difference in number line estimation remained unexplained in some grade levels after considering the effect of spatial skills and spatial anxiety. These remaining effects suggest that other accounts may also contribute to the boys' advantage in number

Figure 3
Model 6, Gender Difference in Number Line Estimation With Four Spatial Skills as Separate Mediators



Note. Gender was treated as a binary variable with girls = 0 and boys = 1. Solid lines indicate significant paths, and dashed lines indicate nonsignificant paths. Correlations are omitted in the figure for simplicity. Paths are labeled with standardized parameter estimates. T1 = time-point 1; T2 = time-point 2.

line estimation. One possible account is that boys possess a more accurate mental representation of numbers than girls. Evidence for males' higher acuity in numerical representation has been reported among college students (Bull et al., 2013). However, Kersey et al.'s (2018) analyses of over 500 children aged between 6 months and 8 years revealed no substantial gender differences in numerosity perception and counting. Another possibility is that boys tend to use strategies yielding more accurate number line estimates than girls. While prior studies have found that both children and adults adopt a range of number line estimation strategies that vary in their effectiveness (Ashcraft & Moore, 2012; Peeters et al., 2017; Petitto, 1990; Schneider et al., 2008), it is unclear whether boys and girls differ in strategy choices on number line estimation of whole numbers in early elementary school. Among sixth graders on a fraction number line estimation task, Geary et al. (2021) recently found a gender difference in estimation accuracy but not strategy use. Nevertheless, investigating gender differences in young children's strategies of number line estimation with whole numbers may be a fruitful direction for future research. However, given that the sample size in our analyses within each grade level were relatively small for path analyses (Kline, 2015), these results should be interpreted with caution.

Our results showed that spatial anxiety did not mediate the gender difference in number line estimation. One possible reason is that the spatial anxiety scale in the present study assessed children's feelings about spatial tasks that are distinctive from the number line estimation task. For example, the scale asked how children felt about solving a maze, giving directions, and building with LEGOs (Ramirez et al., 2012). These spatial activities have very different characteristics than the number line estimation task. It is possible that children in the present study viewed the number line estimation task as a math task, and their spatial anxiety was not elicited. Moreover, prior research reported domain specificity of spatial anxiety and math anxiety. Children between Grades 1 and 5 showed that spatial anxiety was associated with lower spatial but not math performance (Lauer, Esposito, & Bauer, 2018).

Limitations

One limitation of the current study is its correlational nature. Although the mediation analysis provides evidence consistent with a mechanistic account of the gender differences in number line estimation, no causal inferences should be made. The causal relations among gender, spatial skills, and number line estimation skills need to be established with experimental studies in the future, for example, by examining whether an intervention that reduces the gender gap in spatial skills also reduces the gender gap in number line estimation.

Another limitation is that we only examined four spatial skills, and our mental transformation measure had only moderate internal consistency. Spatial skills are multifaceted in nature. There are presumably other spatial skills contributing to the gender gap in number line estimation that were not measured in the current study. For example, spatial scaling, the ability to relate distance in one space to distances in another space, correlated with number line knowledge among 5- to 7-year-old children after controlling for age, counting skills, and proportional reasoning (Möhring et al., 2018). Geary et al. (2021) recently reported that visuospatial attention was associated with fraction number line estimation and mediated the boys' advantage in fraction number line estimation. Moreover, as mentioned above, the low reliability of our mental transformation measure might be a reason for it not to be a significant mediator in the current study. Whether these (and possibly other) spatial skills also contribute to the gender difference in number line estimation should be explored in future research.

Finally, our sample only included children between kindergarten and fourth grade. Given that some studies have found that the magnitude of gender differences in number line estimation and spatial skills change with age (Hutchison et al., 2019; Lauer, Ilksoy, & Lourenco, 2018), it is possible that the relation between them changes with age as well. Future research is needed to examine whether spatial skills explain the gender differences in number line estimation among older children and adults.

Conclusion

The present study adds to the increasing literature on the gender difference in number line estimation in childhood, a skill critical for later math achievement. For the first time, we showed spatial skills mediated the gender difference in number line estimation with whole numbers 5 months later, even after controlling for concurrent number line estimation, reading achievement, and reading anxiety. However, spatial anxiety was not a significant mediator. Specifically, we found that proportional reasoning and mental rotation (but not mental transformation or visuospatial working memory) served as significant mediators of the gender difference in later number line estimation. We conclude that boys possessing more proficient spatial skills than girls contributed to the later gender difference in number line estimation and the development of this gender difference over time. These findings are the first to provide direct evidence for factors contributing to the gender difference in number line estimation involving whole numbers. Practically, these findings have important implications for reducing the gender gap in number line estimation: training on spatial skills may simultaneously benefit girls' spatial and numerical skills.

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