

Unbounded Number Line Estimation as a Mechanism Linking Spatial Skills and Mathematical Performance in Adults

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Abstract

Spatial skills are robustly associated with mathematical performance, yet the cognitive mechanisms underlying this relationship in adults remain poorly understood. The present research examined whether unbounded number line estimation mediates the association between spatial skills and mathematical performance in adults. Ninety (90) undergraduate students completed measures of spatial visualization, mental rotation, algebra, fractions, arithmetic, and unbounded number line estimation. Results indicated that spatial skills significantly predicted mathematical performance and that unbounded number line estimation indirectly mediated this relationship across all three mathematical domains. These findings extend spatial representation theory to adulthood, suggesting that stronger spatial skills may support the construction of more precise internal representations of numerical magnitude, which in turn facilitate mathematical proficiency.

Keywords

spatial cognition, mathematical achievement, magnitude representation, unbounded number line estimation, numerical cognition

Extensive research has consistently demonstrated a robust association between spatial abilities and mathematical performance, with individuals exhibiting stronger spatial reasoning skills often outperforming peers in mathematics (Atit et al., 2022; Hawes et al., 2022; Xie et al., 2020). Spatial skills are also malleable, meaning they can improve



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through training, and some studies suggest that enhancing spatial abilities can positively influence mathematical performance (Cheng & Mix, 2014; Hawes et al., 2022). However, studies examining whether improvement in spatial skills through spatial training could transfer to mathematical outcomes provide mixed findings, with some studies reporting limited or no evidence for direct transfer effects from spatial training to mathematical gains (Hawes et al., 2015; Miller & Halpern, 2014; Mix & Chen, 2016; Uttal et al., 2013). These inconsistencies highlight the need to clarify the cognitive mechanisms linking spatial and mathematical skills.

One prominent theoretical framework addressing this relationship is the spatial-numerical representation account, which posits that numerical magnitude is internally represented along a mental number line (MNL; Hawes & Ansari, 2020). Supporting this theory, Gunderson et al. (2012) found that early spatial skills predicted improvements in number line estimation, which in turn forecasted later math performance. Similarly, Tam et al. (2019) reported that number line estimation mediated the relationship between spatial visualization and performance on calculation and word problem tasks in children. While these findings suggest a developmental trajectory in which spatial skills support mathematical achievement through magnitude estimation, other studies report contradictory results. For example, Frick (2019) did not observe a significant mediating role for number line estimation in the relationship between spatial skills and early mathematical performance.

Previous research has predominantly used the bounded number line estimation task, which requires participants to position numbers along a fixed numerical range. However, performance on the bounded number line estimation tasks may be highly influenced by proportion-based strategies rather than reflecting direct numerical magnitude representation (Barth & Paladino, 2011; Cohen & Blanc-Goldhammer, 2011; Cohen & Sarnecka, 2014; Link et al., 2014; Sullivan & Barner, 2014). The unbounded number line task was developed to address this limitation by removing fixed endpoints and emphasizing intuitive magnitude estimation. The unbounded number line task reduces reliance on learned reference points and is thought to provide a measure of numerical estimation ability more closely aligned with magnitude representation (Reinert et al., 2015, 2019; Reinert & Moeller, 2021).

Despite evidence supporting the unbounded number line as a measure of magnitude representation, no study has examined whether number line estimation mediates the relationship between spatial and mathematical skills in adults. Investigating this relationship in mature cognitive systems is important, as adult cognitive strategies and consolidated spatial-numerical mappings may influence how spatial skills interact with mathematics, particularly for advanced domains such as algebra (Xie et al., 2020). Moreover, although the spatial-mathematical link is well-established in children and adolescents, the strength and nature of this association in adults remain less clear (Atit et al., 2022; Hawes et al., 2022; Xie et al., 2020).

Present Study

The present study investigates the role of number line estimation in the relationship between spatial skills and mathematical performance in an adult sample, focusing on the unbounded number line task as a potential mediator. Specifically, the study addresses the following research questions:

- a. How are spatial skills related to performance across advanced mathematical domains in adults?
- b. Does numerical magnitude representation, measured by the unbounded number line task, mediate the relationship between spatial and advanced mathematical skills in adults?

By addressing these questions, the study seeks to clarify the cognitive mechanisms linking spatial and mathematical skills in adulthood and refine theoretical models of numerical cognition.

Method

Participants

Ninety-two (92) undergraduate students from a mid-sized university in Atlantic Canada participated in this study (28 males, 64 females; *Mean age* = 21.00, *SD* = 1.79). Participants were compensated with course credit or \$20 for their participation. As a result of the COVID-19 lockdown, two participants did not complete all measures, and their data were removed from further analysis. Thus, the data from only 90 participants were included in the final analysis. This study was reviewed and approved by the Research Ethics Board at the university in question.

Measures

Spatial Skill Tasks

Spatial skills were assessed using mental rotation and spatial visualization. Within the categorization of spatial skills provided by [Newcombe and Shipley \(2015\)](#), mental rotation falls under intrinsic-dynamic spatial skill, involving mental manipulation such as rotation of objects. On the other hand, spatial visualization can be classified as an intrinsic-static spatial skill involving static visualization, such as imagining how objects fold or unfold. These areas of spatial skill have previously been found to be related to basic arithmetic and algebra ([Frick, 2019](#); [Haciomeroglu, 2015](#); [Georges et al., 2019](#)).

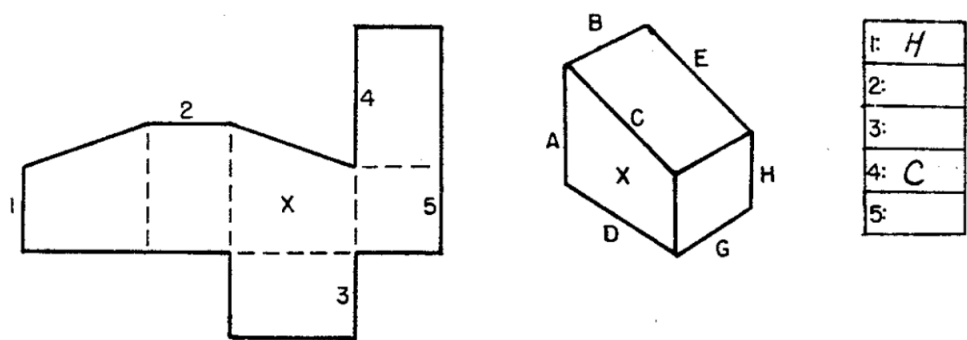
Mental Rotation Test (MRT) — The revised Mental Rotation Test ([Vandenberg & Kuse, 1978](#), and modified by [Peters et al., 1995](#)) was used to assess mental rotation. This 24-item

measure presented five figures per item. Each item comprised a separate figure on the left and four figures on the right. All four figures on the right-hand side differ in terms of orientation. Two of the four figures on the right are the same as the first figure on the left side but have been rotated around the vertical axis of the left figure. Participants were required to identify the two forms among the four figures on the right, which were the same as those on the left. One point was awarded for each pair of correctly identified figures, and 0 for incorrect pairs. The maximum and minimum scores are 24 and 0, respectively. Higher scores indicate higher mental rotation skills. The internal consistency of this measure is high (Cronbach's alpha = 0.85).

Spatial Visualization: Surface Development Test (SDT) — Spatial visualization was assessed using a Surface Development Test (SDT). This measure, developed by Ekstrom et al. (1976), contained 12 items, each consisting of a pair of net and solid shapes. Participants were required to match the edges of the net shape to those of the solid shape when the shape was folded along the dotted lines of the net figure. To complete the test, participants had to visualize the open and closed forms of the shapes and match the numbers on the net to the letters on the solid shapes. See Figure 1 for a sample item. One point was awarded for a correct match, and zero for an incorrect match. To correct for guessing, for each participant, a fraction of their incorrect answers was subtracted from their correct answers (total correct answers - 1/5 of the total incorrect answers). High scores indicate better performance, and low scores indicate poor performance. The internal consistency (Cronbach's alpha) was 0.89.

Figure 1

Sample of Surface Development Task



Note. The side of the flat piece marked with the X will always be the same as the side of the object marked with the X. Therefore, the paper must always be folded so that the X will be on the outside of the object.

Mathematical Skills: Math Placement Test (MPT)

The mathematical skills of the participants were evaluated using a paper-and-pencil test taken from the Mathematical Placement Test (MPT). The MPT is a diagnostic test of basic mathematics skills administered by the Department of Mathematics and Statistics at the university where this study was conducted. Mathematics educators designed it to assess competence levels in varied core areas of mathematics, covering up to at least 12th grade. A total of 45 items were selected from the MPT question pool. These items were subsequently grouped into four mathematical domains: fractions, algebra, geometry, and arithmetic. To ensure that the items were correctly grouped into their respective mathematical domains, two of the co-authors of this study and a graduate student were asked to independently classify the items into fractions, algebra, geometry, and arithmetic. The inter-rater agreement was 100%, indicating that each rater classified items in the same mathematical domain. Sixteen (16) items were classified as fractions, 10 as algebra, 14 as arithmetic, and 5 as geometry questions.

These questions were multiple-choice that required participants to solve the problem and then select the correct answer from four options (a-d). This means that participants required conceptual and procedural knowledge in each mathematical domain. For the arithmetic items, participants were asked to perform arithmetic computations and choose the simplified answer (e.g., simplify $10 + 325 + 14 + 61 = ?$). Similarly, for the fraction items, participants were required to perform arithmetic computations on multiple fractions, including decimals (e.g., to simplify and reduce to the lowest term: $(1/3) \times ((1/2) \times 6)$). The algebra required finding variables in algebraic equations (for example, if $5v + 3 = 2v - 3$, then $v = ?$). The participants were shown various model figures comprising triangles, rectangles, and circles for the geometry items. They were then asked to determine the areas and perimeters of specified parts of the figures. In addition, participants were not allowed to use a calculator but used their own computational and mathematical knowledge. Thus, these items assessed the comprehensive proficiency of each domain.

The percentage of correct responses was determined for each domain, where a higher percentage represented higher scores. Cronbach's alpha was calculated for each of the four subscales. Arithmetic ($\alpha = .68$), fractions ($\alpha = .78$), and algebra ($\alpha = .63$) demonstrated acceptable to good reliability. However, the geometric measure demonstrated poor reliability ($\alpha = .24$) and was removed from the structural equation model.

Number Line Estimation Task

The unbounded number line estimation task was adopted from Reinert et al. (2015). Participants were required to place a given number on a number line with a starting point and no endpoint, using a unit measurement as a guide (see Figure 2). There were 20 empty lines, each measuring 23 cm in length. Participants placed 20 target numbers (55, 112, 18, 71, 66, 32, 96, 103, 13, 23, 67, 60, 36, 39, 105, 52, 22, 53, 84, 42) on the lines, corresponding to unit guides of 4, 8, 3, 6, 7, 4, 8, 7, 6, 3, 4, 6, 8, 3, 7, 4, 3, 8, 6, 7, respectively,

across the 20 trials. The varying unit guides were intended to prevent participants from relying on a consistent scale, encouraging intuitive magnitude estimation rather than calculation-based strategies, as noted by Reinert et al. (2015). All target numbers were within the psychological range of their respective unit guides, ensuring no theoretically impossible trials.

Figure 2

Sample of Unbounded Number Line Estimation Task



Each page contained three items, except for the final page, which had two, and the starting points of the lines were staggered to ensure participants did not use the line lengths of other items as a reference. This design, along with presenting tasks on separate pages and varying unit guides across items (e.g., unit values of 4, 8, 3 on a single page), minimized the risk of interference from multiple number lines on a single page and made it difficult for participants to use prior estimates as reference points due to the changing scale across items. To further confirm this, we examined estimation errors and found no significant decrease in error rates across items on each page ($p > .05$), suggesting that participants did not systematically use previous estimates as guides. Participants were instructed not to refer to previous responses, and the order of numbers was randomized to minimize systematic referencing patterns. Participants completed two training trials without receiving feedback on the accuracy of their responses and were not permitted to use physical means of measurement to place numbers on the lines (e.g., ruler or finger spacing).

Participants had three minutes to complete the task and were scored using the percent absolute error (PAE) principle [$PAE = (\text{estimated number} - \text{target}) / \text{scale} \times 100\%$, Booth & Siegler, 2008]. For example, placing 81 in place of 90 yielded a PAE of 6.96% [$((81-90)/115) \times 100$]. The mean PAE was computed for all 20 items, and the mean of these items was calculated to create an overall performance score. Higher scores on these tasks indicated more errors and poor performance. The internal consistency for this task was good (Cronbach's $\alpha = 0.82$). A bounded number line task was also administered but was excluded from the present analyses due to limited variability in adult performance and its misalignment with the study's theoretical focus on unbounded magnitude representation.

Deductive Logical Reasoning: Nonsense Syllogism Test

We adopted the Nonsense Syllogism Test developed by Ekstrom et al. (1976) to control for deductive logical reasoning as a proxy measure of general cognitive skill. Participants were required to complete formal syllogisms using nonsensical content for this task. For example, there were two preamble statements: a) all trees are fish, b) all fish are horses, and a conclusion: therefore, all trees are horses), made for each item. Participants were asked to identify whether the conclusions deduced from the two preamble statements were logical. If they believed the conclusion was logical, they selected good (denoted by G), and if it was not logical, they selected poor (denoted by P). There were 5 practice items and 30 items on this task, divided into two parts, each allotted four minutes. Participants' total score was converted to percentage points. High scores were indicative of high reasoning competence.

Procedure

Participants were tested individually in a quiet laboratory setting. The researcher provided instructions and answered questions before the participants began each task. The entire testing process took approximately two (2) hours and was divided into two sets in two 1-hour sessions held on separate days. The Surface Development Test, Mental Rotation, and the number line tasks were in Set 1, whereas the logical reasoning and Math Placement Test were in Set 2. Half of the participants completed Set 1 in their first session and Set 2 in their second session, whereas the other half completed Set 2 in their first session and Set 1 in their second session. All measurements were performed using a pencil and paper.

Analysis

Data were analyzed using RStudio (version 2024.12.1). The MVN package (version 5.9; Korkmaz et al., 2014) assessed multivariate normality, while the lavaan package (version 0.6-5; Rosseel, 2012) facilitated SEM and mediation analyses. A Mahalanobis multivariate test identified five outliers among the 90 participants ($Mah < 16.919$, $p < .05$), which were excluded, leaving data from 85 participants for the final analysis. A multivariate Mardia normality test indicated nonsignificant skewness (170.939, $p = .360$) but significant negative kurtosis (-2.023 , $p = .042$).

Using structural equation modelling, we examined the total effect of spatial skills on mathematical abilities, followed by the indirect effects with unbounded number line estimation as a mediator. To reduce model complexity, especially given our modest sample size, we treated the deductive logical reasoning task as an observed control variable in all models and unbounded number line estimation as an observed variable in Models 2 and 3. In Model 1, algebra, fractions, and arithmetic were entered as observed variables predicted by the latent variable spatial skills. Using a mix of latent and observed

variables in SEM is a common approach when balancing model complexity with sample size constraints (Cheung & Lau, 2008; Krause et al., 2010). Given the modest sample size, we employed a bootstrap procedure with 5,000 replications to estimate robust standard errors and confidence intervals (Efron & Tibshirani, 1993; Hayes, 2018; Kline, 2016; Preacher & Hayes, 2008).

According to Hu and Bentler (1999), good model fit selection criteria include a nonsignificant chi-squared (χ^2) test, Comparative Fit Index (CFI) $> .95$, Standardized Root Mean Residual (SRMR) $< .08$, and Root Mean Square Error of Approximation (RMSEA) $< .06$. However, given that the chi-square statistic is highly sensitive to sample size, especially in small samples in this study, and minor model misspecification, emphasis was placed on alternative fit indices (CFI, RMSEA, SRMR) when evaluating model adequacy (Hu & Bentler, 1999; Kline, 2016). All reported estimates (b) are standardized values.

Results

Table 1 presents the results of the descriptive statistics. Table 2 displays the zero-order correlations among mathematical skills, spatial abilities, the unbounded number line estimation task, and logical reasoning. As expected, the mathematical domains (fractions, arithmetic, and algebra) were positively and significantly correlated, reflecting shared underlying competencies in symbolic numerical processing. Spatial visualization demonstrated significant associations with all three mathematical domains, while mental rotation was significantly related to algebra and logical reasoning. These findings are consistent with prior research linking spatial ability to various aspects of mathematical performance. The unbounded number line estimation task exhibited significant correlations with all mathematical outcomes as well as both spatial measures, suggesting its relevance to both spatial reasoning and mathematical achievement. Deductive logical reasoning was modestly associated with arithmetic and mental rotation but showed no significant correlations with the other variables. Given the low reliability of the geometry measure (Cronbach's $\alpha = 0.24$), geometry was also excluded from the SEM analysis to ensure result reliability.

To address the first research question, we tested whether spatial skills were associated with these advanced mathematical abilities in Model 1. A latent spatial skills factor was constructed from two indicators: mental rotation and spatial visualization. This latent variable was used to predict performance in algebra, fractions, and arithmetic, while controlling for deductive logical reasoning. A bootstrap procedure with 5,000 replications was applied to account for non-normality and a small sample size. As shown in Figure 3, the model demonstrated generally acceptable fit based on CFI and SRMR, although RMSEA exceeded conventional thresholds ($\chi^2(5, N = 85) = 10.33, p = .07$, CFI = .97, RMSEA = .11, SRMR = .07). These results indicate that spatial skills significantly predict mathematical performance, even after accounting for deductive logical reasoning.

Table 1
Descriptive Statistics (N = 85)

Measure	M	SD	Min	Max	Skewness
Fraction	64.6	23.3	12.5	100.0	-0.2
Arithmetic	74.0	18.3	21.4	100.0	-0.6
Algebra	71.5	22.4	10.0	100.0	-0.6
Geometry	54.4	24.4	0.0	100.0	-0.2
Mental rotation	13.5	5.0	3.0	23.0	-0.1
Spatial visualization	35.7	11.8	12.2	56.7	-0.1
UNL	9.7	3.4	2.0	21.4	0.4
Logical Reasoning	56.2	12.7	20	80.0	-0.2

Note. UNL is an Unbounded Number Line task and is reported as the mean Percent Absolute Error (PAE). All mathematical domains and logical reasoning tests were scored as percentage correct. Spatial visualization included a correction factor (total correct answers - 1/5 of the total incorrect answers) to control chance guessing, and mental rotation was the total correct response out of the 24 items.

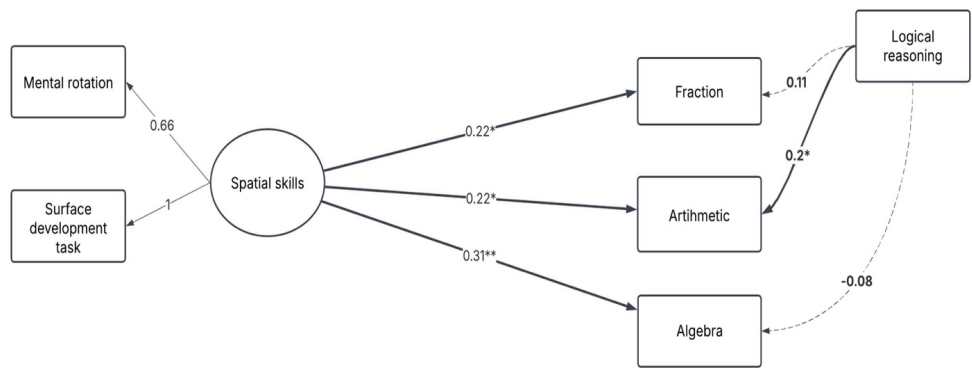
Table 2
Zero-Order Correlations Among the Variables (N = 85)

Measure	1	2	3	4	5	6	7	8
1. Fraction	–							
2. Arithmetic	.70***	–						
3. Algebra	.59***	.52***	–					
4. Geometry	.38***	.27*	.21	–				
5. Spatial Visualization	.24*	.24*	.31**	.04	–			
6. Mental Rotation	.21	.20	.27*	.12	.65***	–		
7. UNL	-.35***	-.32**	-.47***	-.13	-.44***	-.29**	–	
8. Logical Reasoning	.14	.23*	.09	-.09	.14	.26*	-.21	–

Note. UNL is an unbounded number line estimation task. Logical reasoning is measured by deductive logical reasoning task.
p* < .05. *p* < .01. ****p* < .001.

Figure 3

Model 1. Path Diagram Showing the Relationship Between Spatial and Mathematical Skills

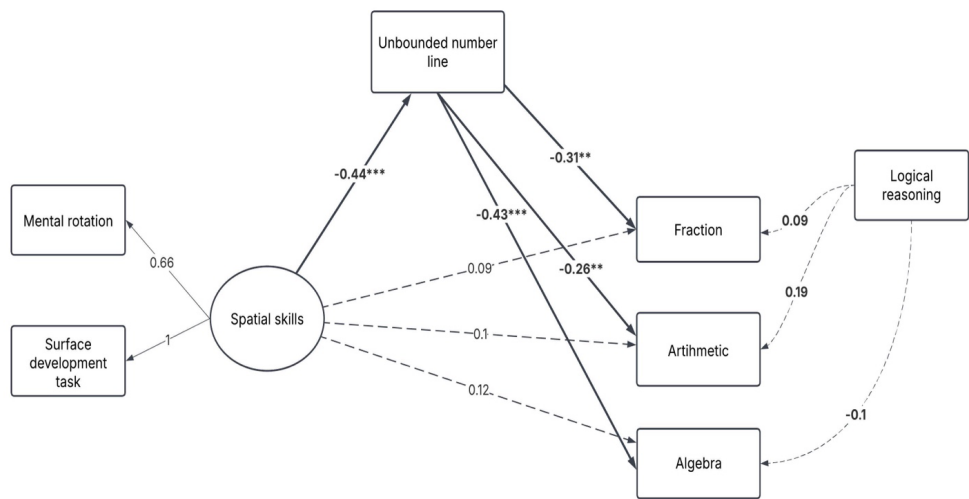


Note. Figure 3 shows the relationship between spatial and mathematical skills, while controlling for deductive logical reasoning. Oval shape represent latent variable and rectangles represent observed variables. Continuous dash lines indicate a nonsignificant path, while continuous thick lines show significant paths.
* $p < .05$. ** $p < .01$. *** $p < .001$.

The second research question investigated whether unbounded number line estimation mediated the relationship between spatial skills and mathematical abilities. In Model 2, again, we modelled spatial skills as a latent variable, measured by mental rotation and spatial visualization, predicting fractions, arithmetic, and algebra as separate observed outcomes, with deductive logical reasoning as a control variable. Unbounded number line estimation was entered as the mediator. A bootstrap procedure with 5,000 replications accounted for non-normality and a small sample size. The results from Model 2 indicated generally good model fit based on CFI and SRMR, with RMSEA at the upper bound of acceptable thresholds $\chi^2(7, N = 85) = 10.67, p = .153, CFI = .98, RMSEA = .08, SRMR = .06$. Figure 4 presents the path diagram of Model 2. As shown in Table 3, the indirect paths from spatial skills through unbounded number line estimation were significant for fractions ($p = .022$), algebra ($p = .003$), and arithmetic ($p = .032$), with 95% confidence intervals excluding zero for all three domains. The direct effects of spatial skills were not significant on fractions ($p = .431$), arithmetic ($p = .367$), and algebra ($p = .257$), as well as on deductive logical reasoning across all math domains. These findings indicate that, after controlling for deductive logical reasoning, unbounded number line estimation fully mediated the relationships between spatial ability and mathematical performance across all three domains.

Figure 4

Model 2. Path Diagram Showing the Relationship Between Spatial and Mathematical Skills and Magnitude Representation



Note. Figure 4 shows the relationship between spatial and mathematical skills unbounded number line while controlling for deductive logical reasoning. Oval shape represent latent variable and rectangles represent observed variables. Continuous dash lines indicate a nonsignificant path, while continuous thick lines show significant paths.

* $p < .05$. ** $p < .01$. *** $p < .001$.

Table 3

Indirect and Direct Effects of Spatial Skills on Mathematical Domains via UNL

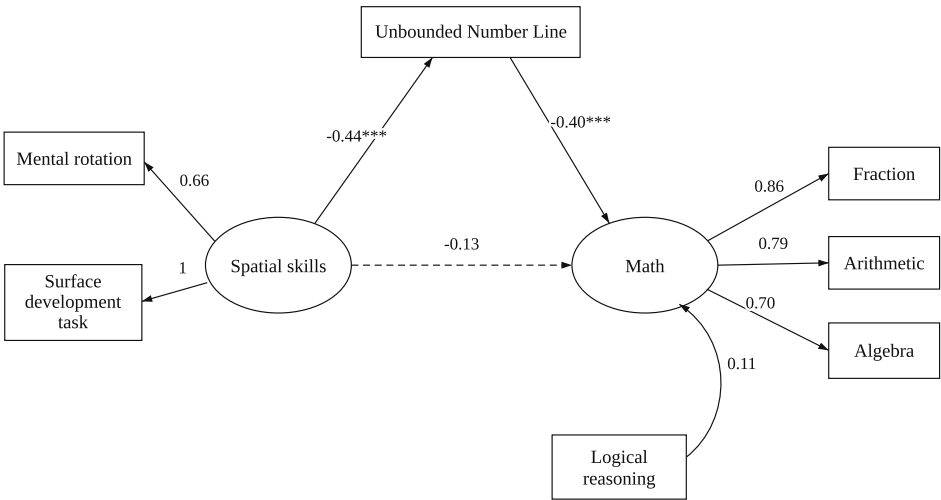
Mathematical domain	Standardized effect	p	95% CI
Indirect effects			
Fraction	.135	.022	[0.296, 1.905]
Arithmetic	.115	.032	[0.131, 1.304]
Algebra	.188	.003	[0.561, 2.254]
Direct effects			
Fraction	.616	.431	[-0.941, 2.104]
Arithmetic	.557	.367	[-2.410, 0.366]
Algebra	.840	.257	[-0.648, 2.246]

Note. Bold-faced p 's are significant paths. The table shows the indirect effect of the unbounded number line task (UNL) in the relationship between spatial skills and the different mathematical domains. The 95% confidence intervals (CI) for indirect and direct effects were calculated using the percentile method from the bootstrap distribution with 5,000 iterations.

In a third model, we examined whether this relationship exists even when math abilities are examined as a latent variable. To achieve this, we created a latent math ability variable by combining fractions, algebra and arithmetic. We then maintained the latent spatial skills variable, which was created from the spatial ability indicators. We predicted latent math achievement from latent spatial ability and included an unbounded number line as a mediator. Although the chi-square test was significant, the model showed acceptable fit based on alternative fit indices, as noted in the analysis section: $\chi^2(13, N = 85) = 24.462, p = .027$, CFI = 0.937, RMSEA = 0.102, SRMR = 0.082. Figure 5 presents the path diagram of Model 3. The indirect path from spatial skills through unbounded number line estimation to math achievement was significant ($b = 0.176, p = .007$), with 95% CI [0.425, 1.911]. In contrast, the direct path from spatial skills to math achievement was nonsignificant ($b = 0.126, p = .425$) as well as from deductive logical reasoning to math ($b = 0.108, p = .362$). These findings indicate that unbounded number line estimation fully mediated the relationship between spatial skills and general mathematical achievement, after controlling for deductive logical reasoning.

Figure 5

Model 3: Mediation Model Showing Paths From UNL Knowledge to Mathematical Achievement



Note. The diagram above shows various mediation paths connecting latent spatial skills to latent mathematical achievement through an unbounded number line measure, while controlling for deductive logical reasoning. Oval shapes represent latent variables and rectangles represent observed variables. Continuous thick lines indicate significant paths, whereas faint dashed lines indicate nonsignificant paths.

* $p < .05$. ** $p < .01$. *** $p < .001$.

Discussion

The present study addressed two primary research questions. First, we examined how spatial and mathematical skill domains relate in adults. Second, we investigated whether unbounded number line estimation mediates this association. Results confirmed that spatial skills significantly predict mathematical performance and that this relationship operates indirectly through magnitude representation, as captured by unbounded number line estimation. Consistent with prior work (Atit et al., 2022; Hawes et al., 2022; Xie et al., 2020), spatial skills were found to significantly predict mathematical performance across domains, even after controlling for general reasoning ability. Critically, structural equation modelling demonstrated that unbounded number line estimation fully mediated the relationship between spatial skills and performance in fractions, algebra, and arithmetic. These findings extend the spatial representation theory to adulthood, highlighting numerical magnitude representation as a key mechanism linking spatial and mathematical abilities.

The observed mediation underscores the possible functional integration of spatial and numerical systems. Situated within the broader spatial representation theory, the unbounded number line task may capture the ability to mentally scale numerical magnitudes without reliance on fixed endpoints, encouraging intuitive estimation on an open continuum. This process requires both spatial visualization and abstract numerical reasoning, suggesting that adults with stronger spatial skills may construct more precise magnitude representations. While spatial visualization may support the construction of static spatial representations of magnitude, mental rotation may contribute by supporting the transformation and maintenance of metric spatial relations, which are necessary for scaling numerical magnitudes along a continuous spatial representation. In conceptual terms, spatial visualization may help individuals form a mental representation of numerical magnitude, whereas mental rotation may help preserve relative distances as that representation is extended or rescaled on an unbounded number line. These internal representations, in turn, appear to support symbolic mathematical processes such as algebraic manipulation, fraction reasoning, and arithmetic calculation.

The results strengthen the spatial representation account by demonstrating that spatial abilities influence adult mathematical performance primarily through their contribution to magnitude representation. The complete mediation by unbounded number line suggests that, in adulthood, the link between spatial and mathematical skills operates indirectly through internalized magnitude estimation rather than through spatial reasoning alone. This aligns with evidence that numerical magnitude representation is a core cognitive process underlying higher-order mathematics (Reinert et al., 2015, 2019; Reinert & Moeller, 2021).

Implications

The findings have important theoretical implications for understanding adult numerical cognition. They suggest that magnitude representation continues to play a central role in the cognitive architecture supporting mathematical performance. By demonstrating that unbounded number line estimation mediates the association between spatial and mathematical skills, the study refines theoretical models of numerical processing and emphasizes the continuing relevance of spatial–numerical integration in adulthood.

The mediation pattern indicates that magnitude representation may function as a cognitive interface linking spatial visualization with symbolic mathematical reasoning. This relationship appeared especially robust for algebra, a domain that relies heavily on abstract and relational thinking. Future research should examine these associations across different age groups and methodological approaches to clarify how magnitude-based mechanisms support complex mathematical cognition throughout development.

Limitations and Future Directions

Several limitations should be acknowledged. First, the modest sample size may limit generalizability, despite the use of bootstrapping methods to address distributional concerns. Replication with larger and more diverse samples is warranted. Second, the exclusion of the geometry subscale due to low reliability prevented examination of spatially rich mathematical content, such as geometry, which prior work has shown to be closely linked with spatial visualization (Mix & Cheng, 2012). Developing more reliable geometry measures for adults remains an important future direction. Third, although steps were taken to reduce reference-based strategies in the unbounded number line task (e.g., varying unit guides, staggering starting points), it is still possible that some participants relied on implicit anchoring. Additionally, the variation in unit size across trials may have introduced psychological range effects that lowered accuracy. Future research could address this by using consistent unit guides and presenting each trial independently to reduce carry-over.

Finally, spatial skills were modeled as a single latent construct. Future studies should distinguish between mental rotation and spatial visualization to clarify their unique contributions to mathematics. Incorporating additional cognitive variables, such as working memory and executive function (Bull & Lee, 2014), would also allow for a more comprehensive account of the spatial–mathematical relationship. Longitudinal studies could further illuminate how spatial and numerical systems interact across developmental stages and whether the mediating role of magnitude representation is stable across the lifespan.

Conclusion

This study examined whether unbounded number line estimation mediates the relationship between spatial skills and mathematical performance in adults. The findings provide converging evidence that spatial abilities influence mathematics by contributing to magnitude representation. The complete mediation observed across mathematical domains supports the view that magnitude estimation serves as a key cognitive mechanism connecting spatial and symbolic processing in adulthood. By isolating unbounded number line estimation as a central pathway, the study contributes to a more integrated theoretical understanding of adult numerical cognition. It highlights that spatial and numerical processes remain functionally intertwined beyond childhood and that their interaction may underpin the efficiency of higher-order mathematical reasoning. Collectively, these findings advance theoretical accounts of how spatial representations support mathematical thought in mature cognitive systems.

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Data Availability: The data and materials supporting the findings of this study are available from the corresponding author upon reasonable request.

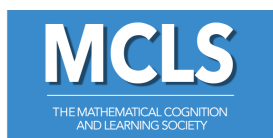
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