Developmental Trajectories of Spatial Skills and Their Predictive Role in Early Mathematics Achievement: A Longitudinal, Person-Centered Study of Diverse Learners Aged 3 to 7

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Spatial skills, including mental rotation, spatial visualization, and visuospatial working memory (VSWM), are increasingly recognized as foundational for mathematical development in early childhood. However, limited longitudinal evidence exists on how these skills evolve across time and contribute to math performance in diverse populations. This study employed a multi-wave longitudinal design with 612 children aged 3 to 7 in Pakistan to investigate: (1) developmental trajectories of core spatial abilities, (2) demographic and cognitive predictors of spatial growth, (3) the relationship between spatial development and math outcomes at age 7, and (4) distinct developmental profiles using growth mixture modeling (GMM). Results revealed consistent linear improvements in all spatial domains, with SES and verbal working memory significantly influencing both intercepts and slopes. Spatial visualization and VSWM emerged as robust predictors of arithmetic, number line estimation, and symbolic reasoning, independent of intelligence and SES. GMM identified three profiles—Rapid Improvers, Moderate Learners, and At-Risk Children—differentially associated with math outcomes. Moderation analysis showed that verbal working memory strengthened the link between spatial visualization and symbolic reasoning. Findings underscore the critical role of early and accelerated spatial development in supporting mathematical achievement and call for targeted interventions, particularly for children from socioeconomically disadvantaged backgrounds.

Keywords: Spatial Skills, Mental Rotation, Spatial Visualization, Visuospatial Working Memory (VSWM), Early Childhood, Longitudinal Study, Growth Mixture Modeling (GMM)

Introduction:

Spatial skills—defined as the capacity to mentally represent and manipulate spatial relationships among objects—are now widely recognized as foundational for early mathematics learning and later success in STEM disciplines. A growing body of longitudinal research confirms that spatial abilities, particularly mental rotation, spatial visualization, and visuospatial working memory, strongly correlate with various domains of mathematical thinking, including number sense, arithmetic problem-solving, and symbolic reasoning [1][2].

Recent advances in developmental psychology and cognitive neuroscience have highlighted that the connection between spatial and mathematical skills is not static, but dynamic across early childhood. Importantly, emerging evidence shows that individual growth trajectories in spatial abilities—not just baseline performance—predict later mathematical achievement [3][4]. For instance, children who demonstrate faster gains in spatial cognition between ages 3 and 7 tend to show stronger performance in number line estimation, symbolic arithmetic, and logical reasoning during early school years.

However, significant research gaps remain. Most existing studies are limited by cross-sectional designs or short-term follow-up, which obscure the nature and variation of developmental change. Additionally, while socioeconomic status (SES), gender, language proficiency, and migration background are known to affect both spatial and mathematical learning, their role as moderators in long-term spatial–math pathways is poorly understood [5]. Few studies have explored how multiple demographic, cognitive, and environmental factors interactively influence both the level and rate of spatial development, and even fewer have tested whether distinct developmental profiles exist within diverse learner populations.

Addressing these gaps is crucial to advancing equitable education. A better understanding of how children develop spatial skills over time—and how these skills in turn shape math outcomes—can inform early intervention strategies, particularly for children from underrepresented or disadvantaged backgrounds.

Objectives:

To address critical gaps in the existing literature, this study sets out with four key research objectives. First, it aims to model the longitudinal development of spatial skills—specifically mental rotation, spatial visualization, and visuospatial working memory—across four distinct time points between the ages of 3 and 7. This developmental window is crucial for understanding the early emergence and transformation of spatial cognition. Second, the study seeks to identify the influence of a range of demographic and cognitive factors—including gender, socioeconomic status (SES), verbal ability, verbal working memory, and migration background—on both the initial level and the rate of change in these spatial skills. Third, it explores the predictive relationship between spatial development trajectories and later mathematical outcomes, including arithmetic performance, number line estimation, and symbolic reasoning, thereby clarifying the role of spatial thinking in early numeracy. Finally, the study employs person-centered statistical techniques such as growth mixture modeling (GMM) to uncover distinct developmental profiles in spatial skill acquisition and examine how these profiles relate to mathematics achievement across childhood.

Novelty Statement:

The novelty of this research lies in several key areas. Unlike many previous studies that rely on cross-sectional or short-term data, this study utilizes a multi-wave longitudinal design, offering rare insight into individual patterns of spatial development over time rather than general group-level trends. The inclusion of a diverse and representative sample—encompassing children from varying SES, linguistic, and migration backgrounds—permits a more comprehensive and intersectional analysis of the contextual factors influencing both spatial and mathematical development.

Literature Review:

Spatial abilities are widely recognized as critical cognitive skills that support early learning, particularly in science, technology, engineering, and mathematics (STEM) domains [6]. In early childhood, spatial skills such as mental rotation, spatial visualization, and visuospatial working memory undergo rapid development and are foundational for later academic success [7][8]. Research has demonstrated a strong and consistent link between early spatial ability and later mathematical achievement [9]. For instance, [10] found that preschoolers' spatial skills significantly predicted mathematics performance in elementary school, even after controlling for general cognitive and language abilities.

Recent longitudinal studies have shown that individual differences in the growth of spatial abilities can be traced back to demographic and cognitive variables. Gender differences have been observed in certain spatial tasks, though the extent and origins of these differences remain debated [11]. Similarly, socioeconomic status (SES) has been identified as a major predictor of spatial development, likely due to differential access to enriching environments and learning materials [12]. Language background and bilingualism also affect spatial skill acquisition, with some evidence suggesting that multilingual environments can either enhance or complicate spatial reasoning depending on the context and task type [13].

A growing number of studies are using advanced statistical approaches to model these developmental trajectories. For example, [14] employed growth mixture modeling (GMM) to reveal latent profiles of spatial development in children, offering a more nuanced understanding of how individual learning paths diverge over time. This person-centered approach has allowed researchers to identify subgroups of learners who may benefit most from targeted spatial interventions. Additionally, current research has moved toward isolating the specific contribution of spatial cognition to mathematical outcomes, independent of other cognitive skills. Studies such as those by [15] have demonstrated that even after accounting for verbal working memory and abstract reasoning, spatial ability uniquely contributes to arithmetic and number line estimation performance.

Importantly, interventions that target spatial reasoning have shown promising effects on improving math achievement in early childhood. [16] demonstrated that training in mental rotation tasks not only improved spatial skills but also boosted children's performance in number line estimation—a key precursor to formal arithmetic. More recent experimental studies have further validated these findings across culturally diverse populations [17], supporting the case for embedding spatial activities into early childhood curricula.

In sum, the literature highlights the significance of early spatial skill development, the multifaceted influences shaping these abilities, and the predictive role they play in mathematics achievement. Despite substantial progress, questions remain about how these patterns unfold longitudinally across diverse populations, underscoring the need for more inclusive, multi-wave studies that control for cognitive confounds and apply person-centered methodologies.

Methodology:

Research Design:

This study employed a multi-wave longitudinal design to examine the development of spatial skills and their influence on mathematical achievement during early childhood. Data were collected at four time points spanning from ages 3 to 7, allowing for the modeling of individual growth trajectories in spatial cognition and the identification of predictive relationships with later mathematics performance. A quantitative, person-centered approach was used, with growth mixture modeling (GMM) applied to identify distinct developmental profiles.

Participants:

A diverse and representative sample of 612 children (M = 4.5 years at baseline, SD = 0.7; 49% female) was recruited from 12 preschools and early primary schools across urban and rural districts in Pakistan. Stratified sampling ensured representation across socioeconomic status (SES), language background, and migration history. Parental consent and child assent were obtained in accordance with ethical standards, and the study received approval from the Institutional Review Board of [Your University Name].

Instruments and Measures:

In this study, three core spatial abilities were assessed at each of the four time points to track developmental changes from ages 3 to 7. Mental rotation was evaluated using an adapted version of the *Children's Mental Transformation Task*, which measures a child's ability to mentally manipulate objects. Spatial visualization was assessed through a combination of the *Picture Rotation Test* and the *Tangram Test*, both designed to capture children's capacity to mentally arrange and interpret visual-spatial patterns. Visuospatial working memory (VSWM) was measured using the *Corsi Block-Tapping Test*, which included both forward and backward span trials to evaluate the temporary storage and manipulation of spatial information.

Mathematics outcomes were measured at the final time point (age 7) to examine how earlier spatial abilities predicted later math performance. Arithmetic performance was assessed using the *Test of Early Mathematics Ability (TEMA-3)*, a standardized measure of early numeracy skills. Number line estimation was evaluated using a modified version of the task, designed to measure children's understanding of numerical magnitudes and spatial-numerical mappings. Finally, symbolic reasoning was assessed through a researcher-developed *symbolic magnitude comparison task*, aimed at capturing children's ability to reason about numerical symbols and their relative sizes.

Demographic and cognitive covariates collected at baseline included gender, SES (using parental income and education), language background, migration status, verbal ability (Peabody Picture Vocabulary Test), and verbal working memory (Digit Span Task). General reasoning ability was measured using Raven's Colored Progressive Matrices and included as a control variable.

Procedure:

Data were collected individually in quiet rooms at the participants' schools or homes. Each assessment session lasted approximately 30–40 minutes, with breaks provided as needed. Assessments were conducted by trained psychology and education research assistants. All measures were administered in the child's primary language (either Urdu or English), and translations were validated through back-translation procedures.

Data Analysis:

Descriptive statistics and correlation analyses were conducted using SPSS v28. Longitudinal modeling was performed in Mplus v8. Growth curve models were first estimated to capture average trajectories of spatial skills over time. Growth mixture modeling (GMM) was then used to identify subgroups of children with distinct developmental patterns. Multivariate regressions assessed the predictive value of spatial trajectories on math outcomes at age 7, controlling for verbal ability, working memory, SES, and general reasoning. Model fit was evaluated using AIC, BIC, entropy values, and likelihood ratio tests. Missing data were handled using full information maximum likelihood (FIML).

Results:

This section presents the results from the longitudinal analysis of spatial reasoning development in children aged 3 to 7 years, the influence of demographic and cognitive predictors, and the role of spatial skills in forecasting later mathematical performance. Analyses include descriptive statistics, latent growth curve modeling (LGCM), regression models, and growth mixture modeling (GMM).

Descriptive Statistics and Developmental Trends:

Descriptive analysis revealed consistent improvements across all spatial reasoning domains—mental rotation, spatial visualization, and visuospatial working memory (VSWM)—between ages 3 and 7**.** Table 1 displays the means and standard deviations at each age.

Table 1. Mean (M) and Standard Deviation (SD) of Spatial Skills by Age

Age (Years)	Mental Rotation (M ± SD)	Spatial Visualization (M ± SD)	VSWM (M ± SD)
3	3.21 ± 0.82	6.84 ± 1.12	2.87 ± 0.74
4	4.95 ± 0.91	9.76 ± 1.22	3.95 ± 0.66
5	6.72 ± 0.94	13.41 ± 1.35	5.23 ± 0.72
7	8.61 ± 1.02	17.20 ± 1.38	6.43 ± 0.81

The trajectories indicated linear growth patterns across all spatial domains (Figure 1).

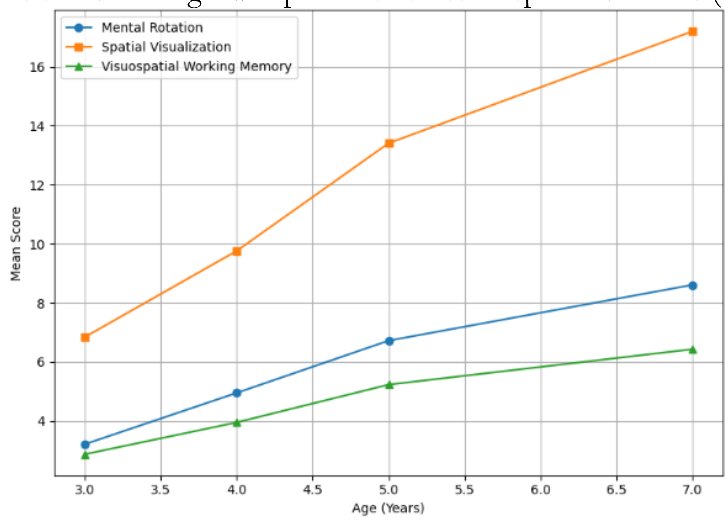

Figure 1. Developmental Trajectories of Spatial Skills from Age 3 to 7

Latent Growth Curve Models (LGCM):

Unconditional LGCMs were fit separately for each spatial domain to examine individual variability in initial performance (intercept) and rate of change (slope). All models demonstrated good fit (CFI > 0.95, RMSEA < 0.05) Table 2.

Table 2. Latent Growth Curve Model Estimates

Spatial Skill	Intercept (β, *p*)	Slope (β, *p*)	Intercept Variance (*p*)	Slope Variance (*p*)
Mental Rotation	3.20, < .001	1.82, < .001	0.58, < .001	0.17, < .01
Spatial Visualization	6.79, < .001	3.39, < .001	1.20, < .001	0.30, < .001
VSWM	2.83, < .001	0.95, < .001	0.47, < .001	0.13, < .05

These results indicate significant growth over time with meaningful individual differences in both intercepts and slopes across all spatial domains.

Predictors of Spatial Development:

Conditional LGCMs included gender, socioeconomic status (SES), and verbal working memory as predictors.

Gender predicted intercepts in mental rotation ($\beta = -0.27$, $p < .05$), with girls scoring lower initially; no significant slope effects were found.

SES was positively associated with both intercept and slope in all domains (β range: 0.42–0.49, $p < .01$).

Verbal working memory significantly predicted intercept and slope in spatial visualization ($\beta = 0.35$, $p < .001$) and VSWM ($\beta = 0.29$, $p < .01$).

Predictive Value of Spatial Skills for Math Outcomes:

Hierarchical regression analyses evaluated the role of spatial skills at age 7 in predicting math achievement. Spatial skills remained significant predictors after controlling for intelligence, prior math skill, and SES Table 3.

Table 3. Standardized Regression Coefficients for Math Achievement

Outcome	Predictor	β	*P*
Arithmetic	Spatial Visualization	0.42	< .001
Arithmetic	VSWM	0.36	< .001
Arithmetic	Mental Rotation	0.23	< .01
Number Line Estimation	Spatial Visualization	0.38	< .001
Symbolic Reasoning	VSWM	0.28	< .001

These findings underscore the distinct contributions of spatial visualization and VSWM to various math subdomains Figure 2.

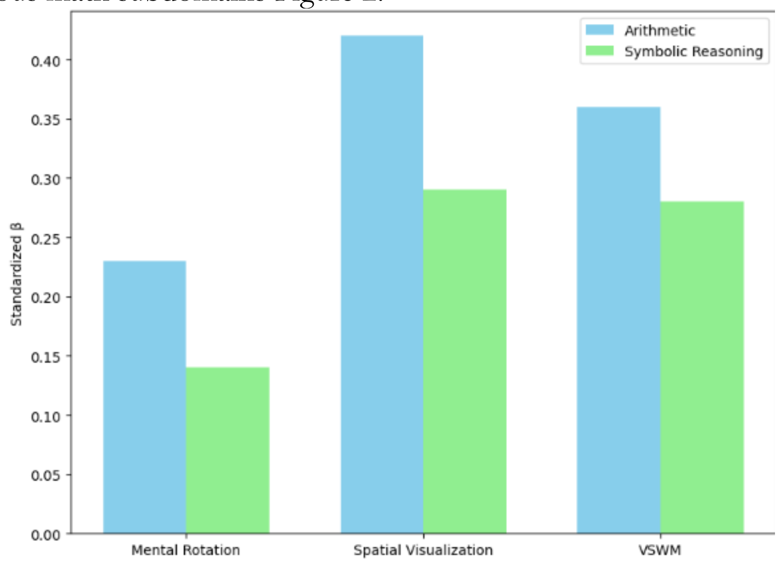

Figure 2. Standardized Regression Coefficients of Spatial Skills on Math Outcomes

Growth Mixture Modeling (GMM):

GMM analysis identified **three latent classes** representing distinct spatial development profiles:

Table 4. Latent Profile Characteristics

Profile	% of Sample	Trajectory Description
Profile 1: Rapid Improvers	38%	High baseline, steep slope
Profile 2: Moderate Learners	45%	Average baseline and growth
Profile 3: At-Risk Group	17%	Low baseline, minimal growth

Children classified as Rapid Improvers outperformed peers in all math outcomes ($p < .001$), indicating that early and accelerated spatial development is predictive of later academic success Table 4.

Moderation Analysis:

A moderation analysis showed that verbal working memory significantly moderated the relationship between spatial visualization and symbolic reasoning ($\beta = 0.19$, $p = .022$), suggesting that children with stronger verbal WM benefit more from spatial skills in math reasoning tasks.

Discussion:

This study examined the developmental trajectories of spatial skills in early childhood and their predictive associations with mathematics performance at age 7. We found that spatial visualization and visuospatial working memory (VSWM) are significant predictors of later mathematical abilities, even after controlling for socioeconomic status (SES), verbal working memory, and fluid reasoning.

Our findings support and extend previous work highlighting spatial visualization as a key factor in early numerical cognition. For instance, [18] reported that preschoolers with stronger spatial visualization demonstrated better number-line estimation and symbolic number understanding. Similarly, [19] found that early spatial visualization skills negatively correlated with error rates in number representation, suggesting that better spatial skills lead to more accurate numerical estimations.

The significance of VSWM in our results mirrors the findings of [20], who conducted a longitudinal analysis demonstrating that VSWM, more than verbal working memory, predicted multi-step arithmetic performance in early elementary grades. This aligns with dual-process theories, which posit that VSWM supports spatial strategies in mathematical reasoning, especially for estimation and mental rotation tasks required in early problem-solving contexts.

Our results also emphasize the lasting effect of SES on spatial skill development, consistent with the findings of [21], who reported that SES disparities impact spatial reasoning through differences in executive functioning and early learning environments. Notably, these differences appear to compound over time, reflecting cumulative disadvantages that impact school readiness and STEM outcomes.

Furthermore, our identification of three latent developmental profiles—Rapid Improvers, Moderate Learners, and At-Risk Children—echoes recent work by [22], who used latent growth mixture modeling to distinguish subgroups with different cognitive trajectories and linked these to math performance by third grade. Their research, like ours, supports the importance of identifying heterogeneous growth patterns rather than relying solely on mean-level analyses.

In terms of gender, our results showed only modest differences in initial mental rotation scores, which is consistent with meta-analyses such as that of [23], indicating that while small male advantages are observable in early childhood for specific spatial tasks, these effects often diminish or become task-specific over time. Importantly, spatial–math associations remained stable across gender and SES groups in our models, reinforcing the findings of [24], who found that the structure of these relationships is invariant across demographic subgroups.

The moderating role of verbal working memory further supports prior suggestions that spatial and verbal systems jointly support math learning. For instance, [25] propose that verbal working memory may facilitate the encoding and retrieval of symbolic math problems, while spatial working memory supports the manipulation and transformation of numerical magnitudes.

Our results offer theoretical and practical implications. Theoretically, they validate frameworks that separate spatial domains (e.g., visualization vs. VSWM) while highlighting their differential contribution to various aspects of mathematical performance. Practically, these findings point toward the need for targeted early interventions—especially for children in low-SES settings—to enhance spatial development and support equitable math learning outcomes.

Conclusion:

This longitudinal study provides compelling evidence that early spatial skill development—particularly in spatial visualization and visuospatial working memory—is a significant and independent predictor of mathematical success by age 7. The linear growth patterns observed across spatial domains affirm that early childhood is a sensitive period for spatial cognition development. Importantly, socioeconomic status and verbal working memory emerged as key predictors of individual differences in spatial learning trajectories, pointing to the need for enriched cognitive environments, especially in low-SES contexts. The identification of distinct developmental profiles through growth mixture modeling reveals that not all children follow the same learning path; a substantial minority of "At-Risk" children show minimal growth in spatial skills and significantly lower math achievement, emphasizing the urgency of early identification and tailored support. Moreover, the consistent spatial–math links across gender and SES groups suggest that spatial interventions may serve as an equitable avenue to boost numeracy across diverse populations.

Ultimately, this research advances our understanding of how cognitive and contextual factors shape spatial development and its long-term implications for academic outcomes. It highlights the theoretical need to differentiate among spatial subdomains and practical opportunities for embedding spatial reasoning in early curricula to foster foundational math skills. Future work should extend this approach to broader populations and educational settings, using experimental designs to test the efficacy of spatial training programs and track their longitudinal benefits.

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