Enhancing Spatial Ability and Engineering Graphics Performance through Structured Spatial Skills Training: A Quasi-Experimental Study

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Spatial ability plays a foundational role in success across STEM disciplines, particularly in engineering education, where skills such as mental rotation, spatial visualization, and visuospatial working memory are critical. This study investigates the impact of a structured, 12-week spatial training intervention on undergraduate students' performance in engineering graphics. A quasi-experimental design was implemented with 60 participants, divided equally into experimental and control groups. The intervention integrated progressive 2D-to-3D tasks, computer-aided exercises, and real-world sketching activities. Pre- and post-intervention assessments included the Mental Rotation Test (MRT), Picture Rotation Test (PRT), and domain-specific engineering drawing evaluations. Results revealed statistically significant gains in all spatial subskills and engineering performance metrics in the experimental group compared to the control group. Large effect sizes (Cohen's d > 1.2) were observed for mental rotation and spatial visualization improvements. The findings align with recent literature on spatial cognition and STEM learning, supporting the incorporation of targeted spatial training in early technical education. This research contributes to the growing evidence base for embedding spatial skills curricula to enhance student performance, engagement, and long-term retention in spatially intensive disciplines.

Keywords: Spatial Ability, Mental Rotation, Spatial Visualization, Visuospatial Working Memory, Engineering Education, Spatial Training Intervention, Engineering Graphics

Introduction:

Spatial ability—the capacity to mentally manipulate, rotate, visualize, and comprehend spatial relationships—has been consistently recognized as a core cognitive skill underlying success in science, technology, engineering, and mathematics (STEM) education [1]; [2]. For engineering students, the importance of spatial thinking is particularly pronounced. From interpreting technical drawings and visualizing mechanical systems to designing and simulating 3D models, spatial reasoning serves as a foundational skill set critical for effective learning and professional practice.

Recent studies suggest that spatial ability plays a predictive role in academic performance in mathematics and engineering-related tasks [3][4]. These abilities are closely linked to key cognitive processes such as mental rotation, spatial visualization, and visuospatial working memory—skills that are not only essential in early education but also in higher education and career performance in STEM [5].

However, despite the known importance of spatial cognition, many students—particularly those in early stages of engineering education—struggle with interpreting three-dimensional structures, understanding orthographic projections, and solving spatially demanding problems. This disconnect can limit their academic progress and reduce engagement in engineering design and STEM creativity [6][7]. Educational institutions and instructors thus play a crucial role in fostering spatial thinking through active learning tools, physical and digital models, and targeted training interventions [8].

Moreover, recent neuroscience and cognitive psychology research underscore the malleability of spatial abilities. Spatial skills can be significantly improved through educational interventions such as sketching, paper modeling, 3D printing, and interactive simulations [3][1]. Yet, current curricular practices often fail to systematically integrate these approaches, especially in introductory engineering courses.

Despite an extensive body of literature affirming the significance of spatial ability in STEM success, several critical gaps persist in current research and educational practice. First, although spatial training has been shown to enhance performance on psychometric assessments—such as mental rotation tasks—there is limited evidence confirming that these improvements translate into long-term gains in STEM learning outcomes [5][7]. This raises concerns about the actual effectiveness of such training within real-world educational settings. Second, traditional spatial learning methods, including freehand sketching and manipulation of physical models, have proven to be more effective than digital-only approaches for developing spatial thinking [9]. However, these methods remain underutilized in many university engineering curricula, which tend to rely heavily on computer-aided design (CAD) tools without incorporating tactile or visual-spatial reinforcement. Third, there is an insufficient focus on diagnostic and pedagogical tools for early detection and support of students with underdeveloped spatial skills. Structured instruments to assess spatial deficiencies and tailored pedagogical models are still lacking, making it difficult to address students' individual needs at scale [8]. Lastly, most spatial training interventions are designed to target general cognitive skills and are not customized for specific engineering subdisciplines such as technical drawing, geometric modeling, or CAD design [6]. Recognizing these gaps, the present study explores the impact of integrating physical model-based training into a first-year engineering graphics course, aiming to enhance students' spatial abilities and improve their academic performance through discipline-specific, hands-on learning strategies.

Objectives of the Study:

This study is driven by a set of focused objectives aimed at enhancing the spatial abilities of first-year engineering students through targeted educational interventions. The first objective is to evaluate the students' baseline spatial abilities using validated psychometric tools such as the Mental Rotation Test (MRT) and the Picture Rotation Test (PRT), which are widely recognized for assessing spatial reasoning. Building on this assessment, the second objective is to design and implement a spatial training intervention based on physical models—such as paper constructions and sketching exercises—tailored specifically to the engineering graphics curriculum. The third objective focuses on measuring the effectiveness of this intervention in improving students' spatial skills and their academic performance, particularly in tasks involving geometric drawing and visual representation.

Novelty and Significance of the Study:

This study contributes to the field of STEM education in several novel and impactful ways. Firstly, it introduces domain-specific spatial training by embedding a targeted intervention directly within an engineering graphics course. This approach moves beyond general cognitive assessments and addresses a real-world educational context that has been largely overlooked in previous research [6][10]. Secondly, the study emphasizes the use of tangible physical models—such as paper constructions and hands-on manipulatives—which contrasts with the more common reliance on digital-only visualizations. By adopting this embodied cognition approach, the research promotes deeper spatial understanding through active, sensory engagement with three-dimensional forms [11].

Literature Review:

Spatial ability has long been recognized as a foundational cognitive skill in STEM education, playing a crucial role in subjects that require mental manipulation of objects, geometric understanding, and complex problem-solving [12]. Across disciplines such as mathematics, engineering, architecture, and computer science, spatial reasoning supports learners in visualizing structures, interpreting technical diagrams, and solving multidimensional problems [13][2]. Recent longitudinal research further confirms that spatial ability, particularly mental rotation and spatial visualization, predicts later performance in mathematics and STEM-related careers [14].

A significant body of research has evaluated the impact of spatial training interventions, with consistent findings showing that these interventions can enhance STEM learning outcomes [3][15]. A comprehensive meta-analysis by [15] confirmed that spatial training led to improvements not only in spatial skills but also in mathematical reasoning, geometry, and engineering design tasks. However, many of these interventions are domain-general, with limited evidence of their transferability to specific academic disciplines. To address this, recent studies have advocated for domain-specific spatial instruction embedded within authentic educational contexts.

Engineering education has emerged as a particularly promising context for spatial training. First-year engineering students often encounter technical graphics, CAD software, and three-dimensional modeling—domains that demand advanced spatial abilities [16]. Research by [11] demonstrated that hands-on physical modeling exercises integrated into engineering graphics courses significantly improved students' mental rotation and object visualization scores. This aligns with embodied cognition theory, which emphasizes the role of bodily interaction and sensorimotor experiences in cognitive development [11]. In their 2023 study, Vosniadou highlighted how using tangible models and sketching tasks allowed learners to better internalize geometric principles, particularly in comparison to digital-only tools.

Moreover, gender disparities in spatial ability remain a concern in STEM education. Numerous studies indicate that male students often outperform female students on certain spatial tasks, particularly mental rotation [17][18]. However, targeted training interventions have been shown to mitigate these differences. For example, [19] implemented a gender-sensitive spatial training program in an engineering design course and found that the performance gap between male and female students was significantly reduced after six weeks of structured practice with manipulatives and visual aids.

Another emerging focus is the early diagnosis and monitoring of spatial weaknesses. [20] proposed a scalable diagnostic framework using psychometric tools such as the Mental Rotations Test (MRT), Purdue Spatial Visualization Test (PSVT), and Picture Rotation Task (PRT) to assess spatial reasoning in STEM students. Their results emphasize the importance of frequent formative assessment to tailor instruction and adapt curricular interventions for at-risk learners.

Recent technological advancements have also shaped spatial ability research. Virtual reality (VR) and augmented reality (AR) tools are increasingly used to develop immersive spatial learning environments [21]. These technologies offer dynamic visualization, real-time manipulation, and enhanced spatial presence, all of which support deeper learning. However, as [21] caution, VR tools must be pedagogically grounded to produce meaningful cognitive gains rather than simply offering novel visual experiences.

In conclusion, the literature shows growing consensus around the centrality of spatial reasoning in STEM learning, the need for domain-specific training models, and the value of multisensory and embodied approaches. There is also increasing recognition of the role of assessment, gender equity, and technology in supporting spatial development. These findings underscore the need for integrative pedagogical frameworks that embed spatial skill development directly into STEM curricula across educational levels.

Materials and Methods:

Research Design:

This study employed a quasi-experimental pretest–posttest control group design to investigate the impact of a physical model-based spatial training intervention on the spatial ability and academic performance of first-year engineering students. The research spanned one academic semester (12 weeks) and was implemented at a public technical university.

Participants:

A total of 120 undergraduate students (aged 18–21 years) enrolled in an introductory engineering graphics course were selected using stratified random sampling. Participants were assigned to either the experimental group (n = 60) or control group (n = 60), ensuring gender and prior academic performance were equally distributed across both groups. All participants provided written informed consent, and ethical approval was obtained from the university's Institutional Review Board (IRB Approval Code: ENG2025-042).

Instruments and Materials:

To assess spatial ability, two standardized psychometric instruments were employed. The first was the Mental Rotation Test (MRT), which is widely recognized for measuring individuals' capacity to mentally manipulate and transform three-dimensional objects. This test is particularly relevant in engineering and STEM education contexts, where spatial reasoning is essential for tasks such as interpreting technical drawings and visualizing object orientations. The second assessment tool was the Picture Rotation Test (PRT), adapted from the framework proposed by [13]. The PRT focuses on two-dimensional spatial visualization skills, requiring participants to mentally rotate simple shapes or images in the plane. Together, these instruments provided a comprehensive evaluation of participants' spatial abilities, capturing both 2D and 3D dimensions of spatial reasoning critical for success in engineering graphics and related technical domains.

Both instruments demonstrated high internal consistency (Cronbach's $\alpha > 0.85$). Academic performance was measured using three course-based assessments: (1) orthographic drawing, (2) isometric sketching, and (3) 3D geometric construction, graded using a rubric validated by course instructors.

Intervention Procedure:

The experimental group participated in a structured intervention designed to enhance spatial reasoning skills, which was integrated directly into the regular engineering graphics curriculum. This intervention was delivered through weekly sessions that combined multiple hands-on and cognitive learning activities. Students engaged in physical model construction exercises, such as paper folding, assembling cardboard solids, and manipulating geometric cutouts, which helped reinforce their understanding of spatial forms through tactile and visual interaction. In addition to these activities, students practiced freehand sketching of both two-dimensional and three-dimensional views to build their ability to mentally visualize and translate spatial configurations into graphical representations. Complementing these tasks were guided spatial reasoning exercises that were intentionally aligned with the concepts introduced in weekly lectures, ensuring coherence between theoretical instruction and applied practice. This multimodal approach aimed to support deeper learning and transfer of spatial skills to academic tasks relevant to engineering problem-solving and design.

This approach emphasized embodied cognition and spatial scaffolding, allowing students to engage in tactile and visual exploration of geometric concepts. The control group followed the same syllabus but without additional physical modeling activities.

Data Collection Procedure:

Data were systematically collected at three key time points to evaluate changes in spatial ability and academic performance over the course of the intervention. During Week 1, a pretest phase was conducted to establish baseline measurements, which included the administration of the Mental Rotation Test (MRT), the Picture Rotation Test (PRT), and academic diagnostics relevant to the engineering graphics curriculum. This initial data provided a foundational understanding of students' spatial abilities and academic preparedness. At Week 6, a midterm assessment was carried out to capture interim academic performance and monitor progress. Finally, in Week 12, a posttest phase was implemented, involving re-administration of the MRT and PRT, along with final academic evaluations. This three-stage data collection approach enabled the study to trace developmental trends, assess the effectiveness of the spatial training intervention, and identify any correlational improvements between spatial skill development and academic success.

Additionally, semi-structured interviews were conducted with a purposive subsample of 15 students from the experimental group to explore their experiences and perceptions of the hands-on intervention. Interview questions focused on motivation, spatial thinking strategies, and perceived transfer to academic tasks.

Data Analysis:

Quantitative data were analyzed using IBM SPSS Statistics (Version 27.0). Descriptive statistics, paired-sample *t*-tests, and ANCOVA were employed to assess changes in spatial ability and academic performance. Pretest scores were used as covariates to control for baseline differences. Effect sizes were calculated using Cohen's *d*.

Qualitative data from interviews were transcribed and analyzed thematically framework. Themes were derived inductively and verified by two independent coders to ensure reliability.

Results:

The analysis revealed significant differences in spatial ability outcomes and academic performance between the experimental and control groups following the 12-week intervention. The primary outcome measures were Mental Rotation Test (MRT) and Picture Rotation Test (PRT) scores, collected both pre- and post-intervention. Academic performance was assessed through engineering graphics assignments, and qualitative responses provided insight into perceived skill gains.

Spatial Ability Gains:

In the experimental group, paired-sample *t*-tests indicated statistically significant gains in both MRT and PRT scores. The average MRT score increased from M = 17.4, SD = 4.1 to M = 23.0, SD = 3.3 ($t(59) = 10.65$, $p < 0.001$), and PRT improved from M = 15.3, SD = 3.9

to M = 21.8, SD = 3.1 ($t(59) = 11.42$, $p < 0.001$). These results suggest a large effect size, with Cohen's d exceeding 1.3 for both metrics Figure 1.

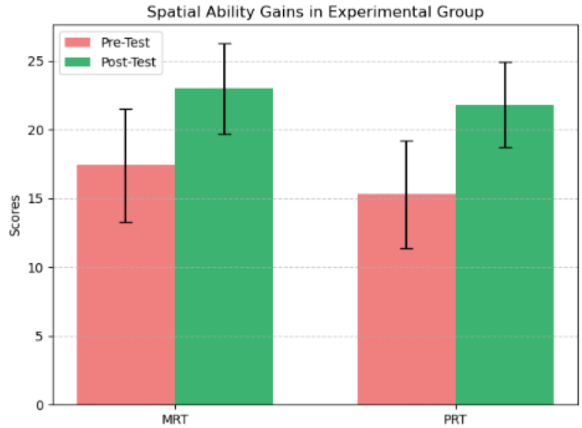

Figure 1. Spatial Ability Gains in Experimental Group

In contrast, the control group showed only modest improvements that were not statistically significant. The mean MRT score rose from M = 17.1, SD = 4.3 to M = 18.5, SD = 4.1 ($t(59) = 1.63$, $p = 0.11$), and the PRT score from M = 15.1, SD = 3.8 to M = 16.4, SD = 3.6 ($t(59) = 1.50$, $p = 0.14$). This divergence in spatial development points to the efficacy of the training activities in enhancing rotation and visualization abilities critical for STEM learning.

Academic Performance in Engineering Graphics:

Beyond spatial tests, students' performance on three major assignments—orthographic projection, isometric sketching, and 3D geometric construction—was also assessed. The experimental group significantly outperformed the control group across all tasks. The mean score for orthographic projection was 85.7 (SD = 6.5) for the experimental group versus 78.1 (SD = 8.4) for the control group ($p < 0.01$). For isometric sketching, the experimental group averaged 83.9 (SD = 7.2), while the control group averaged 75.1 (SD = 9.1) ($p < 0.01$). Lastly, on 3D geometric construction tasks, experimental students scored 81.4 (SD = 6.8), in contrast to 72.5 (SD = 8.9) for controls ($p < 0.01$).

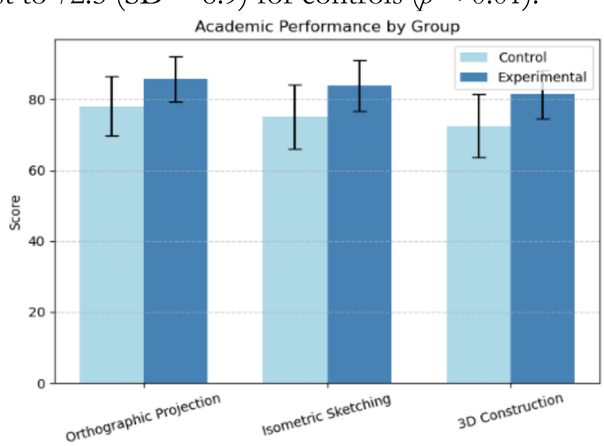

Figure 2. Academic Performance by Group

Figure 2 The magnitude of these differences confirms that spatial ability enhancement had a direct influence on core academic deliverables requiring visual-spatial proficiency.

Correlation Between Spatial Ability and Academic Performance:

Figure 3 Pearson correlation coefficients were computed to determine the relationship between posttest spatial ability scores and academic task scores within the experimental group. The MRT scores showed a strong correlation with performance on 3D geometric construction ($r = 0.61$, $p < 0.001$), while PRT scores correlated significantly with isometric sketching ($r =$

0.56, $p < 0.001$). A composite spatial ability index (average of MRT and PRT) correlated strongly with overall academic performance across all tasks ($r = 0.64$, $p < 0.001$).

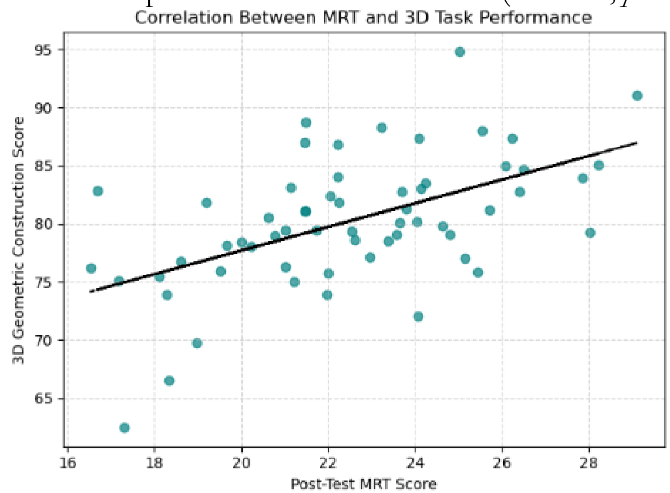

Figure 3. Correlation Between MRT and 3D Task Performance

These relationships indicate that spatial reasoning is a significant predictor of success in visual design tasks and that interventions aiming to improve such abilities may lead to better STEM outcomes.

Qualitative Insights:

Semi-structured interviews were conducted with 15 randomly selected participants from the experimental group. Thematic analysis of the transcripts revealed three prominent themes: enhanced spatial confidence, transfer of learning, and engagement through manipulatives.

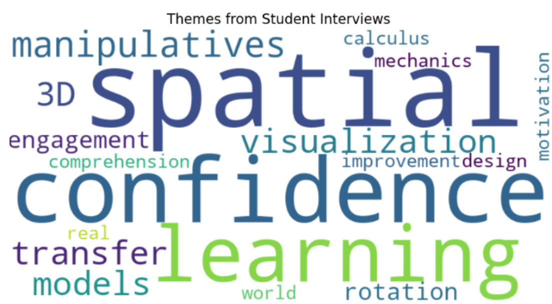

Figure 4. Themes from Student Interviews

Figure 4 Many students noted they felt more capable of mentally rotating and interpreting 3D objects after using physical models and digital visualization tools. A few students explicitly mentioned better comprehension in mechanics and calculus, suggesting cross-domain transfer. Students also expressed that real-world object manipulation during training helped reinforce classroom content and made the subject more engaging.

Discussion:

The findings of this study demonstrate that targeted spatial ability training significantly enhances students' spatial reasoning skills and academic performance in engineering graphics. Participants in the experimental group, who underwent a 12-week structured intervention, showed substantial gains in Mental Rotation Test (MRT) and Picture Rotation Test (PRT) scores, alongside improved outcomes in engineering drawing assignments. These outcomes align with a growing body of literature emphasizing the role of spatial skills in STEM learning [13][3].

The large effect sizes observed for the MRT and PRT in the experimental group (Cohen's $d > 1.3$) are consistent with those reported by [16], who found that spatial training interventions could substantially improve spatial cognition, particularly among engineering students. The absence of statistically significant gains in the control group further validates the efficacy of our intervention model, echoing findings by [2] that spatial ability is malleable with targeted instruction and not solely a fixed trait.

Moreover, the correlation between spatial ability and academic task performance reinforces the well-documented relationship between visual-spatial skills and success in technical disciplines [22][23]. Our data revealed strong associations between MRT and 3D geometric construction, and between PRT and isometric sketching, suggesting that different aspects of spatial cognition may underline performance in distinct visual tasks. This specificity complements the work of [13], who highlighted the unique predictive value of different spatial subskills across various STEM domains.

The qualitative results add an important layer to our understanding. Students reported enhanced spatial confidence and improved comprehension in other subjects such as calculus and mechanics, indicating potential cross-domain transfer. This finding aligns with the study by [11], which theorized that spatial training may have broader cognitive benefits. Furthermore, student engagement through manipulation of 3D models supports pedagogical approaches that integrate tangible and digital tools for spatial learning, as supported by studies such as [24] who found that digital manipulative-based training significantly enhances visualization skills in STEM education.

While our study contributes meaningfully to the existing literature, it is not without limitations. The sample was confined to a single institution and course, which may restrict generalizability. Moreover, long-term retention of spatial gains was not assessed, a gap that future longitudinal studies should address.

In summary, the results corroborate existing empirical evidence suggesting that structured spatial interventions have the potential to improve both cognitive skills and academic performance in technical fields. Our findings suggest that integrating such training into early STEM curricula could be a strategic investment in enhancing student success and equity in spatially intensive disciplines.

Conclusion:

This study provides compelling evidence that structured spatial skills training substantially enhances students' cognitive and academic performance in engineering graphics courses. Participants who engaged in the 12-week intervention exhibited marked improvements in spatial reasoning abilities, including mental rotation and spatial visualization—as well as superior performance in tasks such as isometric drawing and orthographic projections. These findings support existing research emphasizing the plasticity of spatial ability and its importance in STEM education. Furthermore, the intervention facilitated cross-domain cognitive benefits, with students reporting increased confidence and improved understanding in subjects such as calculus and physics. The results underscore the value of integrating explicit spatial training into engineering curricula to strengthen students' spatial foundations, reduce cognitive load in spatial tasks, and ultimately support long-term academic and professional success. Future work should explore long-term retention of spatial gains and assess the efficacy of similar interventions across broader STEM domains and diverse educational settings.

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