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Investigating STEM Career Interests: How Can Spatial Orientation, Mental Rotation, and Spatial Visualization Explain Them?

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ABSTRACT

Spatial ability plays a crucial role in shaping students' interest and career paths in STEM (Science, Technology, Engineering, and Mathematics). This quantitative study involved 60 science students aged 15–17 in Bandung, Indonesia, utilizing a spatial ability test to measure mental rotation, spatial visualization, and spatial orientation, along with a career interest questionnaire to assess STEM and non-STEM preferences. Logistic regression analysis confirmed that spatial ability significantly influenced students' STEM interest ($p = 0.004$) with a moderate contribution. Further analysis using the Independent Samples T-Test revealed that students interested in STEM had significantly higher mental rotation ($p < 0.001$, Cohen's $d = -1.000$) and spatial visualization ($p = 0.002$, Cohen's $d = -0.797$) abilities than non-STEM students, while spatial orientation showed no significant difference ($p = 0.112$, Cohen's $d = -0.317$). These findings highlight the role of spatial ability as a predictor of STEM interest, emphasizing the need for educational interventions such as visualization-based learning, three-dimensional object manipulation, and technology-assisted spatial training, including computer-aided design (CAD) software and mental rotation exercises. Integrating these strategies into mathematics and science curricula can enhance spatial skills and support students' engagement in STEM education and careers.

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A. INTRODUCTION

The ability to work in STEM is crucial for active engagement in both social and professional contexts (Irwin, 2001; Rothwell, 2013). Addressing global issues such as sustainable energy, healthcare, and climate change demands interdisciplinary approaches within STEM (Shernoff et al., 2017). Creative and innovative solutions arise from integrating diverse perspectives within the STEM workforce, fostering problem-solving capabilities and driving innovation (Roberge & van Dick, 2010). However, one cognitive aspect often overlooked in STEM skill development is spatial reasoning.

Spatial reasoning plays a critical role across various STEM fields. This ability encompasses understanding, visualizing, and manipulating objects and their spatial relationships across different dimensions. Harris et al. (2021) define spatial reasoning as the cognitive capacity to represent and manipulate objects along with their spatial interconnections. Additionally, spatial skills involve various cognitive processes essential for solving spatial tasks, such as mental rotation, spatial visualization, and spatial orientation. These skills are crucial across STEM disciplines, including analyzing molecular structures in chemistry, designing objects in engineering, or interpreting visual data in earth sciences and physics (DeWitt & Bultitude, 2020). Spatial ability can be categorized into three main components: spatial orientation, spatial visualization, and mental rotation, each with distinct features and practical applications (Harris et al., 2021; Badmus & Jita, 2022; Wai et al., 2009).

Spatial orientation refers to the ability to recognize, remember, and imagine spatial relationships between objects, including visualizing alternative viewpoints or different spatial perspectives. This skill is crucial for navigating and understanding environments from an egocentric perspective (Newcombe, 2016). In contrast, spatial visualization involves mentally manipulating and transforming visual images, such as executing multi-step transformations of objects or predicting the outcome of paper folding into a specific shape. This ability is essential for problem-solving tasks that require geometric reasoning or visualizing complex structures, particularly in design and engineering contexts (Harris et al., 2021; Li & Wang, 2021). Mental rotation, as a specific type of spatial visualization, refers to the ability to mentally rotate objects in two or three dimensions to understand their orientation (Badmus & Jita, 2022). This ability plays a crucial role in spatial reasoning, especially in STEM fields that require an understanding of complex spatial relationships (Wai et al., 2009). While often used interchangeably, spatial orientation, spatial visualization, and mental rotation measure different aspects of spatial reasoning, with spatial orientation focusing on navigation and environmental understanding, spatial visualization on intricate mental manipulations, and mental rotation on object rotation for orientation identification (Badmus & Jita, 2022).

Spatial reasoning enables individuals to solve complex problems by visualizing relationships and patterns and making predictions based on visual representations (D. Uttal & Cohen, 2012). This cognitive skill is particularly crucial in STEM disciplines, where tasks often involve mental manipulation of objects, understanding spatial relationships, and interpreting multidimensional data (Newcombe, 2016). According to Khine (2017), success in many STEM fields depends on spatial thinking skills, whether in design, analysis, or exploring new ideas. For example, engineers rely on spatial visualization to design structures, while chemists use spatial reasoning to understand molecular configurations. Additionally, research by Wai et al. (2009) highlights that strong spatial ability is a key predictor of achievement in STEM careers, reinforcing the need for early spatial skill development. Therefore, STEM education must place special emphasis on enhancing spatial reasoning through targeted interventions such as hands-on activities, computer-aided design (CAD) tools, and virtual simulations to produce a competent workforce ready to tackle global challenges.

The findings of Wai et al. (2009), based on a large dataset of 400,000 individuals, highlight the significant role of spatial ability in developing expertise in STEM fields. They suggest that incorporating spatial ability assessments into modern talent identification processes can uncover adolescents with untapped STEM potential. Consequently, spatial thinking is vital for enhancing performance and preparing individuals for STEM careers. Research also indicates that from an early age, individuals with strong spatial abilities tend to excel in mathematics and science, even when factors such as IQ and socioeconomic status are considered (Bower et al., 2020; Gilligan et al., 2017; Hodgkiss et al., 2018; Mix et al., 2016). Recent meta-analyses show a positive correlation between spatial ability and mathematical achievement ($r = 0.36$) and emphasize the benefits of spatial interventions on math performance (Atit et al., 2022; Hawes et al., 2022). However, despite its clear benefits, spatial reasoning often receives insufficient attention in educational curricula. For example, policy changes in the UK have reduced the focus on spatial reasoning in early childhood education (Gilligan et al., 2017).

Although previous research has highlighted the relationship between spatial ability and success in STEM, gaps remain in understanding how this ability specifically influences interest and aspirations toward STEM. Many studies focus on the link between spatial ability and academic performance, yet few explore how this factor can be leveraged to foster interest and engagement in STEM from an early age. Therefore, this study aims to address this gap by further investigating the role of spatial reasoning in shaping STEM interest and how integrating this ability into education can enhance STEM participation.

This study seeks to deepen the understanding of the relationship between spatial ability and STEM interest. By emphasizing the role of spatial reasoning in shaping STEM skills and aspirations, this research contributes to a broader understanding of how spatial ability can be integrated into STEM education for more effective learning outcomes. Thus, the findings of this study are expected to provide new insights into the importance of early spatial ability development in fostering engagement in STEM fields.

B. METHODS

This study employed a quantitative research approach involving 60 science-track students aged 15 to 17 from three different schools in Bandung. The sample was randomly selected from two out of nine available classes, with data already collected from all nine classes across the three schools. This ensured sufficient variation in spatial ability and career interests. The selection process involved random sampling from the existing dataset rather than direct participant recruitment, maintaining objectivity in the sampling procedure.

The study utilized a spatial ability test consisting of 30 questions from (Ramful et al., 2016), divided into three sections: 10 questions on mental rotation, 10 questions on spatial visualization, and 10 questions on spatial orientation. The test was administered within an 18-minute time frame. The validity and reliability of this instrument have been well-established in previous research. No adaptations were made, as the test was used in its original validated and reliable form. After completing the test, students were asked to fill out a questionnaire regarding their career preferences, categorizing them into STEM (Science, Technology, Engineering, and Mathematics) or non-STEM career aspirations.

Data analysis involved logistic regression to investigate the relationship between students' spatial abilities and their interest in STEM fields. Additionally, an Independent Samples t-Test was conducted to compare the spatial ability test scores of students aspiring to STEM careers with those aiming for non-STEM careers. The study accounted for data completeness, and no outliers were removed, as all recorded data met the inclusion criteria. These analyses aimed to identify whether significant differences exist in spatial abilities between the two groups. The findings of this study are expected to provide insights into whether spatial ability can serve as an early indicator for identifying students with potential or interest in STEM-related careers.

C. RESULT AND DISCUSSION

The presentation of research findings is systematically structured to address the research questions posed. Below are the results of the descriptive analysis of students' spatial abilities, grouped based on their career interests, i.e., STEM and Non-STEM. This analysis aims to explain the differences in spatial abilities between the two groups following the measurement of three types of spatial abilities: Spatial Orientation, Mental Rotation, and Spatial Visualization, as shown in Table 1 below.

Table 1. Descriptive Analysis Results of Spatial Ability in STEM and Non-STEM Groups

Spatial Ability	Group	N	Mean	SD	SE	Coefficient of variation
Spatial Orientation	Non-STEM	30	6,900	1,494	0,273	0,216
	STEM	30	7,400	1,653	0,302	0,223
Mental Rotation	Non-STEM	30	3,167	1,621	0,296	0,512
	STEM	30	5,100	2,203	0,402	0,432
Spatial Visualization	Non-STEM	30	2,700	1,368	0,250	0,507
	STEM	30	4,167	2,214	0,404	0,531

Table 1 highlights the differences in spatial abilities between students with career interests in STEM and Non-STEM fields. In the Spatial Orientation aspect, the STEM group has a slightly higher average score (7.400) compared to the Non-STEM group (6.900). For Mental Rotation, the difference is more pronounced, with the STEM group scoring significantly higher on average (5.100) compared to the Non-STEM group (3.167). A similar pattern is observed in Spatial Visualization, where the STEM group (4.167) outperforms the Non-STEM group (2.700). The standard deviation indicates that there is greater variability in results within the STEM group, particularly for Mental Rotation and Spatial Visualization. The coefficient of variation suggests that although the STEM group has higher mean scores, the level of variation within this group is also greater compared to the Non-STEM group.

1. Correlation Analysis

Logistic regression analysis was performed to examine the influence of spatial abilities on students' career interests, as shown in Table 2.

Table 2. Logistic Regression Analysis

Model	Deviance	df	X^2	p	McFadden R^2	Nagelkerke R^2
H_0	83,178	60				
H_1	69,619	57	13,559	0,004	0,113194	0,1875

The logistic regression results indicate that spatial abilities, including Spatial Orientation, Spatial Visualization, and Mental Rotation, significantly influence students' career interests ($p = 0.004$). The reduction in deviance (from 83.178 to 69.619) suggests that the inclusion of these spatial abilities enhances the predictive capability of the model. The McFadden R^2 value of 0.113 and Nagelkerke R^2 value of 0.1875 indicate that spatial abilities contribute to explaining a meaningful proportion of the variance in students' career interests, though other factors may also play a role.

The significant relationship between spatial abilities and career interests underscores the cognitive demands of STEM fields, where the ability to mentally manipulate objects and understand spatial relationships is crucial. Spatial Orientation, Spatial Visualization, and Mental Rotation facilitate problem-solving in disciplines such as engineering, physics, and computer science. This finding aligns with Yang et al. (2024), who emphasize the role of spatial cognition in professional success across multiple fields, particularly in STEM.

Tsigeman et al. (2023) further demonstrate that STEM professionals consistently outperform non-STEM individuals in spatial tasks, reinforcing the idea that strong spatial skills are a key differentiator in STEM fields. Additionally, Sorby et al. (2018) highlight that targeted spatial training improves students' academic performance and STEM GPAs, suggesting that interventions aimed at enhancing spatial skills can be beneficial in increasing STEM engagement and success.

Despite the clear importance of spatial abilities, their influence on career interests remains only moderate, as indicated by the R^2 values. This suggests that while spatial abilities are a significant factor, other cognitive and environmental influences also shape students' career trajectories. Future research should focus on identifying these additional determinants, particularly in educational settings, to provide a more comprehensive understanding of how spatial skills interact with broader career decision-making processes.

2. Independent Samples t-Test

The analysis was conducted using an independent samples t-test, assuming normality and homogeneity of variance. If these assumptions were not met, the non-parametric Welch test was used as an alternative, as shown in Table 3 and Table 4.

Table 3. Normality Test (Shapiro-Wilk)

Spatial Ability	Career interests	W	p
Spatial Orientation	Non-STEM	0,946	0,129
	STEM	0,944	0,117
Mental Rotation	Non-STEM	0,932	0,054
	STEM	0,935	0,068
Spatial Visualization	Non-STEM	0,936	0,07
	STEM	0,976	0,723

Table 4. Homogeneity Test (Brown-Forsythe)

Spatial Ability	F	df_1	df_2	p
Spatial Orientation	0,397	1	58	0,531
Mental Rotation	2,572	1	58	0,114
Spatial Visualization	5,519	1	58	0,022

Based on the prerequisite tests, the normality test (Shapiro-Wilk) indicates that the data for Spatial Orientation, Mental Rotation, and Spatial Visualization have p-values above 0.05, suggesting that the data are normally distributed. However, the homogeneity of variance test (Brown-Forsythe) shows that Spatial Orientation and Mental Rotation have p-values above 0.05, indicating homogeneity of variance between groups, whereas Spatial Visualization has a p-value of 0.022, suggesting non-homogeneous variance. Consequently, Spatial Visualization was analyzed using the non-parametric Welch test, as shown in Table 5.

Table 5. Comparison of Spatial Ability between STEM and Non-STEM Career Interest Groups

Spatial Ability	Independent Samples T-Test					
	Test	Statistic	*df*	*p*	Cohen's d	SE Cohen's d
Spatial Orientation	Student	-1,229	58	0,112	-0,317	0,261
Mental Rotation	Student	-3,872	58	< 0,001	-1	0,289
Spatial Visualization	Welch	-3,086	48	0,002	-0,797	0,278

a. Spatial Orientation: Analysis and Discussion

The results indicate that Spatial Orientation does not significantly differ between STEM and Non-STEM groups (p = 0.112), with a small effect size (Cohen's d = -0.317). This suggests that while STEM students may have slightly higher Spatial Orientation scores, the difference is not substantial enough to be statistically meaningful. This finding aligns with Tomai et al. (2023), who observed that Spatial Orientation differences between STEM and Non-STEM groups are often minimal. This supports the notion that Spatial Orientation, as a cognitive skill, may not be as crucial for distinguishing between students pursuing different career paths as other spatial abilities. However, this contrasts with the research of Harris et al. (2021), which suggests that Spatial Orientation plays a key role in mathematical performance and is a significant predictor of mathematical task execution. Their study argues that individuals with stronger spatial orientation skills tend to perform better in problem-solving and geometric reasoning tasks, which are integral to STEM education, as shown in Figure 1.

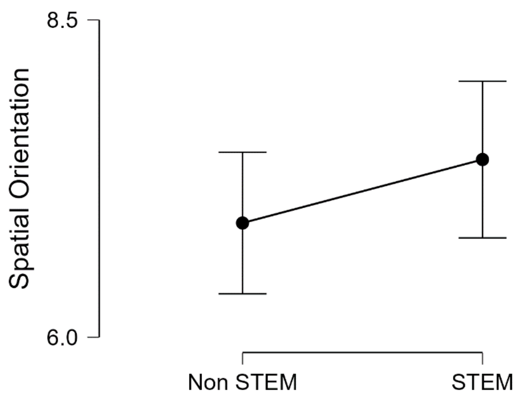

Figure 1. Spatial Orientation

Based Figure 1 presents a comparison of Spatial Orientation scores between Non-STEM and STEM groups. The average score of the STEM group is slightly higher than that of the Non-STEM group. However, the relatively large error bars in both groups indicate that this difference is not statistically significant. This finding further confirms that while spatial orientation may contribute to cognitive performance, its impact on career interest differentiation is less pronounced than that of other spatial abilities.

Despite the lack of statistical significance, it is important to consider contextual factors that may influence Spatial Orientation performance. Prior research suggests that environmental factors, such as early exposure to spatial tasks (e.g., navigation activities, video games, and spatial puzzles), could influence an individual's spatial orientation development (Newcombe & Shipley, 2015). Given that STEM fields often require extensive engagement with spatial problem-solving, students with an inclination towards STEM careers may develop better spatial orientation skills over time, even if initial differences are not substantial.

Another aspect to consider is the educational background and instructional methods experienced by students in STEM versus Non-STEM domains. Some studies suggest that spatial skills, including Spatial Orientation, can be improved through targeted training and curriculum interventions (Uttal et al., 2013). If Spatial Orientation is indeed critical for mathematical reasoning, as suggested by (Harris et al., 2021), integrating spatial training programs into STEM education could be beneficial in fostering higher achievement and interest in STEM fields.

b. Mental Rotation and Spatial Visualization: Significant Differences

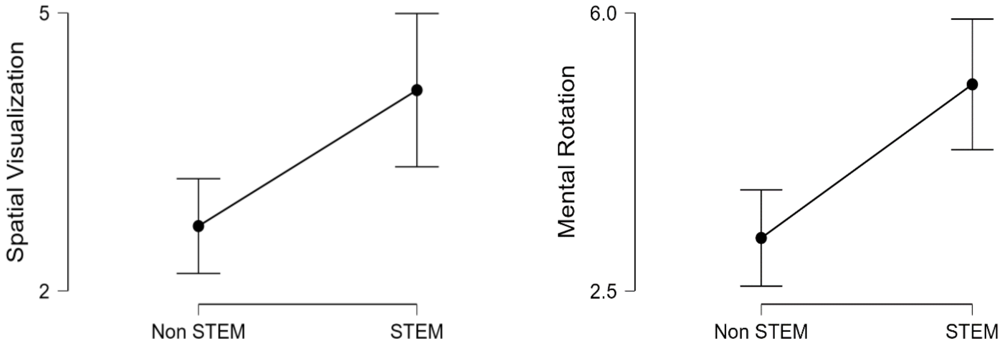

Figure 2. Spatial Visualization and Mental Rotation

In contrast, Mental Rotation ability shows a highly significant difference ($p < 0.001$) with a large effect size (Cohen's d = -1.000). This strongly indicates that students with STEM career interests possess superior mental rotation skills compared to their Non-STEM counterparts. This finding is in agreement with Esipenko et al. (2018), who reported that STEM student exhibit stronger mental rotation abilities than those pursuing Humanities disciplines. Furthermore, studies by Calabrese et al. (2006) confirm that mental rotation is essential in STEM-related professions, reinforcing the notion that spatial reasoning is fundamental to success in technical and scientific disciplines.

For Spatial Visualization, a significant difference was found ($p = 0.002$) with a medium effect size (Cohen's d = -0.797), suggesting that STEM-oriented students perform better in spatial visualization tasks. Figure 2 presents a clear visualization of these differences, where the STEM group scores significantly higher with minimal overlap in error bars. This aligns with Lee et al. (2019), who emphasized the importance of spatial visualization in STEM academic achievement. Badmus & Jita (2022) further argue that spatial visualization is a crucial cognitive skill differentiating STEM and Non-STEM students, as it directly correlates with problem-solving and conceptual understanding in STEM fields. Hodgkiss et al. (2018) reinforce this by demonstrating that spatial visualization and mental folding predict science achievement, highlighting a cognitive advantage that STEM students may develop through their education.

Figures 1 and Figure 2 illustrate the differences in spatial abilities, highlighting significant performance gaps between STEM and Non-STEM students. These disparities underscore the importance of early spatial skill development as a foundational component of STEM education. Given the well-documented link between spatial abilities and success in STEM disciplines, future research should investigate the impact of targeted spatial training on career choices and explore whether structured interventions can help mitigate cognitive differences between STEM and Non-STEM students. Longitudinal studies are necessary to determine whether improvements in spatial skills lead to sustained engagement and achievement in STEM fields.

D. CONCLUSION AND SUGGESTIONS

The correlation analysis using logistic regression indicates that spatial abilities significantly influence students' career interests, with higher spatial ability levels associated with a greater likelihood of interest in STEM fields. Although its contribution to explaining career interest variation is moderate (18.75%), these findings confirm that spatial abilities—particularly Mental Rotation and Spatial Visualization—play a role in distinguishing students with STEM and Non-STEM career interests. Meanwhile, Spatial Orientation does not show a significant difference between the two groups, suggesting that this aspect may be less decisive in STEM career selection. This aligns with previous research indicating that while spatial abilities are important for STEM engagement, certain spatial skills, such as mental rotation, are more closely linked to success in technical and scientific disciplines.

The independent samples t-test further confirms significant differences in Mental Rotation and Spatial Visualization between STEM and Non-STEM groups, with STEM students demonstrating higher scores. These findings highlight the necessity of targeted interventions to strengthen spatial reasoning skills, particularly in areas directly relevant to STEM fields. Therefore, educational institutions should integrate spatial visualization training, such as 3D modelling, technical drawing, and interactive simulations, to enhance these abilities from an early stage. Additionally, incorporating spatial reasoning tasks into mathematics and science curricula may help foster deeper cognitive engagement with STEM subjects. Given that factors beyond spatial ability also influence career decisions, further research is needed to identify additional determinants—such as cognitive, motivational, and environmental influences—that can more comprehensively support students' participation and success in STEM fields.

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