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Integration of GIS Technology and STEM in Geography Learning to Improve Students' Spatial Thinking Skills

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Abstract: The integration of Geographic Information System (GIS) technology and the STEM approach in geography education remains limited, particularly due to teachers' insufficient technological proficiency**.** This study examines the partial and interactive effects of GIS based instruction and STEM-oriented learning on the spatial thinking skills of senior high school students. A quasi-experimental 2 × 2 factorial design was employed, involving 136 students drawn from intact geography classes, where individual randomization was not feasible. Spatial thinking skills were measured using a validated and reliable test instrument. Data were analyzed using descriptive statistics and two-way ANCOVA. The results indicated a significant main effect of GIS ($\eta^2p = 0.657$, large effect), a moderate effect of STEM ($\eta^2p = 0.093$), and a moderate-to-large interaction effect between GIS and STEM ($\eta^2p = 0.128$). These results indicate that the combined implementation of GIS and STEM provides stronger support for the development of students' spatial thinking skills than either approach applied independently. This study contributes conceptually by clarifying the role of GIS as a cognitive mediator within STEM-based geography learning, thereby extending existing research that has predominantly emphasized the technical application of GIS or the isolated effects of STEM instruction.

Keyword: technology GIS; STEM approach; geography; spatial thinking

INTRODUCTION

Spatial thinking has long been a focus of study that has attracted the attention of geographers because of its ability to explain the complex relationships between space, place, and human activity. Given that geography is inherently spatial, the prominence of spatial thinking within this discipline is theoretically unsurprising (Bednarz & Lee, 2019). However, despite its conceptual centrality, spatial thinking has often been treated as an implicit outcome rather than an explicitly operationalized cognitive construct in geography education research.

The publication *Learning to Think Spatially* by the National Research Council (2006) represents a foundational milestone that formalized spatial thinking as an essential educational competency. The NRC framework emphasized spatial thinking as a combination of spatial concepts, representational tools, and reasoning processes necessary for addressing complex, data-rich problems. While this framework remains theoretically influential, its role in contemporary research should be understood as foundational rather than sufficient, particularly in light of rapid developments in digital and geospatial technologies. Subsequent scholars have further expanded the conceptual boundaries of spatial thinking, highlighting its relationship with spatial ability and spatial relationships (Bednarz & Lee, 2019; Golledge & Stimson, 1997; Lee & Bednarz, 2012). Nevertheless, these definitions are rarely synthesized into a coherent instructional or analytical framework that directly informs classroom practice.

In the context of 21st-century education, students are expected to demonstrate scientific literacy, metacognitive awareness, critical and creative thinking, and collaborative problem-solving skills (Wijayanto, Sutriani, & Luthfi, 2020). Geography learning is uniquely positioned to foster these competencies; however, empirical evidence suggests that many students still exhibit limited understanding of fundamental spatial concepts related to national territory, borders, and regional identity (Nursa'Ban, Kumaidi, & Mukminan, 2020). This condition reflects not merely a lack of factual knowledge, but a deeper deficiency in students' critical spatial thinking skills.

Geospatial technology-including Geographic Information Systems (GIS), remote sensing (RS), and global navigation satellite systems (GNSS) has been widely recognized as a powerful means of representing, analyzing, and interpreting spatial data. Collectively, these technologies function as spatial information systems that can support higher-order spatial reasoning (Mašterová, 2023). Rather than serving only as technical tools, geospatial technologies have the potential to act as cognitive supports that make abstract spatial relationships visible and manipulable for learners. Despite this potential, geography instruction in many secondary schools remains dominated by conventional media such as textbooks and slide presentations, which are limited in their capacity to convey dynamic spatial processes (Hadi, Mukminan, Muhsinatun, & Sariyono 2021). Teachers frequently report constraints related to time, technological preparedness, and instructional design (Rahayu, Murjainah, & Idris, 2019). Within this context, the Technological Pedagogical Content Knowledge (TPACK) framework has been proposed as a means of integrating technological competence with pedagogical and disciplinary knowledge (Purwanto, Utaya, Handoyo, & Bachri, 2020). However, TPACK-oriented integration often emphasizes technical proficiency, leaving the cognitive dimension of spatial thinking under-theorized.

From an interdisciplinary perspective, spatial thinking is closely aligned with science, technology, engineering, and mathematics (STEM) education, particularly in relation to problem solving, data interpretation, and systems thinking. Geospatial technologies, especially GIS, naturally intersect with STEM domains by combining computational tools, spatial data, and analytical reasoning. In this study, GIS is deliberately positioned not merely as instructional media, but as a cognitive mediator that enables the enactment of spatial thinking within STEM-oriented learning tasks. Previous studies have explored the application of STEM approaches in geography education, including the development of STEM-integrated instructional modules and inquiry-based learning designs (Zuhria, Purwanto, Masitoh, Soelistijo, & Ella, 2023), This module has been proven to improve students' spatial thinking skills, but has not yet optimised the practical use of geospatial technology in its implementation.

Another study developed an integrated geography and physics course focusing on remote sensing, with the aim of expanding STEM education in secondary schools in its research (Lindner et al., 2019). Although showing great potential in bridging interdisciplinary concepts, the direct use of geospatial tools or platforms in the teaching and learning process has not been specifically described. Meanwhile, in research (Putra, Sumarmi, Deffinika, & Islam, 2021). A project-based learning approach with a blended learning model has also been implemented to improve geographical and spatial thinking skills. This approach uses STEM principles as a framework, but does not explicitly involve the use of geospatial tools such as GIS or remote sensing in learning activities.

While these studies demonstrate positive learning outcomes, they tend to emphasize pedagogical structure or interdisciplinary integration without explicitly incorporating geospatial tools such as GIS into the learning process. Conversely, research focusing on geospatial technology integration highlights its potential to enhance spatial understanding and student engagement (Manakane, Latue, & Rakuasa, 2023; Mašterová, 2023; Osborne, Van de gevel, Eck, & Sugg, 2020), yet often treats STEM principles as peripheral rather than integral to instructional design. As a result, existing research remains fragmented, either emphasizing STEM without fully leveraging geospatial technologies, or employing GIS in a technically oriented manner without a clear cognitive or interdisciplinary framework.

This fragmentation constitutes a critical theoretical gap: without an integrative framework, it remains unclear how and why GIS-supported STEM instruction contributes to the development of students' spatial thinking skills. Consequently, the cognitive mechanisms underlying observed learning gains remain insufficiently explained. Therefore, this study addresses this gap by examining the partial and interactive effects of GIS technology and the STEM approach on senior high school students' spatial thinking skills. The contribution of this research lies in advancing a conceptual understanding of GIS as a cognitive mediator within STEM-based geography learning, thereby moving beyond confirmatory evidence toward theory-informed integration.

METHODS

This study used a quasi-experimental research design with a 2x2 factorial design. This type and design of research was used to test the effect of GIS technology and the STEM approach, as well as the interaction between the two, on students' spatial thinking abilities. The 2x2 factorial design can be seen in Table 1.

Table 1. 2x2 Factorial Design

Technology / Approach	GIS (A1)	Non GIS (A2)
STEM (B1)	A1.B1	A2.B1
Non STEM (B2)	A1.B2	A2.B2

Table 1 shows four groups with different treatments. In group A1B1, students received GIS technology treatment and STEM approach. In group A2B1, students received non-GIS technology treatment and STEM approach. In group A1B2, students received GIS technology treatment and non-STEM approach. In group A2B2, students received non-GIS technology treatment and non-STEM approach. Each group received different learning treatments. In group A1B1, the learning treatment was project-based spatial analysis. In group A2B1, the learning treatment was manual experimentation and modelling. In group A1B2, the learning treatment was conventional learning-based geographic information systems. In group A2B2, the learning treatment was printed maps combined with lectures.

The subjects of this study were Year 11 students at State Senior High School 08 Yogyakarta and State Senior High School 10 Yogyakarta. Both schools had special classes for geography. Therefore, the researcher used existing classes because the researcher also used a quasi-experiment. In this study, there was no individual randomisation, and the researcher only arranged the treatment. The sample in this study consisted of 136 students. These 136 students took a pretest to determine their initial spatial thinking abilities and a posttest to determine the improvement in their spatial thinking abilities after the treatment. The research design scheme is shown in Table 2.

Table 2. Research Scheme Design

Group	**Pretest**	**Treatment**	**Posttest**
A1B1	Q_1	GIS + STEM	Q_2
A1B2	Q_1	GIS + Non-STEM	Q_2
A2B1	Q_1	Non-GIS + STEM	Q_2
A2B2	Q_1	Non-GIS + Non-STEM	Q_2

Data collection was conducted using tests. The research instrument used was a test sheet consisting of 33 multiple-choice questions. The test instrument was designed based on three components of spatial thinking, namely concepts of space, using tools of representation, and process of reasoning. The GIS variable referred to three indicators, namely Input, Process, and Output. The STEM variable refers to four indicators, namely Science, Technology, Engineering, and Mathematics. The test instrument was then tested for validity and reliability to determine whether the instrument was valid or not.

The validity test used is content validity, which is determined by expert agreement. Experts are based on the field measured by the researcher. To determine this agreement, the validity index proposed by Aiken (1980) can be used. If the V coefficient value is greater than or equal to 0.8, the instrument is considered to have adequate content validity or is said to be valid. The content validity conducted by three experts on 33 items is classified as valid and can be seen in Table 3.

Table 3. Results of Instrument Validity Testing

Question item	**Aiken's V**	**Description**
1	0.917	Valid
2	0.917	Valid
3	0.917	Valid
4	0.917	Valid
5	0.833	Valid
6	0.917	Valid
7	0.833	Valid
8	0.833	Valid
9	0.917	Valid
10	0.833	Valid
11	0.917	Valid
12	0.833	Valid
13	0.917	Valid
14	0.917	Valid
15	0.917	Valid
16	0.917	Valid
17	0.917	Valid

18	0.833	Valid
19	0.833	Valid
20	0.833	Valid
21	0.917	Valid
22	0.833	Valid
23	0.917	Valid
24	0.917	Valid
25	0.917	Valid
26	0.833	Valid
27	0.833	Valid
28	0.833	Valid
29	0.833	Valid
30	0.917	Valid
31	0.917	Valid
32	0.833	Valid
33	0.917	Valid

The scores in Table 3 show that all items obtained a V coefficient score greater than or equal to 0.8. Thus, it can be concluded that the instrument used is valid. Next, the reliability of the instrument was tested. The reliability test in this study was conducted by looking at the Cronbach's Alpha value. A research instrument is said to be reliable if the Cronbach's Alpha value is > 0.60. The reliability test values can be seen in Table 4.

Table 4. Reliability Test Results

N of Items	**Cronbach’s Alpha**
33	0.734

Table 4 of the reliability test results show that 0.734>0.6. It can be concluded that the instrument is reliable. The validity and reliability test results are appropriate, so the instrument is suitable for use. Next, the researcher will analyse the data using two-way analysis of covariance (Two-way ANCOVA).

Two-way analysis of covariance (Two-Way ANCOVA) was used to test the effect of two independent variables on one dependent variable by controlling for the effect of covariates. The two independent variables were GIS and STEM, while the dependent variable was spatial thinking ability. This analysis also controlled for the effect of covariates, which in this study were pretest scores. Before testing the hypothesis using Two-Way ANCOVA, a prerequisite test is carried out to ensure that the data meets the necessary assumptions. The prerequisite tests that must be carried out are: 1) normality test, 2) data variation homogeneity test, and 3) linear regression coefficient homogeneity test. All four of the aforementioned requirements must be met for the Two-Way ANCOVA hypothesis test. If one of the prerequisite tests is not met, then testing will be carried out using the non-parametric Kolmogorov Smirnov statistical technique. All of this data analysis was assisted by SPSS statistics.

RESULTS AND DISCUSSION

Results

The results of data processing are explained in the discussion of tests in the study, namely prerequisite tests and hypothesis tests of the effect and interaction of GIS and STEM on the spatial thinking abilities of high school students. The results of the normality prerequisite test are shown in Table 5.

Table 5. Prerequisite Test Results

Value	**Kolmogorov-Smirnov**		
	Statistic	**df**	**GIS.**
Residual for posttest	0.064	136	0.200

The Kolmogorov-Smirnov test results indicate that the posttest data residuals are normally distributed [D(136) = 0.064, p = 0.200]. The p-value = .200 (which is the lower limit of actual significance) is greater than 0.05, so the null hypothesis is rejected and the residual data is normally distributed. This means that, according to the K-S test, the residuals are considered normal. Next is the Levene's test, which is used to test the homogeneity of variance (one of the important assumptions in ANOVA or ANCOVA). In this context, this test examines whether the error variance of the dependent variable Posttest is the same across all groups defined by the combination of independent variables (Pretest, GIS, STEM, and their interaction). The results of the Levene's test are shown in Table 6.

Table 6. Levene's Test Results

Levene's Test of Equality of Error Variances[a]			
F	**df1**	**df2**	**GIS.**
2.639	3	132	0.052

The Levene test results indicate that the variance of the treatment data in class one is homogeneous with the others [F(3,132) = 2.639, p = 0.052). The p-value = 0.052 > 0.05, so the assumption of variance homogeneity can be accepted. Thus, the assumption of variance homogeneity is fulfilled for the ANCOVA to proceed. Furthermore, the Linear Regression Coefficient Homogeneity Test refers to the significance of the interaction between the covariate (Pretest) and the independent factors (VariableGIS, VariableSTEM, and their interaction). This assumption tests whether the linear relationship between the covariate (control variable) and the dependent variable is the same in all treatment groups by looking at the significant p-value.0.05 assumption is met. The results can be seen in Table 7.

Table 7. Results of Homogeneity Test of Linear Regression Coefficients

Interaction	**Value GIS.**
Variabel GIS x Variabel STEM	0.114
Variabel GIS x Pretest	0.394
Variabel STEM x Pretest	0.128
VariabelGIS x VariabelSTEM x Pretest	0.308

There was no significant interaction between GIS, STEM, and pretest (p > 0.05), so the assumption of regression homogeneity was fulfilled. The use of ANCOVA (Analysis of Covariance) was valid. The prerequisite tests conducted by the researcher were fulfilled and could proceed to the next stage. The research hypothesis test uses data analysis and interpretation of two-way ANCOVA analysis. The researcher analysed two-way variance (Two-Way ANCOVA) to test the effect of two independent variables on one dependent variable by controlling for the effect of covariates. The covariate variable is the pretest score (students' initial ability score). Based on the results of the two-way ANCOVA analysis, the partial eta squared ($\eta^2 p$) value is used to interpret the magnitude of each factor's influence on students' spatial thinking abilities. Referring to Cohen's criteria, an $\eta^2 p$ value of around 0.01 is categorised as a small effect, around 0.06 as a moderate effect, and ≥0.14 as a large effect. The results of the hypothesis test can be seen in Table 8.

Table 8. Hypothesis Test Results

Hypothesis test results	**Significance Value**	**Partial eta squerd**
The effect of GIS implementation on spatial thinking skills	0.000	0.657
The effect of STEM implementation on spatial thinking skills	0.000	0.093
The interaction between GIS and STEM implementation on spatial thinking skills	0.000	0.128

(1) By controlling for students' pretest scores, the results of the two-way ANCOVA test showed a significant effect of GIS technology use on students' posttest scores [$F(1,131) = 250.715$, $p<0.001$, $\eta^2p = 0.657$]. with a large effect size (Partial Eta Squared = .657). The analysis results show that the implementation of GIS technology has an η^2p value of 0.657, which indicates a very large effect on students' spatial thinking abilities. This value shows that approximately 65.7% of the variation in spatial thinking abilities can be explained by the use of GIS technology after controlling for covariate effects. The magnitude of this effect can be understood because GIS functions as a spatial cognitive tool that directly trains students' visualisation, spatial relationship analysis, and spatial reasoning. The hypothesis test results with a p-value > 0.001 indicate that the null hypothesis (H_0) is rejected.

(2) By controlling for students' pretest scores, the two-way test results show a significant effect of the STEM approach on students' posttest scores [$F(1,131) = 13.452$, $p<0.001$, $\eta^2p = 0.093$]. The partial Eta Squared for STEM is only 0.093. The STEM approach shows an η^2p value of 0.093, which falls into the moderate effect category. This means that the STEM approach contributes to approximately 9.3% of the variation in students' spatial thinking abilities. This more moderate effect indicates that STEM acts as a supporting pedagogical framework that encourages the integration of cross-disciplinary concepts, problem solving, and systemic thinking, but does not directly facilitate spatial cognitive processes as intensively as GIS technology. The hypothesis test results with a p value > 0.001 reject the null hypothesis (H_0).

(3) By controlling for students' pretest scores, the results of the two-way ANCOVA test showed that the interaction between the use of GIS and the STEM approach on posttest scores was statistically significant, with a value of [$F(1,131) = 19.314$ $p<0.001$, $\eta^2p = 0.128$]. Partial Eta Squared value = 0.128. These analysis results indicate a significant interaction between GIS implementation and the STEM approach with an η^2p value of 0.128, which is in the moderate to large category. These findings indicate that the effectiveness of GIS in improving students' spatial thinking skills is influenced by the application of the STEM approach, and vice versa. Thus, the combination of GIS and STEM provides a stronger synergistic effect than the application of each separately. The hypothesis test results with a p>0.001 value reject the null hypothesis (H_0).

Discussion

The influence of GIS technology on spatial thinking skills

The results of the study indicate that the use of Geographic Information System (GIS) technology has a significant effect on students' spatial thinking abilities after controlling for initial abilities. This finding not only confirms the effectiveness of GIS as a learning medium, but also indicates that GIS acts as a cognitive tool that mediates the way students represent, manipulate, and reason spatial information. Cognitively, GIS allows students to integrate various spatial representations-such as thematic maps, satellite imagery, and attribute data-into a single interactive visual environment. This interaction encourages spatial encoding and spatial transformation processes, namely the ability to identify patterns, relationships, and spatial changes dynamically. Thus, the improvement in spatial thinking skills is not solely due to exposure to technology, but to the spatial reasoning process triggered through the exploration of GIS-based geographic data.

The coefficient of determination ($\eta^2 p = 0.093$) indicates that the analysis model is able to explain a large proportion of the variance in students' spatial thinking scores. However, this value needs to be interpreted with caution, as it does not represent the sole contribution of GIS, but rather the result of interactions between treatment, students' initial abilities, and the learning context. Therefore, this finding is not claimed to be an absolute causal relationship, but rather strong empirical evidence that GIS functions as a key facilitator in spatial thinking learning. The results of this study reinforce the importance of integrating spatial technology, including GIS, into geography learning. These findings expand on previous findings that emphasise the role of geospatial technology in geography learning, by showing that the effectiveness of GIS is highly dependent on how the technology is used to stimulate spatial reasoning, rather than merely as a tool for digital map visualisation.

The results of this study are also in line with the opinions of a number of researchers, including Carbonell and Medler, who emphasise the importance of mastering geospatial thinking in the context of using, reading and understanding maps, which is a core skill in geography learning. Geography studies all objects and phenomena from a spatial perspective, making the use of maps a necessity (Rahmawati, Irawan, & Purwanto, 2023). In his research, Rahayu et al., (2019) states that Google Earth has an impact on improving students' spatial thinking skills. In line with this study, during the treatment process, the researcher provided an understanding of Google Earth, which indicates that actions or treatments in the classroom learning process have a significant impact on improving students' spatial thinking skills and learning outcomes.

Research supports the National Research Council's recommendation that GIS be used as a tool in geography curricula due to GIS's capabilities for visualisation, data interaction, and spatial analysis (Jo, Hong, & Verma, 2016). According to Jo et al., (2016), Web-GIS-based activities have proven to be effective in strengthening students' spatial skills in the context of geography learning. This is an important point in strengthening the researchers' argument that the application of GIS is significant in improving students' spatial thinking skills. Although the research by Jo, Hong and Verma refers more to university students, the need for spatial thinking skills is also applicable in secondary school geography learning.

The effect of the STEM approach on spatial thinking skills

The STEM approach in this study also showed a significant effect on students' spatial thinking abilities, with a partial eta squared value ($\eta^2p = 0.093$) that was classified as moderate. These findings indicate that STEM contributes to the development of spatial thinking, but with a smaller effect size compared to the use of GIS. This moderate effect size indicates that the STEM approach does not automatically optimise spatial thinking abilities if it is not explicitly designed to target spatial reasoning processes. In practice, the implementation of STEM in the classroom often emphasises contextual problem solving, project work, and cross-disciplinary integration, but does not necessarily require students to perform in-depth spatial analysis.

In the study (Bodzin, Hammond, Fu, & Farina, 2020), The existence of valid and reliable instruments is important as a measuring tool to ensure that STEM-based learning interventions not only improve cognitive abilities, such as spatial thinking and geography skills, but also have a positive effect on students' attitudes and interests. (Zuhria et al., 2023) These findings reinforce the argument that specially designed learning media with integrated STEM and spatial approaches can be an effective means of facilitating the development of students' spatial thinking skills. These differences support previous findings that the STEM approach is effective in improving students' spatial thinking abilities.

A STEM approach that integrates four disciplines with a focus on spatial aspects, thereby helping students understand concepts, phenomena, and issues based on spatial relationships and their surrounding environment (Rahmawati et al., 2023). In addition, the complexity of STEM tasks, teachers' readiness in designing spatial-based activities, and limited learning time can be factors that limit the impact of the STEM approach on spatial thinking. Therefore, these results provide important findings that STEM needs to be equipped with cognitive tools that explicitly stimulate spatial abilities in order to optimise its impact.

Interaction between GIS technology implementation and STEM approaches on spatial thinking skills

The analysis results show a significant interaction between the use of GIS and the STEM approach on spatial thinking skills ($\eta^2p = 0.128$). This finding confirms that the influence of each variable is not additive but rather mutually reinforcing when integrated into a single learning framework. Conceptually, GIS provides rich and accurate spatial representations, while the STEM approach provides an authentic, inquiry-based problem-solving context. The integration of the two creates learning conditions in which students not only understand what and where a phenomenon occurs, but also why and how that phenomenon can be analysed and solved spatially. This process encourages the simultaneous development of representational competence and spatial reasoning.

The impact of GIS use on students' spatial thinking abilities also varies depending on whether learning is applied in a STEM context or not. This is in line with his research (Ridhaa, Kamil, Abdi, Yunus, & Safiah, 2020), emphasises that GIS learning materials designed based on spatial thinking explicitly provide strong support for students' spatial abilities. With this in mind, the results of the study show that maximum spatial ability is achieved when GIS is used within a STEM framework, rather than separately.

The research Putra et al., (2021) and Bodzin et al., (2020), Both studies state that the STEM approach is highly effective in improving spatial thinking skills. in addition, (Duarte, Teodoro, & Gonçalves, 2022; Halengkara, Salsabila, & Nurhayati, 2022; Jo et al., 2016), these three studies also indicate that GIS technology can improve spatial thinking skills. Several of the above studies, which researchers refer to in conducting their research, provide evidence that the integration of GIS technology and the STEM approach is effective in improving students' spatial thinking skills.

Theoretically, this study contributes by strengthening the spatial thinking framework as a result of the interaction between representational technology (GIS) and problem-solving-based pedagogical approaches (STEM). The challenge faced by educators in the era of globalisation and modernity is the rapid development of educational technology (Hidiyah, Sumarmi, Bachri, & Mkumbachi, 2023). In particular, the use of Geographic Information Systems (GIS) in the STEM approach requires the integration of technology, spatial data, and interdisciplinary learning. This study not only confirms the effectiveness of GIS or STEM separately, but also shows that spatial thinking skills develop optimally through the integration of both in a single learning unit. These findings expand the theory of spatial thinking by positioning GIS as a cognitive mediator and STEM as a contextual driver in the development of students' spatial reasoning. Thus, this study provides empirical confirmation and offers an integrative framework that can be used as a basis for developing GIS and STEM-based technology learning designs in geography.

In practical terms, the integration of GIS in STEM learning is recommended, particularly in geography subjects that require analysis of patterns, distribution, and spatial relationships, such as environmental dynamics, disaster mitigation, and regional planning. This implementation requires prerequisites in the form of teacher readiness in operating basic GIS, as well as the design of tasks that explicitly target spatial thinking skills. This approach is most effectively applied at the secondary school level using project-based or problem-based learning models, where students can explore real spatial data and relate it to everyday contexts. Thus, the integration of GIS–STEM not only enhances spatial thinking skills but also supports the development of 21st-century skills in a more focused and meaningful way.

CONCLUSION

This study examined the effects of GIS technology and a STEM-based instructional approach on senior high school students’ spatial thinking using a quasi-experimental 2 × 2 factorial design. The findings indicate that GIS-based instruction exerted a substantial influence on students’ spatial thinking, while the STEM approach demonstrated a moderate effect. In addition, the interaction between GIS technology and the STEM approach suggests that their combined implementation contributes differently to spatial thinking development compared to the application of each approach in isolation. By controlling students’ prior spatial ability through the inclusion of pretest scores as a covariate, this study provides empirical evidence that the observed effects are not solely attributable to initial differences among groups. However, the magnitude of the effect sizes particularly for GIS should be interpreted cautiously, given the quasi-experimental design, the absence of individual randomization, and the contextual nature of the instructional implementation, which may introduce potential overestimation. From a conceptual perspective, the results position GIS as a cognitive tool that supports spatial representation and reasoning, while the STEM approach functions as a pedagogical framework that contextualizes spatial problem-solving through interdisciplinary learning. Accordingly, this study extends previous GIS or STEM research by clarifying the role of their interaction in fostering spatial thinking rather than merely confirming their individual effectiveness. Despite its contributions, this study is limited by its sample scope and instructional context. Future research is recommended to employ more rigorous experimental controls, report detailed treatment fidelity, and further investigate the cognitive mechanisms underlying GIS–STEM integration in geography education. The author states that artificial intelligence is used to a limited extent in the translation and editing process to improve the clarity and readability of the manuscript. All content, data analysis, interpretation of results, and conclusions are the result of the author's own thinking and are the author's sole responsibility.

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