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Interactive geometry simulation and students' spatial understanding: The roles of cognitive load, collaboration, and enjoyment

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Abstract

Students' difficulties in understanding geometric structures and spatial relationships remain a major challenge in mathematics education. This study investigated the effects of interactive geometry simulation (IGS) and examined how cognitive load (CL), collaboration (Col), and enjoyment (EJ) relate to students' spatial conceptual understanding (SC) in solid geometry learning. A quasi-experimental pre-/post-test control group design was conducted with 108 sixth-grade students. Data were collected through conceptual understanding tests and perception questionnaires and analyzed using repeated measures analysis of variance, multivariate analysis of variance, and correlation analysis. Results revealed a significant interaction effect between instructional group and time, $F(1,106) = 10.172$, $p < .001$, $\eta^2 = .108$, indicating greater learning gains among students using IGS. The experimental group reported significantly higher Col, EJ, and SC, while CL remained comparable. EJ showed the strongest association with SC ($r = .566$), followed by Col ($r = .314$). These findings provide novel evidence of the integrated roles of cognitive, social, and affective processes and inform the design of engaging simulation-based geometry instruction.

Keywords: spatial conceptual understanding, interactive simulation, geometry learning, collaboration, enjoyment, cognitive load

INTRODUCTION

Students' difficulties in geometry and spatial reasoning remain a persistent concern in mathematics education worldwide. Large-scale international assessments, including PISA and TIMSS, consistently show that many students struggle with geometric reasoning and spatial representation tasks. For example, the average mathematics score in PISA 2022 across OECD countries was 472, while Indonesia scored 366 (OECD, 2023). Similarly, TIMSS 2019 reported that many students achieved only low to intermediate proficiency levels, indicating limited ability to analyze geometric structures and manipulate spatial representations. These findings suggest that students often experience difficulties with spatial visualization, shape transformation, and interpreting two-dimensional representations of three-dimensional objects (Fujita et al., 2020; Gilligan-Lee et al., 2022), highlighting the need to better understand the cognitive processes involved in geometry learning.

A growing body of research attributes these challenges to the insufficient development of spatial thinking within mathematics curricula and instructional practices. Spatial thinking involves cognitive processes such as mental rotation, spatial visualization, and spatial working memory, which are essential for understanding geometric relationships and structures. A large-scale meta-analysis reported a moderate correlation between spatial ability and mathematics performance ($r \approx 0.36$), indicating that improvements in spatial ability can contribute to overall mathematical achievement (Atit et al., 2021). In addition, spatial working memory has been identified as a critical mechanism supporting both numerical and geometric reasoning, emphasizing the importance of spatial information processing in mathematical learning (Silverman & Ashkenazi, 2022). Developmental research further indicates that spatial

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Contribution to the literature

- This study addresses a gap in the literature by integrating cognitive, social, and affective dimensions in simulation-based geometry learning, which are typically examined separately.
- It introduces interactive geometry simulation (IGS) as a comprehensive learning environment that combines interactive visualization, collaboration (Col), and enjoyment (EJ) without increasing cognitive load (CL).
- The study provides empirical evidence that EJ and Col are significantly associated with spatial conceptual understanding (SC), with EJ showing the strongest relationship.

abilities such as spatial scaling and mental rotation can predict students' mathematics performance from the elementary school level (Gilligan-Lee et al., 2022). From a cognitive perspective, spatial visualization, mental rotation, and working memory function synergistically to connect spatial reasoning with numerical and geometric processing (Hawes & Ansari, 2020). When these processes are insufficiently supported during instruction, students often experience difficulties in coordinating multiple representations, interpreting geometric structures, and constructing stable spatial mental models.

Beyond cognitive limitations, students' difficulties in geometry are also associated with challenges in coordinating multiple spatial representations. Many learners struggle to relate two-dimensional representations to three-dimensional structures, such as interpreting nets of solids, identifying relationships among edges and faces, or understanding surface area and volume conceptually. Research suggests that visual representation alone is insufficient; students must integrate visualization with knowledge of geometric properties to construct accurate spatial understanding (Fujita et al., 2020). Furthermore, geometry learning often imposes substantial CL because learners are required to process multiple visual and conceptual elements simultaneously (Farzan et al., 2025; Rachmawati et al., 2025). These challenges indicate the need for learning environments that support representational coordination while reducing unnecessary cognitive demands. IGS offer a potential solution by enabling dynamic visualization and direct manipulation of three-dimensional objects, thereby facilitating the construction of spatial mental models and conceptual understanding.

In response to these challenges, recent studies have increasingly explored the use of technology-enhanced learning environments to support spatial understanding. Digital tools such as dynamic geometry environments, GeoGebra three-dimensional, and augmented reality (AR) have been shown to improve spatial visualization, mental rotation, volumetric reasoning, and students' motivation in learning mathematics (Morales Méndez & Lozano Avilés, 2025; Ng et al., 2020). AR-based geometry games have also demonstrated moderate improvements in spatial perception and visualization abilities (Mandala et al., 2025). In addition, technology-supported collaborative learning environments can enhance conceptual understanding and mathematical reasoning more effectively than individual technology use or traditional instruction (Demir & Zengin, 2023; Gurmu et al., 2024). Research grounded in cognitive load theory (CLT) further indicates that dynamic representations accompanied by appropriate scaffolding strategies can reduce extraneous CL and improve students' learning performance in geometry (Hsu & Hsu, 2024). Simulation-based and three-dimensional modeling environments have also been reported to reduce perceived task complexity while increasing learning satisfaction and spatial reasoning (Borboeva et al., 2025). Moreover, affective dimensions such as EJ and positive emotions have been shown to play an important role in mathematics learning by increasing engagement, self-efficacy, and academic achievement (Liu et al., 2018; Živković et al., 2023). Moreover, although these technologies have demonstrated positive educational outcomes, most studies primarily focus on learning achievement or spatial visualization. Less attention has been given to how multiple learning processes are simultaneously supported within a single technology-enhanced geometry learning environment.

Despite these advances, existing studies tend to examine cognitive, social, and affective factors in isolation. Empirical research that simultaneously investigates how CL management, collaborative interaction, and EJ operate together within technology-supported geometry simulations remains limited. Moreover, few studies have examined these dimensions within a single simulation-based geometry learning environment specifically designed to support three-dimensional spatial understanding. Therefore, the novelty of this study lies in integrating CL, Col, and EJ into a unified analytical framework and examining their relationships with students' SC through IGS. Understanding the interaction among these dimensions is essential for designing learning environments that effectively support students' spatial conceptual development. Therefore, this study aims to examine the relationships among CL, Col, EJ, and students' SC in solid geometry learning using IGS. By exploring the interplay between cognitive, social, and affective dimensions within a technology-enhanced learning environment, this research seeks to provide a more integrated understanding of how instructional design can support the development of spatial understanding in mathematics learning contexts. The findings are expected to contribute theoretically to the literature on digital mathematics education and practically to inform the design of technology-based geometry instruction that combines interactive visualization, collaborative engagement, and meaningful learning experiences to strengthen students' understanding of three-dimensional geometric structures.

LITERATURE REVIEW

Interactive Geometry Simulation in Geometry Learning

Advances in digital technology have expanded the use of IGS as instructional tools that allow dynamic manipulation and visualization of geometric objects. Technologies such as AR and dynamic geometry software enable learners to explore three-dimensional structures in ways that are more interactive and exploratory than static representations. Empirical studies indicate that AR-based visualization can support students' understanding of spatial relationships among geometric elements, such as edges, faces, and space diagonals, by providing more realistic visual experiences (Amir et al., 2020). More broadly, systematic reviews and meta-analyses suggest that interactive geometry technologies have positive effects on students' conceptual understanding and spatial abilities (Ahmad & Junaini, 2020; Hillmayr et al., 2020; Juandi et al., 2021).

Nevertheless, research also indicates that three-dimensional visualization alone is insufficient to develop deep geometric understanding. Effective geometry learning requires students to integrate visual representations with knowledge of geometric properties, including relationships among edges, angles, and planes (Fujita et al., 2020). Consequently, the effectiveness of geometry simulations is not determined solely by the quality of visualization but also by how learning environments support the construction of conceptual understanding.

Spatial Conceptual in Geometry Learning

Understanding geometry is closely related to students' ability to construct accurate spatial representations. In mathematics education, this capability is commonly associated with spatial reasoning and spatial visualization, which involve constructing and manipulating mental representations of objects and their spatial relationships (Fujita et al., 2020; Gilligan-Lee et al., 2022). SC involves not only imagining three-dimensional forms but also integrating visual representations with conceptual knowledge of geometric structures.

Research suggests that processes such as mental rotation, transformations between two-dimensional and three-dimensional representations, and interpretation of spatial perspectives are essential components in understanding the structure of solid figures (Frick, 2018; Fujita et al., 2020). In addition, understanding geometric elements such as edges, faces, and diagonals plays an important role in connecting visual representations with formal mathematical concepts. Spatial abilities have also been shown to correlate with mathematics performance, as they support students in organizing and manipulating spatial structures during problem solving (Hawes & Ansari, 2020; Hawes et al., 2022; Silverman & Ashkenazi, 2022). Simulation-based learning environments provide opportunities for learners to explore spatial relationships through manipulation of three-dimensional objects, thereby facilitating the construction of clearer mental representations of geometric structures.

Although SC is closely related to spatial visualization, the two constructs are distinct. Spatial visualization refers to the ability to mentally represent, manipulate, rotate, and transform objects and their spatial relationships (Frick, 2018; Fujita et al., 2020). SC, by contrast, involves reasoning about geometric properties, relationships, and structures represented through those visualizations (Gilligan-Lee et al., 2022; Hawes & Ansari, 2020). Consequently, strong visualization skills do not necessarily imply a corresponding understanding of geometric properties and relationships (Fujita et al., 2020). Spatial visualization can therefore be regarded as a cognitive foundation that supports, but does not fully constitute, SC.

In the present study, SC is defined as students' ability to interpret and connect visual representations of geometric objects with conceptual knowledge of their structures and properties. This construct encompasses understanding relationships among geometric elements, interpreting transformations between two-dimensional and three-dimensional representations, and constructing coherent mental representations of solid figures. Consistent with this definition, the construct was operationalized through indicators of spatial visualization, including recognizing relationships among geometric elements, interpreting transformations from nets to solid figures, and constructing mental representations of three-dimensional objects. These indicators were selected because they provide observable evidence of students' understanding of geometric structures and relationships. Accordingly, spatial visualization was treated as an indicator of SC rather than as an equivalent construct.

Integrating Cognitive Load, Collaboration, and Enjoyment in Simulation Geometry Learning

Understanding the structure of three-dimensional geometric objects requires complex information processing and therefore imposes substantial cognitive demands. CLT explains that learning effectiveness is influenced by the limited capacity of working memory to process new information (Anmarkrud et al., 2019; Choi & Lee, 2022). Within this framework, CL consists of three components: intrinsic load, extraneous load, and germane load. Intrinsic load refers to the inherent complexity of learning materials, whereas extraneous load arises from inefficient presentation of information. Germane load, in contrast, represents the mental effort devoted to constructing conceptual schemas (Klepsch & Seufert, 2020). In technology-based learning environments, interactive visualization can facilitate the integration of verbal and visual information, thereby reduce extraneous CL and support the development of mental models (Buchner et al., 2022; İbili, 2019). However, overly complex technologies or excessive visual elements may increase CL and hinder conceptual understanding (Jeffri & Awang Rambli, 2021). These findings highlight the importance of instructional design in ensuring that technological tools support rather than overload learners' cognitive processes.

Col represents a crucial component of mathematics learning because it enables students to construct knowledge through social interaction. Meta-analyses indicate that cooperative learning approaches have positive effects on students' mathematics achievement and attitudes toward mathematics (Capar & Tarim, 2015; Turgut & Gülşen Turgut, 2018). In technology-enhanced learning contexts, Col is often facilitated through computer-supported collaborative learning (CSCL) environments that allow students to discuss ideas and build shared understanding using digital platforms (Sung et al., 2017). Collaborative interaction allows students to articulate explanations, present arguments, and revise their understanding through negotiation of meaning. These processes may trigger socio-cognitive conflict, which plays a significant role in the restructuring of conceptual knowledge (de la Hera et al., 2019; Tenenbaum et al., 2020). In simulation-based geometry learning, discussions about the results of exploring geometric objects can help students clarify structural relationships among elements of three-dimensional figures.

Beyond cognitive and social factors, affective dimensions also play an important role in mathematics learning. One relevant academic emotion is EJ, defined as the positive feeling that emerges when students engage in learning activities. Research shows that EJ is positively associated with intrinsic motivation, learning engagement, and academic achievement (García et al., 2016; Pekrun et al., 2017). Students who experience positive emotions during mathematics learning tend to demonstrate greater persistence and adopt deeper learning strategies (Abín et al., 2020). In technology-enhanced learning environments, interactive tools such as simulations and dynamic geometry applications have been reported to increase students' motivation and positive attitudes toward mathematics (Attard & Holmes, 2020; Hillmayr et al., 2020). Interactive technologies allow learners to explore concepts visually while receiving immediate feedback, making learning experiences more engaging and stimulating.

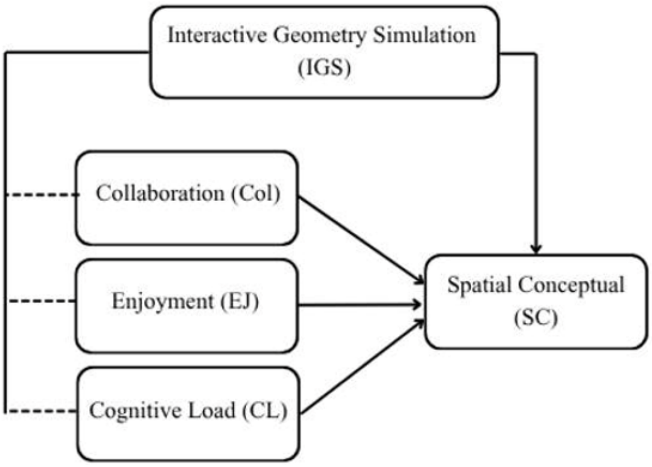

Figure 1. Conceptual framework of the study (the authors' own elaboration)

Based on CLT, social constructivism, and the control-value theory of achievement emotions, this study proposes a conceptual framework explaining the relationships among CL, Col, EJ, and students' SC within an IGS environment. As illustrated in **Figure 1**, IGS functions as a technology-enhanced learning environment that supports cognitive processing, collaborative interaction, and positive emotional experiences during geometry learning. Through features such as object rotation, net exploration, and guided calculation simulations, IGS provides opportunities for students to explore geometric concepts, interact with peers, and engage actively in learning activities, which are expected to support the development of SC.

RESEARCH AIMS AND RESEARCH QUESTIONS

The purpose of this study is to examine the relationships among CL, Col, EJ, and students' SC in solid geometry learning using IGS. The study therefore sought answers to the following questions:

1. Does the use of IGS improve students' learning outcomes compared with conventional instruction?
2. Are there differences in CL, Col, EJ, and SC between instructional groups?
3. How are CL, Col, and EJ associated with SC?

METHODOLOGY

Research Design

This study employed a quantitative approach using a quasi-experimental pre-/post-test control group design to examine the effects of IGS on elementary students' geometry learning. The design was selected because the study was conducted in existing classroom settings where random assignment was not feasible. Quasi-experimental designs are widely used in educational research to evaluate instructional interventions under authentic learning conditions. To minimize threats to internal validity, all participants were drawn from the same grade level, followed the same curriculum, completed an identical pre-test, and were taught by the same mathematics teacher. Both groups followed the same learning objectives, instructional schedule, lesson plan, and instructional time allocation, with the instructional medium constituting the only planned difference between the two groups.

The study involved two main groups: a control group and an experimental group. Both groups learned the same instructional content and followed similar learning procedures; however, they differed in the instructional media used during the learning process. The control group participated in conventional instruction that involved printed modules, teacher explanations, group discussions, and student worksheets. In contrast, the experimental group participated in learning activities enriched with IGS as a supporting instructional medium that provided interactive three-dimensional visualization to facilitate students' understanding of solid geometry concepts.

Conceptually, the research design followed a pre-test-treatment-post-test sequence. At the beginning of the study, all students completed a pre-test to measure their initial understanding of solid geometry concepts. Subsequently, both groups participated in instructional activities with different treatments according to the research design. After the instructional period was completed, students took a post-test to assess improvements in conceptual understanding. In addition, students completed a perception questionnaire designed to capture their learning experiences related to CL, CoI, EJ, and SC.

Development of the Interactive Geometry Simulation

The IGS application was developed as a technology-based learning medium intended to support students' understanding of solid geometry concepts through interactive three-dimensional visualization. The application was developed using the Unity platform, which allowed the integration of three-dimensional geometric models with interactive features accessible through Android-based mobile devices. This platform was selected because it enabled dynamic and responsive visual simulations that were easily accessible to students within a digital learning environment.

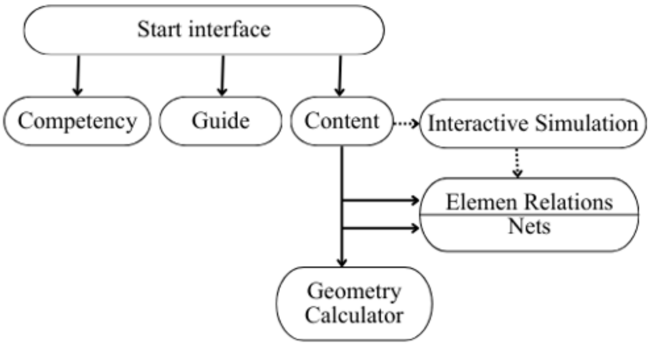

Figure 2. Design of IGS (the authors' own elaboration)

Conceptually, IGS was designed as a supplementary learning medium that complemented the use of printed instructional modules. The application consisted of two main components: conceptual materials and interactive simulations. The conceptual materials presented explanations of geometric properties, relationships among geometric elements, and formulas for surface area and volume. Three-dimensional visualization allowed students to observe relationships among edges, diagonals, and angles more clearly through object rotation features that enabled viewing from multiple perspectives.

Pedagogically, IGS was designed to support representational coordination and spatial reasoning by enabling students to actively explore relationships among geometric elements and connect two-dimensional representations with three-dimensional structures. These learning experiences were expected to facilitate SC while reducing unnecessary cognitive demands during geometry learning.

In addition, IGS included an exploration feature for solid nets, allowing students to observe the transformation of three-dimensional objects into two-dimensional representations dynamically. Through this feature, learners could open and close the nets and rotate the shapes to understand the relationship between two-dimensional and three-dimensional representations. The application also provided a calculation simulation feature that allowed students to input parameters such as length, width, height, or radius to calculate the surface area and volume of geometric solids automatically. The system then displayed the calculation results along with the solution steps in both visual and textual formats. The development process of the IGS application involved three stages: design, development, and implementation, as illustrated in **Figure 2**. Prior to implementation, the application was reviewed by experts in mathematics education and educational technology to evaluate content accuracy, pedagogical suitability, and usability. Revisions were made based on expert feedback before the application was used in the study.

Figure 3. User interface of the IGS application (the authors' own screenshots from the geometry simulation application)

From a user-interface perspective, the IGS application was designed with usability considerations appropriate for elementary school students. The interface included simple instructions and intuitive navigation, enabling students to explore geometric concepts independently or collaboratively. Through object manipulation, net exploration, and guided calculation simulations, students could visualize geometric relationships and engage actively with solid geometry concepts. Examples of the user interface and main features available in the IGS application are presented in **Figure 3**.

Research Participants

The participants of this study were 108 sixth-grade students from MI Hasyim Asy'ari Malang, distributed across four existing classrooms: class 6A (28 students), class 6B (27 students), class 6C (27 students), and class 6D (26 students). Participants were selected using cluster sampling based on existing sixth-grade classrooms. This approach was considered appropriate because instructional activities were organized at the classroom level and allowed the intervention to be implemented without disrupting regular school schedules. The selected classes represented the entire population of sixth-grade students within the school. All participants were at the same educational level and followed a uniform mathematics curriculum, particularly in the topic of solid geometry. Group assignment was based on the existing classroom structure to maintain the natural learning environment. Accordingly, class 6A and class 6B were assigned as the control group, while class 6C and class 6D served as the experimental group. The control group participated in conventional instruction using printed modules and teacher explanations, whereas the experimental group engaged in learning activities enriched with the IGS application as an interactive visualization tool for exploring solid geometry concepts. The detailed distribution of participants across classes and treatment groups (**Table 1**).

Table 1. Distribution of research participants

Class	Group	n	Male	Female
Grade 6A	Control	28	13	15
Grade 6B	Control	27	15	12
Grade 6C	Experiment	27	14	13
Grade 6D	Experiment	26	15	11
Total		108	57	51

Note. n: Number of students

Prior to the instructional intervention, all students completed a pre-test to assess their initial understanding of solid geometry concepts. This step ensured that the baseline conditions of the control and experimental groups could be compared objectively. Prior to data collection, permission to conduct the study was obtained from the school administration. Participation in the study was voluntary, and informed consent was obtained from students' parents or legal guardians. Students were informed that the collected data would be used solely for research purposes, and all responses were anonymized to ensure confidentiality and privacy.

Research Procedure

The instructional process consisted of several stages designed systematically to evaluate the effects of IGS on students' understanding of solid geometry concepts. The research procedure included pre-testing, instructional implementation, post-testing, and the completion of a student perception questionnaire. The first stage

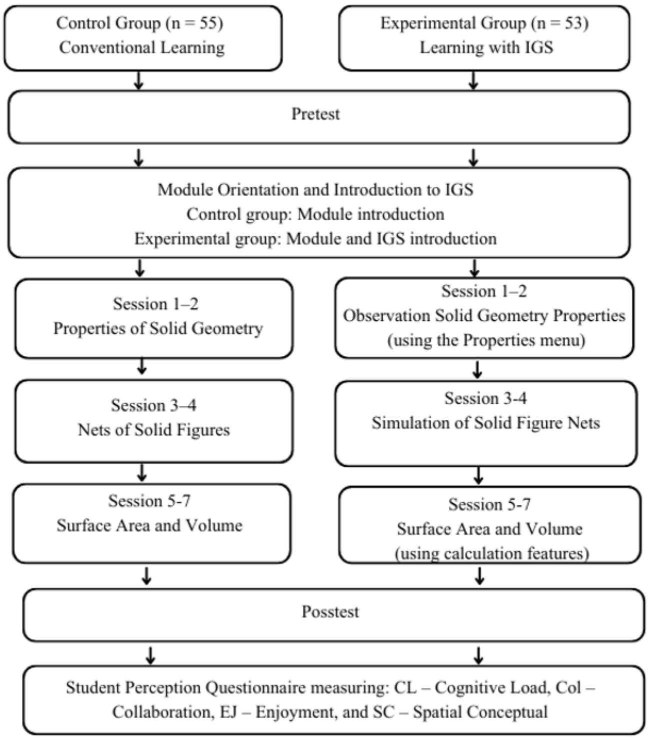

Figure 4. Research procedure (authors' own elaboration)

involved administering the pre-test, which aimed to measure students' prior knowledge of solid geometry before the instructional intervention began. All students in both the control and experimental groups completed the same pre-test instrument, enabling an objective comparison of the two groups' initial conditions. The second stage involved the implementation of the instructional intervention. During this phase, students participated in learning activities over a period of seven weeks, with two sessions per week, equivalent to five instructional periods per week, where each instructional period lasted 35 minutes. The learning materials covered major solid geometry topics, including cubes, rectangular prisms, prisms, pyramids, cylinders, cones, and spheres. Both groups studied the same content, used equivalent worksheets, followed identical learning objectives, participated in similar discussion activities, and received the same instructional time and teacher facilitation. The only difference was the use of IGS as the instructional medium in the experimental group.

The control group received conventional instruction, which involved the use of printed modules, teacher explanations, group discussions, and student worksheets. In contrast, the experimental group engaged in learning activities supported by the IGS application, which served as an interactive visualization tool to facilitate exploration of solid geometry concepts. Within the experimental group, students used the IGS application to observe three-dimensional geometric objects through features such as object rotation, net exploration, and simulations for calculating surface area and volume. These activities enabled students to examine relationships among geometric elements more clearly through interactive visualization. Throughout the learning process, students worked in small collaborative groups to discuss concepts and complete assigned tasks. The teacher acted as a facilitator, guiding students in understanding the material and supporting their use of the simulation application. After the instructional phase was completed, students participated in a post-test, which aimed to measure improvements in their understanding of solid geometry concepts following the learning intervention. The post-test was administered to both groups using the same instrument as the pre-test, allowing direct comparison of learning outcomes.

The final stage involved the completion of a student perception questionnaire designed to capture students' learning experiences during the instructional process. The questionnaire measured four main constructs: CL, Col, EJ, and SC. Through this instrument, the study not only evaluated students' learning outcomes but also examined their perceptions of the learning experience under different instructional conditions. The overall sequence of the research procedure is illustrated (**Figure 4**), which presents the stages of the study from the preparation phase to the evaluation of learning outcomes.

Research Instruments

This study employed two primary research instruments: a cognitive test and a student perception questionnaire. The cognitive test was used to measure students' understanding of solid geometry concepts, while the questionnaire was administered to capture students' learning experiences during the instructional process.

The cognitive test was administered as both a pre- and post-test, each consisting of 10 multiple-choice items designed for sixth-grade students. The test blueprint was developed based on the sixth-grade geometry curriculum and covered three indicators:

(1) identifying geometric elements and properties,

(2) interpreting spatial relationships and transformations between two-dimensional and three-dimensional representations, and

(3) applying concepts of surface area and volume in problem-solving situations.

The decision to use 10 multiple-choice items was based on the focused scope of the targeted learning outcomes and the age characteristics of the participants. The items were designed to represent the three core indicators of SC addressed in the instructional intervention while maintaining an assessment length appropriate for sixth-grade students. This approach allowed the instrument to provide adequate coverage of the targeted concepts without imposing excessive testing demands on young learners. Each item was scored dichotomously (1 = correct, 0 = incorrect), resulting in a

Table 2. Construct structure, subdimensions, and distribution of questionnaire items

Construct	Sub-dimension	Item number	Measurement focus
CL	Intrinsic CL	2, 3, 5	The perceived complexity of solid geometry concepts and the difficulty students experience in understanding relationships among geometric elements such as edges, diagonals, angles, and formulas for surface area and volume.
	Extraneous CL	1, 7	Cognitive demands arising from the presentation of instructional information or learning instructions that may influence students' attention and focus during learning.
	Germane CL	4, 6, 8	Students' mental effort in constructing conceptual understanding through observing geometric shapes, understanding nets of solids, and following problem-solving procedures.
Col	Active participation	9, 10, 13, 15	The extent to which students actively participate in group discussions, share ideas, and exchange perspectives with peers during learning activities.
	Group responsibility	11, 12, 14, 16	Students' willingness to cooperate, assist peers, and work collectively in completing tasks and understanding the learning material.
EJ	Learning EJ	17, 18, 20, 21	Students' feelings of enjoyment and interest while participating in solid geometry learning activities.
	Learning motivation	19, 22, 23, 24	Students' internal motivation to attempt tasks, explore concepts, and further engage with solid geometry learning.
SC	Spatial visualization	25, 26, 27, 28	Students' ability to imagine and understand the structure of three-dimensional objects through observing shapes, recognizing relationships among geometric elements, and interpreting transformations from nets to solid figures.

maximum score of 10. Prior to implementation, the instrument was reviewed by two mathematics education experts to ensure content relevance, clarity, and alignment with the intended learning objectives. Revisions were made based on their feedback. Item analysis indicated satisfactory psychometric properties. Item difficulty indices ranged from 0.425 to 0.563, indicating moderate levels of difficulty across all items. Item-rest correlations ranged from 0.330 to 0.587, demonstrating acceptable to very good discriminatory power. Reliability analysis yielded a Cronbach's alpha coefficient of 0.755, indicating satisfactory internal consistency for educational research purposes. The complete spatial conceptual understanding test and validation evidence are presented in **Appendix A**.

The second instrument was a student perception questionnaire consisting of 28 items measured using a five-point Likert scale. The questionnaire assessed four main constructs: CL, Col, EJ, and SC. All questionnaire items were formulated using statements that were neutral with respect to the instructional media, allowing the instrument to be applied consistently to both the control and experimental groups. The structure of the constructs, their subdimensions, and the distribution of questionnaire items used in this study are presented in detail in **Table 2**. The questionnaire items were adapted from established constructs in previous studies on CL, collaborative learning, learning EJ, and spatial understanding. The complete questionnaire items are presented in **Appendix B**. Prior to implementation, the cognitive test and questionnaire were reviewed by two mathematics education experts and one educational technology expert to evaluate content relevance, clarity, and alignment with the research constructs. Revisions were made based on their feedback to improve item wording, content representativeness, and suitability for sixth-grade students.

To ensure the internal consistency of the questionnaire instrument, reliability analysis was conducted using Cronbach's alpha based on students' responses to the 28 questionnaire items collected after the instructional intervention. Cronbach's alpha coefficients were calculated separately for each construct (CL, Col, EJ, and SC) to evaluate the consistency of responses among items representing the same construct. The results indicated that all constructs demonstrated acceptable levels of reliability, with Cronbach's alpha coefficients ranging from 0.717 to 0.790. The spatial conceptual construct showed the highest reliability (α = 0.790), followed by Col (α = 0.732), CL (α = 0.728), and EJ (α = 0.717). These values exceeded the commonly recommended threshold for educational research, indicating that the questionnaire instrument exhibited satisfactory internal consistency.

Data Analysis

The analysis began with descriptive statistics to summarize the characteristics of the dataset, including the mean (M), standard deviation (SD), minimum, and maximum values for the pre-test scores, post-test scores, and questionnaire scores across each research construct. Prior to conducting inferential analyses, the data were examined to ensure that the assumptions of parametric analysis were met. Normality was tested using the Shapiro-Wilk test, and homogeneity of variance was

Table 3. Descriptive learning outcomes

Test		Valid	M	SD	Shapiro-Wilk	p	Lavene F	p
Pre-test	Control	55	65.89	2.291	0.951	.056	0.004	.948
	Experiment	53	65.91	2.314	0.950	.058	0.004	.948
Post-test	Control	55	72.89	2.291	0.951	.066	3.923	.051
	Experiment	53	82.36	2.909	0.940	.052	3.923	.051

assessed using a homogeneity test. In addition, the reliability of the questionnaire instrument was evaluated using Cronbach's alpha to examine the internal consistency of each construct. To analyze changes in students' learning outcomes and differences between the control and experimental groups, a two-factor repeated measures analysis of varia (ANOVA) was employed. This analysis included two factors: time (pre- and post-test) as the within-subject factor, and instructional group (control and experimental) as the between-subject factor. The analysis was used to identify:

(1) the effect of time on students' learning improvement,

(2) differences in learning outcomes between the instructional groups, and

(3) the interaction between time and instructional group in influencing changes in students' learning scores.

Furthermore, multivariate analysis of variance (MANOVA) was conducted to examine differences in students' perceptions between the control and experimental groups across four main constructs: CL, Col, EJ, and SC. The score for each construct was calculated as the M of students' responses to the questionnaire items representing that construct. In addition to statistical significance, the study also reported effect sizes using partial eta squared (η^2) to indicate the magnitude of the instructional treatment effects on students' learning outcomes and learning experiences.

FINDING OF STUDY

Descriptive Statistics of Students' Learning Outcomes

This study first examined the overall distribution and trends of students' learning outcomes to establish the baseline comparability of the control and experimental groups and to observe changes following the instructional intervention. Descriptive statistics—including M, SD, coefficient of variation, and assumption testing for normality and homogeneity of variance—were calculated for the pre- and post-test scores (**Table 3**).

The descriptive statistics indicated that both groups demonstrated relatively similar initial abilities during the pre-test stage. The M score of the control group (M = 65.89, SD = 2.291) was nearly identical to that of the experimental group (M = 65.91, SD = 2.314). An independent-samples t-test confirmed that this difference was not statistically significant, t(106) = -0.033, p = .974, indicating that the two groups were equivalent at baseline prior to the instructional intervention. Following the instructional intervention, learning outcomes improved in both groups; however, the magnitude of improvement differed considerably. The M post-test score of the control group increased to 72.89 (SD = 2.291), whereas the experimental group achieved a substantially higher M score of 82.36 (SD = 2.909). This difference suggested that the instructional environment enriched with IGS may have provided stronger support for conceptual learning than conventional instruction.

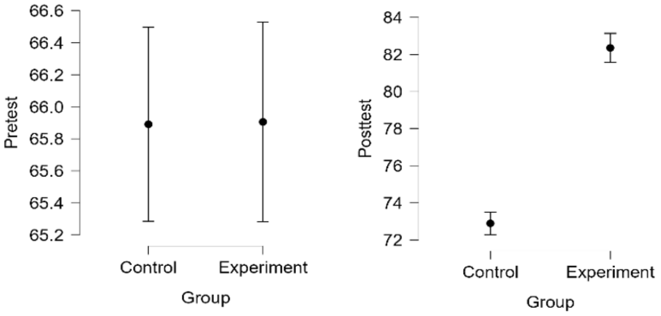

Figure 5. Graph of variables groups (the authors' elaboration based on the research data)

Assumption testing confirmed that the data met the requirements for parametric analysis. The Shapiro-Wilk test indicated that all datasets were normally distributed, with p-values greater than .05 for both the pre-test (control p = .056; experimental p = .058) and post-test (control p = .066; experimental p = .052). In addition, Levene's test showed that the variances between groups were homogeneous for both the pre-test (p = .948) and post-test (p = .051). These results confirmed that the statistical assumptions required for inferential analyses were satisfied. In addition to the descriptive statistics presented in **Table 1**, the pattern of differences in learning outcomes between the two groups was visualized in **Figure 5**.

The visualization further clarified the pattern of change across the two instructional conditions. At the pre-test stage, the M scores of the control and experimental groups were nearly identical, with overlapping confidence intervals, reinforcing the conclusion that both groups began with similar baseline knowledge. In contrast, the post-test results revealed a clear separation between the groups. The experimental group achieved a substantially higher M score than the control group, and the error intervals showed minimal overlap. From a pedagogical perspective, this pattern

Table 4. Result of within subjects effects

	Sum of squares	df	Mean square	F	p	η²
Performance	7,422.93	1	7,422.929	62,616	< .001	0.667
Performance * group	1,205.89	1	1,205.892	10,172	< .001	0.108
Residuals	12.57	106	0.119			

Table 5. Result of between subjects effects

	Sum of squares	df	Mean square	F	p	η²
Group	1,213.00	1	1,213.430	101.1	< .001	0.109
Residuals	1,273.00	106	12.010			

suggested that the integration of IGS supported deeper conceptual engagement with geometric structures, enabling students to achieve greater learning gains.

Effect of Interactive Geometry Simulation on Learning Outcomes

To examine the effect of IGS on students' learning outcomes, a two-factor repeated measures ANOVA was conducted with time (pre-/post-test) as the within-subject factor and instructional group (control vs. experimental) as the between-subject factor. This analysis aimed to identify the effect of time on learning improvement, differences in performance between instructional groups (**Table 4**), and the interaction between time and instructional group (**Table 5**).

The analysis of within-subject effects revealed a significant main effect of time on students' learning outcomes, $F(1, 106) = 62.616$, $p < .001$, $\eta^2 = 0.667$. The effect size ($\eta^2 = 0.667$) indicated a very large effect, meaning that approximately 66.7% of the variance in students' scores was associated with the progression from pre- to post-test. This result suggested that the instructional process, regardless of the learning condition, substantially improved students' understanding of solid geometry concepts. More importantly, the analysis revealed a significant interaction effect between time and instructional group, $F(1, 106) = 10.172$, $p < .001$, $\eta^2 = 0.108$. Although the effect size was smaller than the main effect of time, it still represented a meaningful educational effect, indicating that the magnitude of learning improvement differed between the control and experimental groups. In practical terms, this interaction demonstrated that students who learned using IGS experienced stronger learning gains than those who participated in conventional instruction. Pedagogically, this finding suggests that interactive visualization and direct manipulation of three-dimensional objects enabled students to construct more accurate spatial representations and better understand relationships among geometric elements. The opportunity to explore objects dynamically from multiple perspectives may have reduced the difficulties commonly experienced when interpreting abstract geometric concepts from static representations alone.

The between-subject effects analysis further supported this conclusion. A significant difference in academic performance was observed between the two instructional groups, $F(1, 106) = 101.1$, $p < .001$, $\eta^2 = 0.109$. This effect size indicated that approximately 10.9% of the variance in learning outcomes could be attributed to the instructional approach used. From an instructional perspective, this finding suggested that the use of interactive simulation-based learning environments contributed meaningfully to students' conceptual understanding of solid geometry. These results imply that technology-enhanced geometry instruction should move beyond passive content delivery toward learning experiences that encourage active exploration and visual reasoning. For elementary students, interactive simulations can serve as valuable scaffolds for connecting two-dimensional representations with three-dimensional structures, thereby supporting deeper conceptual understanding and more meaningful learning experiences.

Descriptive Analysis of Learning Perceptions

In addition to evaluating improvements in students' learning outcomes, this study also examined students' perceptions of their learning experiences during the instructional process. This analysis aimed to provide a more comprehensive understanding of how the use of IGS influenced not only academic achievement but also the quality of students' learning experiences. Students' perceptions were measured across four main constructs: CL, Col, EJ, and SC. Descriptive statistics were used to identify the general trends in students' perceptions in both the control and experimental groups. Normality was examined using the Shapiro-Wilk test, while homogeneity of variance was assessed using Levene's test (**Table 6**).

The descriptive results indicated that students' perceptions differed across several dimensions between the two groups. For CL, the M scores of the control group ($M = 3.311$, $SD = 0.258$) and the experimental group ($M = 3.330$, $SD = 0.234$) were relatively similar, suggesting that the perceived level of cognitive demand during the learning process did not differ substantially between the two instructional conditions. This finding is noteworthy because it indicates that the additional interactive features provided by IGS did not increase students'

Table 6. Descriptive learning perceptions

Test		Valid	M	SD	Shapiro-Wilk	p	Lavene F	p
CL	Control	55	3.311	0.258	0.959	.060	0.601	.440
	Experiment	53	3.330	0.234	0.962	.092	0.601	.440
Col	Control	55	3.366	0.234	0.967	.136	1.470	.228
	Experiment	53	3.585	0.193	0.945	.017	1.470	.228
EJ	Control	55	3.216	0.235	0.958	.055	0.221	.639
	Experiment	53	3.804	0.220	0.949	.024	0.221	.639
SC	Control	55	3.227	0.345	0.906	< .001	0.393	.532
	Experiment	53	4.038	0.378	0.942	.012	0.393	.532

Table 7. Result of Shapiro-Wilk's test

Cases	df	Approximate F	Shapiro-Wilk's Λ	Num df	Den df	p
Group	1	91.94	0.219	4	103.0	< .001
Residuals	106					

Table 8. Effect size (eta squared)

Variables	Sum of squares	df	Mean square	F	p	η^2p
CL	0.010	1	0.010	0.158	.692	0.001
Col	1.294	1	1.294	28.03	< .001	0.209
EJ	9.343	1	9.343	180.1	< .001	0.629
SC	17.73	1	17.729	135.8	< .001	0.562

perceived cognitive burden despite requiring engagement with dynamic three-dimensional representations.

In contrast, clearer differences emerged in the constructs of Col, EJ, and SC. The experimental group reported higher levels of Col (M = 3.585) compared with the control group (M = 3.366), indicating that the use of IGS encouraged more active peer interaction and cooperative learning during classroom activities. The higher EJ scores reported by the experimental group (M = 3.804) compared with the control group (M = 3.216) suggest that interactive exploration and immediate visual feedback contributed to a more engaging learning experience. The most pronounced difference appeared in SC, where the experimental group achieved a substantially higher M score (M = 4.038) than the control group (M = 3.227). This result implies that students perceived the simulation environment as effective in helping them visualize geometric relationships and connect two-dimensional representations with three-dimensional structures. Collectively, these findings support the study's objective of examining how cognitive, social, and affective dimensions operate within an IGS environment to facilitate students' SC.

Assumption testing indicated that most datasets satisfied the normality assumption according to the Shapiro-Wilk test, while Levene's test confirmed homogeneity of variance across all perception constructs ($p > .05$). Overall, these findings suggested that the integration of IGS was associated not only with improved learning outcomes but also with more positive learning experiences, particularly in terms of Col, EJ, and SC. The pattern of results indicates that effective geometry learning involves more than cognitive performance alone; meaningful interaction, positive emotional engagement, and opportunities for visual exploration may jointly contribute to students' understanding of geometric concepts. These findings reinforce the importance of designing technology-enhanced learning environments that integrate cognitive, social, and affective dimensions of learning.

Differences in Students' Perceptions Between Groups

To determine whether overall differences in students' perceptions existed between the control and experimental groups, a MANOVA was conducted (**Table 7**). Prior to the analysis, the assumption of homogeneity of covariance matrices was examined using Box's M test. The result was not statistically significant, $\chi^2(10) = 9.076$, $p = .525$, indicating that the covariance matrices were equivalent across groups and that the assumption was satisfied. The multivariate test using Wilks' Lambda indicated a statistically significant difference in students' perceptions between the two groups, $\Lambda = 0.219$, $F(4, 103) = 91.94$, $p < .001$. This result suggested that, when considered simultaneously, the four perception constructs differed significantly between the control and experimental groups. To identify which constructs contributed to this difference, follow-up univariate ANOVA analyses were conducted for each perception variable (**Table 8**).

The results indicated that no significant difference was observed in the CL construct between the two groups, $F(1, 106) = 0.158$, $p = .692$, $\eta^2p = 0.001$, suggesting that both instructional approaches imposed comparable levels of cognitive demand on students. In contrast, significant differences were found for Col, $F(1, 106) = 28.03$, $p < .001$, $\eta^2p = 0.209$, EJ, $F(1, 106) = 180.1$, $p < .001$,

Table 9. Correlation results among variables

Variable		CL	Col	EJ	SC
CL	Pearson's r	-			
	p-value	-			
Col	Pearson's r	-0.062	-		
	p-value	.525	-		
EJ	Pearson's r	0.091	0.352	-	
	p-value	.351	< .001	-	
SC	Pearson's r	0.010	0.314	0.566	-
	p-value	.919	< .001	< .001	-

$\eta^2p = 0.629$, and SC, $F(1, 106) = 135.8$, $p < .001$, $\eta^2p = 0.562$. The effect size values indicated that the strongest instructional effects were observed in EJ and SC. These results suggested that students in the IGS group reported significantly higher levels of learning EJ and SC than those in the control group. To further explore the relationships among students' perception constructs, a Pearson correlation analysis was conducted (**Table 9**).

The results indicated that Col showed a significant positive correlation with EJ ($r = 0.352$, $p < .001$) and SC ($r = 0.314$, $p < .001$). The strongest relationship was found between EJ and SC ($r = 0.566$, $p < .001$), suggesting that students who experienced greater EJ during the learning process also tended to demonstrate clearer SC. In contrast, CL did not show significant correlations with the other perception constructs. These findings suggested that improvements in students' learning experiences—particularly in terms of EJ and collaborative engagement—were associated with stronger SC in geometry learning. In addition to the statistical results presented in the tables, the differences in students' perceptions between the two groups were visualized in **Figure 6** to provide a more intuitive representation of the patterns across the four constructs.

The visualization showed that the M scores for CL were relatively similar between the control and experimental groups, with overlapping error intervals. This pattern confirmed that the perceived level of cognitive demand did not differ substantially between the two instructional approaches. In contrast, clearer differences were observed in Col, EJ, and SC. The experimental group consistently demonstrated higher M scores for these constructs than the control group, with greater separation between the Ms and relatively distinct error intervals. This pattern reinforced the results of the MANOVA and ANOVA analyses, indicating that the use of IGS significantly enhanced collaborative interaction, learning EJ, and students' understanding spatial concepts during the instructional process.

These findings also suggested that higher levels of SC were associated with better learning outcomes in geometry. Clearer spatial understanding enabled students to visualize relationships among geometric elements—such as edges, diagonals, and faces—more effectively. Within the IGS-based learning environment, dynamic visualization and manipulation of geometric objects supported students in constructing more accurate mental representations of spatial structures. Consequently, these enhanced learning experiences were associated with higher levels of conceptual understanding and stronger academic performance, as reflected in the learning outcome results reported earlier.

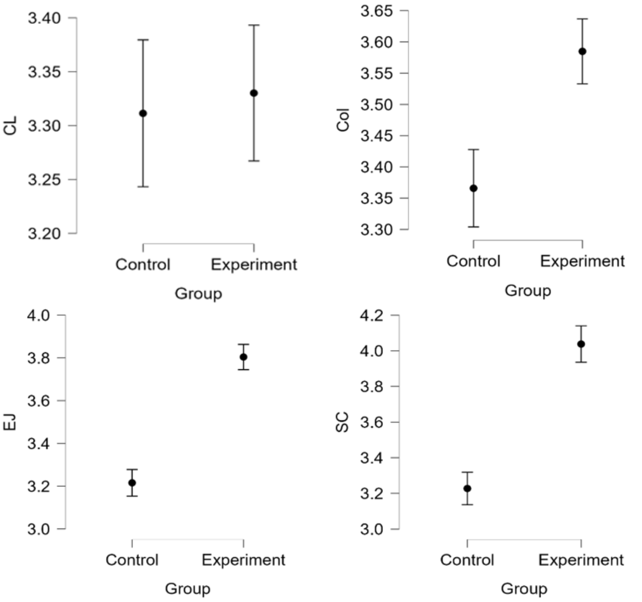

Figure 6. Graph of variables against groups (the authors' elaboration based on the research data)

DISCUSSION

The findings of this study provide empirical evidence that geometry learning supported by IGS not only improves students' academic performance but also shapes richer learning experiences through the interaction of cognitive, social, and affective dimensions. Specifically, the results showed that students who learned using IGS achieved higher levels of SC than those who participated in conventional instruction. This improvement was accompanied by increases in Col and EJ, while the level of CL remained comparable between the two groups. These findings address a research gap identified in the literature, where most studies on technology-enhanced geometry learning tend to examine the impact of technology on learning outcomes or student motivation separately. By examining the relationships among CL, Col, EJ, and SC simultaneously within a simulation-based learning environment, this study provides a more comprehensive explanation of how interactive visual technologies support the development of spatial understanding in geometry learning.

These findings are consistent with previous studies showing that interactive visual representations play a crucial role in supporting geometric understanding because they allow students to connect multiple spatial representations more effectively (Fujita et al., 2020; Gilligan-Lee et al., 2022). Students often experience difficulties in geometry when they are required to transform two-dimensional representations into three-dimensional structures. Simulation-based environments help bridge this gap by providing visual experiences that allow students to observe spatial transformations directly. Previous research also indicates that dynamic manipulation of geometric objects helps students develop more stable spatial mental models than static representations typically found in textbooks (Gurmu et al., 2024; Ng et al., 2020).

In the context of IGS, this support was provided through specific features such as object rotation, net exploration, and guided surface area and volume simulations. These features enabled students to observe geometric objects from multiple perspectives, dynamically transform three-dimensional structures into two-dimensional representations, and connect geometric formulas with visual representations. Such experiences may explain why students in the experimental group demonstrated stronger SC than those receiving conventional instruction.

The effectiveness of simulation-based learning can be explained through the cognitive mechanisms involved in the construction of spatial representations during learning. Geometry simulations provide dynamic visualizations that enable students to observe spatial relationships among geometric elements directly. Manipulative activities such as object rotation, net exploration, and shape transformations help students coordinate multiple geometric representations. In mathematics education literature, this ability is often described through the concept of representational coordination, referring to the ability to integrate visual, symbolic, and conceptual representations in understanding mathematical objects.

In addition, the use of simulation technologies is closely related to the development of spatial reasoning, defined as the ability to mentally manipulate objects in space (Hawes & Ansari, 2020). Visual experiences involving the manipulation of three-dimensional objects can strengthen the formation of spatial mental models that support geometric understanding (Silverman & Ashkenazi, 2022). Therefore, simulation technologies not only provide visual representations of geometric structures but also facilitate the cognitive processes underlying students' spatial reasoning development.

One important contribution of this study is the demonstration that the effectiveness of simulation-based learning is not limited to cognitive factors but is also influenced by the interaction between cognitive, social, and affective dimensions of students' learning experiences. From the cognitive perspective, the results indicated that CL did not differ significantly between the two instructional conditions. This finding suggests that the use of IGS did not impose additional cognitive burden on students despite introducing a visually rich learning environment. Within the framework of CLT, appropriately designed interactive visualizations can reduce extraneous CL by presenting information in a more integrated form (Klepsch & Seufert, 2020). This allows students to allocate their cognitive resources toward constructing conceptual understanding rather than processing irrelevant information (Buchner et al., 2022).

From the social perspective, the findings indicate that the use of IGS is associated with increased CoI during the learning process. Simulation-based environments provide rich contexts for conceptual discussions because students can share interpretations of their explorations of geometric objects. These interactions create opportunities for meaning negotiation, which helps students reconstruct their conceptual understanding. This finding aligns with previous research indicating that technology-supported mathematics learning combined with collaborative activities can enhance students' mathematical reasoning (Demir & Zengin, 2023). From a social constructivist perspective, dialogue among students can trigger socio-cognitive conflict that plays a key role in restructuring conceptual understanding (Tenenbaum et al., 2020).

The study also shows that students who learned using IGS reported significantly higher levels of learning EJ. Positive academic emotions such as EJ play an important role in increasing students' engagement and encouraging the use of deeper learning strategies. Previous research indicates that positive emotions in mathematics learning are associated with higher intrinsic motivation and increased student engagement (Pekrun et al., 2017). In technology-enhanced learning environments, interactive visual exploration can further increase students' interest in mathematical activities and create more meaningful learning experiences (Hillmayr et al., 2020).

The correlation analysis revealed that EJ demonstrated the strongest relationship with SC, followed by CoI. This finding suggests that students' conceptual development is shaped not only by cognitive processes but also by the quality of their learning experiences. Interactive exploration through IGS may be associated with higher levels of EJ because it provides immediate visual feedback and opportunities for active discovery. Students who reported greater EJ also tended to report stronger engagement with geometric concepts and higher levels of SC. However, these relationships should be interpreted as correlational rather than causal. Furthermore, collaborative discussions enable students to articulate ideas, compare interpretations, and negotiate meaning while exploring geometric objects. These interactions help students refine and reorganize their spatial representations, thereby strengthening conceptual understanding. Together, these findings highlight the interconnected roles of affective and social processes in supporting students' SC within simulation-based geometry learning environments.

Overall, this study extends the existing literature by demonstrating that the effectiveness of simulation-based geometry learning should be understood through the interaction between cognitive, social, and affective dimensions of students' learning experiences. Previous studies often examined the influence of technology on learning outcomes or motivation separately. By simultaneously analyzing the relationships among CL, Col, EJ, and SC, this study provides empirical support for an integrated framework of technology-enhanced learning that incorporates these three dimensions.

From a practical perspective, the findings suggest that IGS can serve as an effective learning environment for inquiry-based geometry instruction. Through direct exploration of geometric objects, students can construct conceptual understanding before receiving formal explanations from the teacher. Features such as object rotation, net exploration, and guided calculation simulations provide opportunities for students to visualize spatial relationships, discuss geometric ideas with peers, and connect visual representations with mathematical concepts. However, the successful implementation of this technology depends strongly on teachers' ability to integrate digital tools with appropriate pedagogical strategies. Therefore, strengthening teachers' technological pedagogical content knowledge is essential for optimizing the use of simulation technologies in mathematics instruction.

This study has several limitations that should be considered when interpreting the findings. First, the study was conducted in a single school with relatively homogeneous student characteristics, instructional practices, and learning conditions, which may limit the transferability of the results to other educational contexts. Differences in technological resources, classroom culture, and student backgrounds may influence the effectiveness of IGS and the relationships observed among the study variables. Second, the relatively short intervention period did not allow examination of the long-term effects of IGS on students' spatial reasoning development. Third, CL, Col, EJ, and SC were measured through self-reported questionnaires, which may not fully reflect students' actual learning processes and may also introduce common method bias, potentially inflating the observed relationships among variables due to the use of a shared measurement method. Fourth, SC was assessed using a relatively brief 10-item multiple-choice test. Although the instrument was aligned with the targeted learning objectives and demonstrated acceptable psychometric properties, future studies may employ a larger number of items or incorporate open-ended tasks to capture students' SC more comprehensively. Finally, although significant relationships were identified among the study variables, the correlational analyses do not permit causal conclusions regarding the underlying mechanisms. Further studies may also explore the role of EJ as a mediating variable and employ advanced analytical approaches, such as structural equation modeling or mediation analysis, to investigate the causal pathways among CL, Col, EJ, and SC more comprehensively.

CONCLUSION

This study found that students who learned through IGS achieved greater improvements in solid geometry learning outcomes than students who received conventional instruction. In addition to these achievement gains, students in the IGS group reported higher levels of Col, EJ, and perceived SC, while reporting comparable levels of CL. These findings suggest that interactive simulation environments may provide supportive conditions for geometry learning by combining visual exploration, collaborative activities, and engaging learning experiences.

The correlation analysis showed that EJ had the strongest association with perceived SC, followed by Col. However, these relationships should be interpreted as correlational rather than causal, as the study design and analytical procedures do not permit conclusions regarding direct causal effects among the variables. Nevertheless, the findings highlight the potential importance of considering cognitive, social, and affective dimensions simultaneously when designing technology-enhanced geometry learning environments.

From a practical perspective, IGS provide a promising instructional approach for promoting exploratory and conceptually rich geometry learning. However, broader implementation requires careful integration of technological tools with appropriate pedagogical strategies. Future research should investigate longer-term implementations and explore more immersive visualization technologies to further support spatial reasoning development. Ultimately, these findings highlight the importance of designing digital learning environments that simultaneously engage students' cognitive, social, and affective processes to foster deeper mathematical understanding.

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REFERENCES

Abín, A., Núñez, J. C., Rodríguez, C., Cueli, M., García, T., & Rosário, P. (2020). Predicting mathematics achievement in secondary education: The role of cognitive, motivational, and emotional variables. *Frontiers in Psychology, 11*. https://doi.org/10.3389/fpsyg.2020.00876

Ahmad, N. I. N., & Junaini, S. N. (2020). Augmented reality for learning mathematics: A systematic literature review. *International Journal of Emerging Technologies in Learning, 15*(16), 106-122. https://doi.org/10.3991/ijet.v15i16.14961

Amir, M. F., Fediyanto, N., Rudyanto, H. E., Nur Afifah, D. S., & Tortop, H. S. (2020). Elementary students' perceptions of 3Dmetric: A cross-sectional study. *Heliyon, 6*(6), Article e04052. https://doi.org/10.1016/j.heliyon.2020.e04052

Anmarkrud, Ø., Andresen, A., & Bråten, I. (2019). Cognitive load and working memory in multimedia learning: Conceptual and measurement issues. *Educational Psychologist, 54*(2), 61-83. https://doi.org/10.1080/00461520.2018.1554484

Atit, K., Power, J. R., Pigott, T., Lee, J., Geer, E. A., Uttal, D. H., Ganley, C. M., & Sorby, S. A. (2021). Examining the relations between spatial skills and mathematical performance: A meta-analysis. *Psychonomic Bulletin & Review, 29*(3), 699-720. https://doi.org/10.3758/s13423-021-02012-w

Attard, C., & Holmes, K. (2020). An exploration of teacher and student perceptions of blended learning in four secondary mathematics classrooms. *Mathematics Education Research Journal, 34*(4), 719-740. https://doi.org/10.1007/s13394-020-00359-2

Borboeva, G., Sooronbaeva, K., Kalbekova, M., Seiitkazyeva, G., & Sarygulova, N. (2025). Evaluating the effectiveness of interactive learning technologies in enhancing spatial thinking among mathematics students. *Jurnal Ilmiah Ilmu Terapan Universitas Jambi, 9*(3), 981-994. https://doi.org/10.22437/jiituj.v9i3.42557

Buchner, J., Buntins, K., & Kerres, M. (2022). The impact of augmented reality on cognitive load and performance: A systematic review. *Journal of Computer Assisted Learning, 38*(1), 285-303. https://doi.org/10.1111/jcal.12617

Capar, G., & Tarim, K. (2015). Efficacy of the cooperative learning method on mathematics achievement and attitude: A meta-analysis research. *Kuram ve Uygulamada Eğitim Bilimleri, 15*(2), 553-559. https://doi.org/10.12738/estp.2015.2.2098

Choi, Y., & Lee, H. (2022). Psychometric properties for multidimensional cognitive load scale in an e-learning environment. *International Journal of Environmental Research and Public Health, 19*(10), Article 5822. https://doi.org/10.3390/ijerph19105822

de la Hera, D. P., Sigman, M., & Calero, C. I. (2019). Social interaction and conceptual change pave the way away from children's misconceptions about the earth. *npj Science of Learning, 4*, Article 12. https://doi.org/10.1038/s41539-019-0051-3

Demir, M., & Zengin, Y. (2023). The effect of a technology-enhanced collaborative learning environment on secondary school students' mathematical reasoning: A mixed method design. *Education and Information Technologies, 28*(8), 9855-9883. https://doi.org/10.1007/s10639-023-11587-x

Farzan, F., Wang, C., Ankney, R. L., & Carvalho, P. (2025). Modeling the role of graphical and textual complexity in geometry problem-solving using SEM. *International Conference on Education Research, 2*(1), 42-49. https://doi.org/10.34190/icer.2.1.3884

Frick, A. (2018). Spatial transformation abilities and their relation to later mathematics performance. *Psychological Research, 83*(7), 1465-1484. https://doi.org/10.1007/s00426-018-1008-5

Fujita, T., Kondo, Y., Kumakura, H., Kunimune, S., & Jones, K. (2020). Spatial reasoning skills about 2D representations of 3D geometrical shapes in grades 4 to 9. *Mathematics Education Research Journal, 32*(2), 235-255. https://doi.org/10.1007/s13394-020-00335-w

García, T., Rodríguez, C., Betts, L., Areces, D., & González-Castro, P. (2016). How affective-motivational variables and approaches to learning predict mathematics achievement in upper elementary levels. *Learning and Individual Differences, 49*, 25-31. https://doi.org/10.1016/j.lindif.2016.05.021

Gilligan-Lee, K. A., Hawes, Z. C. K., & Mix, K. S. (2022). Spatial thinking as the missing piece in mathematics curricula. *npj Science of Learning, 7*, Article 10. https://doi.org/10.1038/s41539-022-00128-9

Gurmu, F., Tuge, C., & Hunde, A. B. (2024). Effects of GeoGebra-assisted instructional methods on students' conceptual understanding of geometry. *Cogent Education, 11*(1), Article 2379745. https://doi.org/10.1080/2331186X.2024.2379745

Hawes, Z. C. K., & Ansari, D. (2020). What explains the relationship between spatial and mathematical skills? A review of evidence from brain and behavior. *Psychonomic Bulletin & Review, 27*(3), 465-482. https://doi.org/10.3758/s13423-019-01694-7

Hawes, Z. C. K., Gilligan-Lee, K. A., & Mix, K. S. (2022). Effects of spatial training on mathematics performance: A meta-analysis. *Developmental Psychology, 58*(1), 112-137. https://doi.org/10.1037/dev0001281

Hillmayr, D., Ziernwald, L., Reinhold, F., Hofer, S. I., & Reiss, K. M. (2020). The potential of digital tools to enhance mathematics and science learning in secondary schools: A context-specific meta-analysis. *Computers & Education, 153*(64), Article 103897. https://doi.org/10.1016/j.compedu.2020.103897

Hsu, S. K., & Hsu, Y. (2024). Supporting young learners in learning geometric area concepts through static versus dynamic representation and imagination strategies. *International Journal of Science and Mathematics Education, 23*(2), 441-459. https://doi.org/10.1007/s10763-024-10481-3

İbili, E. (2019). Effect of augmented reality environments on cognitive load: Pedagogical effect, instructional design, motivation and interaction interfaces. *International Journal of Progressive Education, 15*(5), 42-57. https://doi.org/10.29329/ijpe.2019.212.4

Jeffri, N. F. S., & Awang Rambli, D. R. (2021). A review of augmented reality systems and their effects on mental workload and task performance. *Heliyon, 7*(3), Article e06277. https://doi.org/10.1016/j.heliyon.2021.e06277

Juandi, D., Kusumah, Y. S., Tamur, M., Perbowo, K. S., & Wijaya, T. T. (2021). A meta-analysis of Geogebra software decade of assisted mathematics learning: What to learn and where to go? *Heliyon, 7*(5), Article e06953. https://doi.org/10.1016/j.heliyon.2021.e06953

Klepsch, M., & Seufert, T. (2020). Understanding instructional design effects by differentiated measurement of intrinsic, extraneous, and germane cognitive load. *Instructional Science, 48*(1), 45-77. https://doi.org/10.1007/s11251-020-09502-9

Liu, R. De, Zhen, R., Ding, Y., Liu, Y., Wang, J., Jiang, R., & Xu, L. (2018). Teacher support and math engagement: Roles of academic self-efficacy and positive emotions. *Educational Psychology, 38*(1), 3-16. https://doi.org/10.1080/01443410.2017.1359238

Mandala, A. S., Anwar, L., Sa'dijah, C., & Zulnaidi, H. (2025). Development of mobile augmented reality-based geometry learning games to facilitate spatial reasoning. *Infinity Journal, 14*(2), 323-348. https://doi.org/10.22460/infinity.v14i2.p323-348

Morales Méndez, G., & Lozano Avilés, A. B. (2025). Realidad aumentada y GeoGebra 3D para mejorar la inteligencia espacial en la enseñanza de la geometría volumétrica [Augmented reality and GeoGebra 3D to improve spatial intelligence in the teaching of volumetric geometry]. *Revista de Educación a Distancia, 25*(82), 30-2025. https://doi.org/10.6018/red.644051

Ng, O. L., Shi, L., & Ting, F. (2020). Exploring differences in primary students' geometry learning outcomes in two technology-enhanced environments: Dynamic geometry and 3D printing. *International Journal of STEM Education, 7*, Article 50. https://doi.org/10.1186/s40594-020-00244-1

OECD. (2023). PISA 2022 results. *OECD*. https://www.oecd.org/content/dam/oecd/en/publications/reports/2023/11/pisa-2022-results-volume-i-and-ii-country-notes_2fca04b9/turkiye_5a6863b0/d67e6c05-en.pdf

Pekrun, R., Lichtenfeld, S., Marsh, H. W., Murayama, K., & Goetz, T. (2017). Achievement emotions and academic performance: Longitudinal models of reciprocal effects. *Child Development, 88*(5), 1653-1670. https://doi.org/10.1111/cdev.12704

Rachmawati, I., Sabil, H., & Junita, R. (2025). Analisis kemampuan spasial siswa berdasarkan cognitive load theory siswa kelas XII SMA N 13 Kota Jambi [Analysis of students' spatial abilities based on cognitive load theory of class XII students of SMA N 13 Jambi City]. *Jurnal PEKA (Pendidikan Matematika), 9*(1), 62-76. https://doi.org/10.37150/3hysnw33

Silverman, S., & Ashkenazi, S. (2022). The unique role of spatial working memory for mathematics performance. *Journal of Numerical Cognition, 8*(1), 226-243. https://doi.org/10.5964/jnc.7159

Sung, Y. T., Yang, J. M., & Lee, H. Y. (2017). The effects of mobile-computer-supported collaborative learning: Meta-analysis and critical synthesis. *Review of Educational Research, 87*(4), 768-805. https://doi.org/10.3102/0034654317704307

Tenenbaum, H. R., Winstone, N. E., Leman, P. J., & Avery, R. E. (2020). How effective is peer interaction in facilitating learning? A meta-analysis. *Journal of Educational Psychology, 112*(7), 1303-1319. https://doi.org/10.1037/edu0000436

Turgut, S., & Gülşen Turgut, İ. (2018). The effects of cooperative learning on mathematics achievement in Turkey: A meta-analysis study. *International Journal of Instruction, 11*(3), 663-680. https://doi.org/10.12973/iji.2018.11345a

Živković, M., Pellizzoni, S., Doz, E., Cuder, A., Mammarella, I., & Passolunghi, M. C. (2023). Math self-efficacy or anxiety? The role of emotional and motivational contribution in math performance. *Social Psychology of Education, 26*(3), 579-601. https://doi.org/10.1007/s11218-023-09760-8

APPENDIX A

Table A1. Cognitive test blueprint and psychometric summary

Indicator	Item numbers
Identifying geometric elements and properties	1-3
Interpreting two-dimensional-three-dimensional representations	4-6
Applying surface area and volume concepts	7-10

Table A2. Overall reliability statistics

Coefficient	Estimate	Standard error	95% confidence interval	
			Lower	Upper
Coefficient alpha	0.755	0.040	0.678	0.833
M	4.775	0.313	4.162	5.388
SD	2.797	0.158	2.421	3.313

Table A3. Item discrimination indices based on item-rest correlations

Item	Item-rest correlation	Category
Q1	0.478	Good
Q2	0.404	Good
Q3	0.330	Fair
Q4	0.587	Very good
Q5	0.441	Good
Q6	0.388	Fair
Q7	0.422	Good
Q8	0.345	Fair
Q9	0.341	Fair
Q10	0.441	Good

Table A4. Item difficulty indices

Item	M	Category
Q1	0.538	Moderate
Q2	0.500	Moderate
Q3	0.500	Moderate
Q4	0.425	Moderate
Q5	0.438	Moderate
Q6	0.425	Moderate
Q7	0.563	Moderate
Q8	0.438	Moderate
Q9	0.500	Moderate
Q10	0.450	Moderate

Cognitive Test of Spatial Conceptual Understanding

Indicator 1. Identifying elements and properties of solid figures

Question 1. Which property belongs only to a cube?

A. It has 6 faces.
B. All of its faces are congruent squares.
C. It has 12 edges.
D. It has 8 vertices.

Question 2. A solid figure has 6 faces and 8 vertices. How many edges does it have?

A. 10
B. 12
C. 14
D. 16

Question 3. A student says, *"All faces of this solid figure are rectangles, but not all of them are squares."* Which solid figure is being described?

A. Cube
B. Cone
C. Rectangular prism
D. Pyramid

Indicator 2. Interpreting relationships between two-dimensional and three-dimensional representations

Question 4. Rina wants to make a cube from cardboard. She has the following four cube nets. Which net can be folded into a cube without any faces overlapping or being left out?

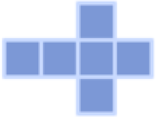
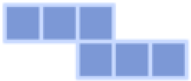
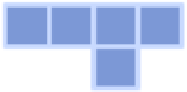
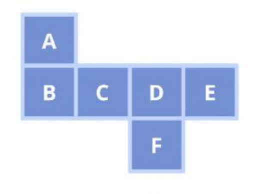
			

Figure A	Figure B	Figure C	Figure D

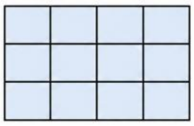
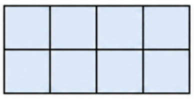
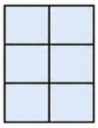
A. Figure A
B. Figure B
C. Figure C
D. Figure D

Question 5. Look at the cube net labeled A, B, C, D, E, and F. If the net is folded into a cube, which face will be opposite face A?



A. B
B. C
C. D
D. F

Question 6. A solid figure is viewed from three directions. Which solid figure is most likely to produce these three views?

		
Top view	Front view	Side view

A. Cube

B. Rectangular prism

C. Cylinder

D. Cone

Indicator 3. Applying surface area and volume concepts

Question 7. Andi makes a cube from cardboard. Then he makes a second cube whose edges are twice as long as those of the first cube. What happens to the amount of cardboard needed to cover the entire surface of the second cube?

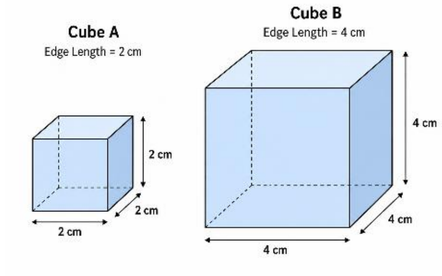
A. It becomes 2 times greater.

B. It becomes 4 times greater.

C. It becomes 6 times greater.

D. It becomes 8 times greater.

Question 8. Two cubes are shown in the figure. Cube A has an edge length of 2 cm. Cube B has an edge length of 4 cm. Without calculating each volume separately, which statement is correct?



A. Cube B can hold 2 times the volume of cube A.

B. Cube B can hold 4 times the volume of cube A.

C. Cube B can hold 6 times the volume of cube A.

D. Cube B can hold 8 times the volume of cube A.

Question 9. Rectangular prism P and rectangular prism Q are used as toy storage boxes. Rectangular prism P measures 10 cm × 5 cm × 4 cm. Rectangular prism Q measures 8 cm × 6 cm × 4 cm. Which box can hold more toys?

A. Rectangular prism P.

B. Rectangular prism Q.

C. Both hold the same amount.

D. Cannot be determined.

Question 10. A rectangular aquarium has a length of 6 cm, a width of 4 cm, and a height of 4 cm. The aquarium is filled halfway with water. What is the volume of water in the aquarium?

A. 24 cm^3

B. 48 cm^3

C. 96 cm^3

D. 192 cm^3

APPENDIX B

Table B1. Construct structure, sources, adaptation procedures, and validation evidence

Construct	Sub-dimension	Item codes	Theoretical source	Adaptation notes	Validation evidence
CL	Intrinsic CL	CL2, CL3, CL5	Anmarkrud et al. (2019), Choi and Lee (2022), Klepsch and Seufert (2020)	Developed from CLT and adapted to the context of sixth-grade solid geometry learning using IGS.	Construct reliability: α = 0.728.
	Extraneous CL	CL1, CL7			
	Germane CL	CL4, CL6, CL8			
Col	Active participation	Col1, Col2, Col5, Col7	Capar and Tarim (2015), Sung et al. (2017), Tenenbaum et al. (2020)	Developed from collaborative learning and CSCL literature and adapted to collaborative geometry learning activities.	Construct reliability: α = 0.732.
	Group responsibility	Col3, Col4, Col6, Col8			
EJ	Learning EJ	EJ1, EJ2, EJ4, EJ5	García et al. (2016), Pekrun et al. (2017), Abín et al. (2020)	Developed from achievement emotion literature and adapted to technology-enhanced geometry learning.	Construct reliability: α = 0.717.
	Learning motivation	EJ3, EJ6, EJ7, EJ8			
SC	Spatial visualization	SC1, SC2, SC3, SC4	Fujita et al. (2020), Gilligan-Lee et al. (2022), Hawes and Ansari (2020)	Developed from spatial reasoning and spatial visualization literature and adapted to assess students' spatial conceptual understanding of solid geometry.	Construct reliability: α = 0.790.

Table B2. Full questionnaire items

Code	Item statement
CL1	I can easily understand the instructions for using the IGS.
CL2	I have to think very hard when using the IGS.
CL3	I find it difficult to understand the relationships among diagonals, edges, and vertices.
CL4	The rotation feature helps me better understand the shape of solid figures.
CL5	I find it difficult to understand the formulas for surface area and volume presented in the IGS.
CL6	Opening the net of a solid figure helps me better understand its two-dimensional representation.
CL7	The screen display contains too much information, making it difficult for me to focus.
CL8	I can easily follow the steps for entering numerical values in the simulation.
Col1	I discuss with my peers when rotating solid figures in the IGS.
Col2	We work together to understand the properties of solid figures using the IGS.
Col3	I help my peers understand the nets of solid figures.
Col4	My peers help me when I make mistakes while entering numerical values in the simulation.
Col5	We discuss the surface area or volume results generated by the simulation.
Col6	We collaborate when exploring how the net of a solid figure unfolds.
Col7	I am willing to listen to my peers' ideas about solid figures.
Col8	Learning with the IGS strengthens cooperation within our group.
EJ1	I enjoy rotating solid figures in the IGS.
EJ2	I feel as if I am playing while exploring the nets of solid figures.
EJ3	Learning formulas through the IGS is more enjoyable than learning from textbooks alone.
EJ4	I do not feel bored when using the simulation.
EJ5	I feel excited when I see the solid figure change after being rotated.
EJ6	I enjoy entering numerical values to observe the resulting surface area and volume.
EJ7	Time seems to pass quickly when learning with the IGS.
EJ8	I would like to learn solid geometry again using the IGS.
SC1	By rotating the solid figure, I can more clearly understand its three-dimensional shape.
SC2	After observing the solid figure in the IGS, I understand the relationships among edges, diagonals, and vertices.
SC3	When the net is unfolded, I can imagine how the solid figure is formed again.
SC4	After using the IGS, I can more easily visualize the internal structure of the solid figure.