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Students' construction of projection concepts through independent exploration in a technology-enhanced learning environment

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Abstract

Conventional descriptive geometry instruction often fails to facilitate accurate spatial visualization, perpetuating epistemological obstacles. This study investigates how integrating independent exploration via GeoGebra impacts students' knowledge construction of orthogonal projection concepts. A descriptive qualitative case study was conducted involving 16 mathematics education students at the State University of Jakarta during the odd semester of 2026. Data were collected using a conceptual understanding test comprising three hierarchical questions and a structured interview guide, and then analyzed through an interactive qualitative model. Findings indicate that GeoGebra functions beyond a mere visual aid; it acts as a cognitive instrument mediating instrumental genesis. Specifically, independent exploration utilizing dragging and 3D manipulation empowered students to diagnose and dismantle persistent epistemological obstacles related to dimensional transformations and planar intersections. However, varying levels of student dependence on instructor scaffolding highlight that successful instrument adaptation relies on individual learning dispositions. The study implies that effectively integrating technology in geometry education requires a differentiated pedagogical approach and a shift toward orchestrated digital exploration.

Keywords: independent exploration; projection concepts; student knowledge construction; technology-enhanced learning

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Introduction

Descriptive geometry plays a central role in mathematics and engineering curricula, bridging visual spatial intuition with the rigor of mathematical logic (Lowrie & Logan, 2023; Resnick et al., 2020; Sebsibe & Abdella, 2025). This discipline demands high-level mental faculties to manipulate three-dimensional (3D) objects and accurately represent them on a two-dimensional (2D) plane. However, teaching and learning descriptive geometry face fundamental pedagogical challenges both internationally and nationally. Students frequently experience significant cognitive difficulties in transitioning from real-space perception to planar representation, often exacerbated by conventional instructional methods that rely heavily on static manual tools like paper and pencil (Izzati & Al Farizi, 2025; Suparman et al., 2024). Consequently, motor inaccuracies, the inability to mentally rotate objects, and reliance on rote procedures persist, leading to deep-rooted epistemological obstacles where planar geometry intuition distorts the understanding of spatial geometry (Gorjanc, n.d.; Gutiérrez de Ravé et al., 2025; Modestou & Gagatsis, 2007; Sudirman et al., 2023).

In response to these visualization challenges, mathematics education researchers and practitioners have increasingly advocated for the integration of Technology-Enhanced Learning (TEL) paradigms (NCSM, 2024). Numerous studies have documented the use of dynamic geometry software (DGS), such as GeoGebra, as a pedagogical innovation to mitigate the limitations of static media (Akyüz, 2015; Misfeldt, 2013). By allowing direct manipulation of mathematical objects and providing instant visual feedback, technology transforms the learning environment from passive information transfer to active, constructivist knowledge building (Capone & Lepore, 2020; Hwang et al., 2020; Rigopouli et al., 2025; Shittu & Alex, 2025).

Previous research has consistently shown that GeoGebra-assisted instruction positively impacts students' general spatial visualization and conceptual understanding (Herrera et al., 2024; Suparman et al., 2024). However, much of the existing literature focuses on the general efficacy of the software or guided, teacher-led procedural instruction. A significant gap remains regarding how students autonomously navigate and overcome specific epistemological obstacles during unguided, independent exploration.

The novelty of this study lies in exploring this gap through the lens of the Instrumental Genesis framework (Flores Salazar et al., 2025; Misfeldt, 2013). GeoGebra is viewed not merely as a visual aid but as an artifact that students must transform into a cognitive instrument through two simultaneous processes: instrumentation (how the software shapes the student's thinking) and instrumentalization (how the student modifies the tool for specific goals). Furthermore, grounded in Vygotsky's concept of semiotic mediation within the Zone of Proximal Development (Pfeiffer et al., 2025), this study emphasizes that dynamic features—particularly dragging—serve as cognitive tools for logical verification rather than mere physical manipulation (Akyüz, 2015). When students independently utilize dragging and 3D rotation, they can visualize contradictions and trigger the cognitive conflicts necessary to dismantle epistemological obstacles (Parra Lara & Ospina Parra, 2024; Sianturi & Ningsih, 2025; Siregar, 2025).

Therefore, this research aims to analyze the knowledge construction processes of students regarding projection concepts facilitated by independent exploration in a GeoGebra-based learning environment. Specifically, this study seeks to understand how students' interactions with dynamic technological features alter their problem-solving strategies and to determine the extent to which this technology-mediated exploration assists in diagnosing and overcoming epistemological obstacles that are resistant to conventional manual instruction.

Methods

Research design and context

This study employs a qualitative approach with an exploratory case study design. This method was selected based on the research objective to deeply understand the latent and complex phenomena of thinking processes and knowledge construction. Case studies allow researchers to investigate detailed interactions between subjects (students) and tools (GeoGebra) within a real learning context, rather than in isolated laboratory conditions (Izzati & Al Farizi, 2025; Sianturi & Ningsih, 2025).

The research was conducted at the Mathematics Education Study Program, Faculty of Mathematics and Natural Sciences (FMIPA), State University of Jakarta, during the odd semester of 2026. The focal course was Descriptive Geometry, a compulsory subject serving as a foundation for advanced geometric understanding.

Participants and ethical considerations

The research subjects comprised 16 students actively enrolled in the course. Subjects were selected using a purposive sampling technique to represent a variation in academic ability (high, medium, low) and diverse learning styles observed during initial lectures. A sample size of 16 was deemed sufficient for an in-depth qualitative study to reach data saturation regarding error patterns and thinking strategies.

Prior to data collection, ethical approval was obtained directly from the research subjects. All participants provided written informed consent, which guaranteed their voluntary participation, the confidentiality of their responses, and their right to withdraw at any time without academic penalty. To ensure data anonymization, all student data were fully anonymized, and participants were exclusively identified by codes (S1 to S16) during the data collection, analysis, and reporting processes.

Researcher positionality

In this study, the first author served a dual role as both the course instructor and the primary researcher. Recognizing the potential for dual-role bias in qualitative research, several mitigation strategies were strictly implemented. First, data analysis was conducted collaboratively with the second and third authors through regular peer debriefing sessions to ensure analytical objectivity. Second, reflexivity was maintained throughout the study; the first author kept a reflexive journal to document and critically assess personal biases and assumptions during both the instructional and analytical phases.

Research procedures and timeline

The study was conducted over a six-week timeline. The initial four weeks were dedicated to the pedagogical intervention, where lectures were conducted with full integration of GeoGebra. During this phase, the lecturer moved beyond solely using blackboards or static presentation slides. Learning was designed using a constructivist approach wherein:

1. The lecturer demonstrated basic concepts using dynamic GeoGebra models.
2. Students were granted access to GeoGebra files (applets) and digital worksheets.
3. Students were assigned to perform independent exploration and solve geometric construction problems (such as projections of lines, planes, and intersections) directly on the software on their respective laptops.
4. The lecturer facilitated class discussions based on student findings, utilizing errors as learning opportunities.

Instruments, Validity, and Reliability

Following the four-week instructional sequence, data were collected in the fifth and sixth weeks using two primary instruments:

1. Descriptive Geometry Conceptual Understanding Test: Administered in the fifth week, this instrument consisted of 3 essay construction questions designed hierarchically to test different levels of understanding:
   a. Question 1 (Basic Concepts): Tested understanding of basic 3D to 2D transformations, specifically the projection of a line lying on a plane α. This question required understanding the relationship between points, lines, and plane traces.
   b. Question 2 (Relational Concepts): Tested the ability to construct a plane β parallel to plane α and passing through a specific point $P(2,3,5)$. This tested the understanding of parallelism invariants in the Monge projection system.
   c. Question 3 (Advanced Concepts & Spatial Visualization): Tested the ability to determine the intersection between a plane α and a solid regular pyramid $T.ABCDE$. This was the highest difficulty level, requiring integrated understanding of plane intersections, visibility (hidden vs. visible lines), and logical consistency of the intersection.
2. Structured Interview Guide: Administered in the sixth week, individual interviews lasting approximately 30 to 45 minutes were conducted. With the participants' consent, all interviews were audio-recorded and subsequently transcribed verbatim. The interview guide was designed to unearth students' metacognitive processes not visible in written test results. Questions covered aspects of initial strategies (entry points), encountered obstacles, the role of specific GeoGebra features (e.g., Rotate 3D View, Perpendicular Line), and reliance on instructional assistance. A thematic coding scheme was developed to analyze responses systematically. Examples of questions included: "What was the first thing you did when opening the task?", "How did you know your construction was incorrect?", and "Which feature triggered your 'Aha!' moment?".

3. Instrument Validation: Prior to administration, the test underwent content validation by two independent experts in mathematics education to ensure its alignment with the curriculum and cognitive demands. A pilot test was also conducted with a non-participating cohort to verify the clarity and reliability of the questions, leading to minor phrasing adjustments.

Data analysis techniques

Data were analyzed using an interactive qualitative model following Miles, Huberman, and Saldaña:

1. Data Reduction: Interview transcripts and test artifacts were systematically reviewed. A thematic coding scheme was developed deductively from the Instrumental Genesis framework and inductively from the raw data. To derive the exploration strategy profiles (Type A, B, C), participant responses regarding their initial actions, feature utilization, and instructor dependence were categorized. To ensure reliability, two researchers independently coded the qualitative data. An inter-coder agreement of 85% was achieved, and any discrepancies were resolved through negotiated consensus during peer debriefing sessions.
2. Data Display: Error matrices were constructed based on the analysis of student work images. Each error was categorized based on the underlying epistemological obstacle (e.g., error in projecting points onto traces, failure of the parallelism principle). Frequencies of these errors were tabulated to provide a systematic overview.
3. Verification/Conclusion Drawing: Findings from tests and interviews were synthesized to build a coherent narrative regarding the knowledge construction process. Triangulation was performed by comparing what students said (interviews) with what they did (GeoGebra construction results). Additionally, member checking was conducted by sharing preliminary interpretations with selected participants to confirm the accuracy of the findings.

Results

Profiles of exploration strategies and technology interaction

Through inductive coding of the interview transcripts—specifically focusing on students' initial actions, feature preferences, and responses to obstacles—three distinct exploration strategy profiles emerged. Table 1 summarizes these patterns and demonstrates how varying levels of instrumental genesis were achieved by the participants.

Table 1: Profile of exploration strategies and student responses (S1-S16)

Strategy Group	Subjects	Behavioral Characteristics	Role of Technology (GeoGebra)	Instructor Dependence
Type A: Dependent-Procedural	S1, S7, S10, S11, S13, S15, S16	Repeatedly reading/listening to instructions before attempting; Rigidly following theoretical steps (Monge Method); Anxious if results differ from the textbook.	Used as "digital paper"; Animation/Slider features aid passive visualization.	Very High; Requires periodic confirmation ("Is this correct?").

Strategy Group	Subjects	Behavioral Characteristics	Role of Technology (GeoGebra)	Instructor Dependence
Type B: Analytic-Conceptual	S2, S6, S8, S9, S12	Observing coordinate axes (X, Y, Z) for orientation; Comparing 2D and 3D views side-by-side; Relying on algebra.	Verification tool; Trace and Perpendicular features for logical validation.	Moderate; Requires "prompting questions" or demonstrations of new features.
Type C: Explorative-Intuitive	S3, S4, S5, S14	Immediately trying features randomly (trial-and-error); Not afraid of making mistakes; Manipulating objects extremely (dragging).	Thinking partner; Discovering geometric invariants through dynamic manipulation.	Low; Lecturer functions as a discussion facilitator or final logic corrector.

These findings indicate that while technology is available to all, learning dispositions heavily influence the manner in which students utilize it. Type A students experienced barriers in the instrumentalization process; they feared "ruining" the drawing and tended to wait for instructions (Flores Salazar et al., 2025). Conversely, Type C students demonstrated a rapid instrumentation process, where GeoGebra features were quickly adopted into new thinking schemas (Misfeldt, 2013).

Systematic analysis of knowledge construction errors

To provide a systematic overview of the cognitive challenges encountered, Table 2 summarizes the frequency of specific construction errors observed in the conceptual understanding test across all 16 participants.

Table 2: Frequency of construction errors among participants (N=16)

Error Category	Description of Epistemological Obstacle	Frequency (n)	Percentage (%)	Participants
Dimensional Transformation (Question 1)	Failure to align spatial points with the corresponding horizontal plane trace.	14	87.50%	S1-S5, S7, S9-S16
Plane Parallelism Misconception (Question 2)	Erroneous translation of 3D coordinates leading to non-parallel planar traces.	14	87.50%	S1-S4, S7-S16
Floating Intersection (Question 3)	Failure to identify intersection points residing on the base (ground plane) of the polyhedron.	16	100%	S1-S16

The high frequencies of these errors provide crucial insights into the deep-seated epistemological obstacles faced by students in understanding projection concepts. The following subsections integrate illustrative cases and interview excerpts to unpack the cognitive mechanisms behind these pervasive errors.

1. **Dimensional transformation errors in line projection (Question No. 1)**

   Question 1 required students to construct the projection of lines a and b lying on a plane α. Although 87.5% of the subjects (excluding S6 and S8) successfully constructed the projection of plane α (α_1, α_2, and α_3) correctly, the vast majority experienced fatal failures in placing points on lines lying within that plane.

In Figure 1, S1 successfully created a line a_2 (vertical projection) connecting P_2 and R_2. However, when drawing line a_1 (horizontal projection), S1 failed to determine the position of P_1 correctly. S1 did not draw a correspondence line (alignment) perpendicular to the X-axis from P_2 to a_1.

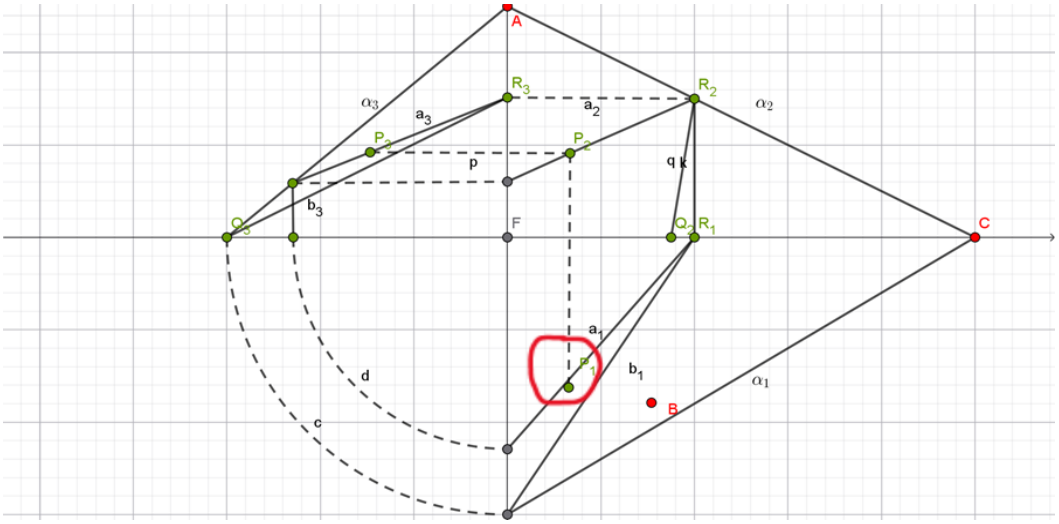

Figure 1. Answer to Question no. 1 from S1

Epistemological Analysis: A more fundamental error was observed in the failure to draw Q_1. It was known that Q_2 lay on the X-axis. In the Monge system, if the vertical projection of a point (Q_2) lies on the X-axis (ground line), then the spatial point lies on the Horizontal Plane (H). Consequently, its horizontal projection (Q_1) must coincide with the position of the point itself on plane H, meaning Q_1 must lie on the horizontal trace of plane α (α_1).

When asked about the biggest obstacle faced during this task, S1 revealed, *"It is difficult to determine the relationship between objects, for example, whether a line is already attached to a plane"*. This confirms a disconnection between "point position in space" and "plane trace representation." Students viewed lines and points as separate graphic elements rather than as representations of spatial entities bound by projection rules.

2. Plane parallelism misconceptions (Question No. 2)

Question 2 requested the construction of the projection of plane β parallel to plane α and passing through point $P(2,3,5)$.

S7 was able to construct the plane α through points A, B, C. However, analysis of Figure 2 showed that when asked to create plane β parallel to α through P, S7 drew the projection of point P as $P_1(2,0,0)$ and $P_2(2,0,2)$, whereas the original coordinates of P were $(2,3,5)$.

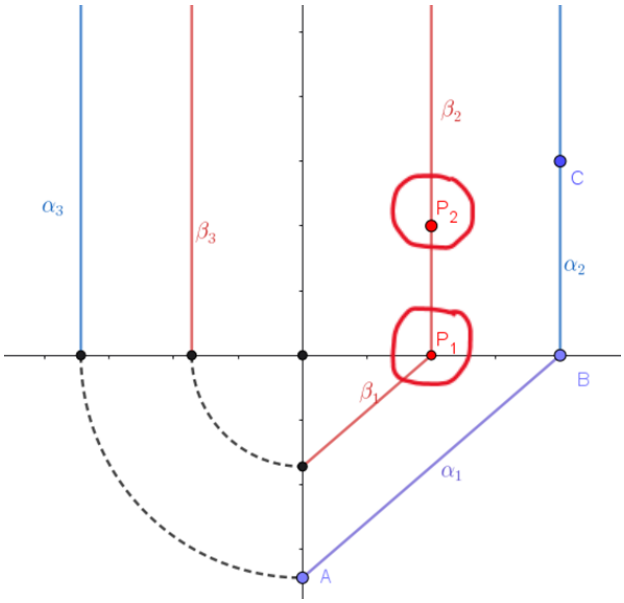

Figure 2. Answer to Question no. 2 from S7

Epistemological Analysis: This error, committed by 14 subjects, is fundamental. In the Monge coordinate system, the abscissa (x) is invariant, the ordinate (y) represents depth (distance from the vertical plane), and the applicate (z) represents height (distance from the horizontal plane).

During the interview, S7 explained their workflow: *"I build the projection on the base plane (horizontal), then draw the line upwards"*. This procedural approach failed because S7 erroneously altered the point coordinates during projection, demonstrating a lack of understanding regarding how 3D coordinates translate to distances on drawing paper. Furthermore, the failure to draw traces of plane β parallel to traces of plane α (β_1 // α_1 and β_2 // α_2) indicates a weak grasp of the fundamental theorem of descriptive geometry regarding parallelism: "Two parallel planes have parallel traces on the same projection plane" (Gorjanc, n.d.; Gutiérrez de Ravé et al., 2025).

3. **Visualization obstacles in solid intersections (Question No. 3)**

Question 3 was the most complex, requiring students to determine the intersection of plane α on a regular pentagonal pyramid $T.ABCDE$. Notably, 100% of the participants struggled with this aspect initially (Table 2).

S10 successfully projected the pyramid and plane α separately. S10 obtained plane traces α_1 and α_2. However, analysis of Figure 3 showed that this student was "stuck" regarding the position of α_1 cutting the pyramid's pentagonal base.

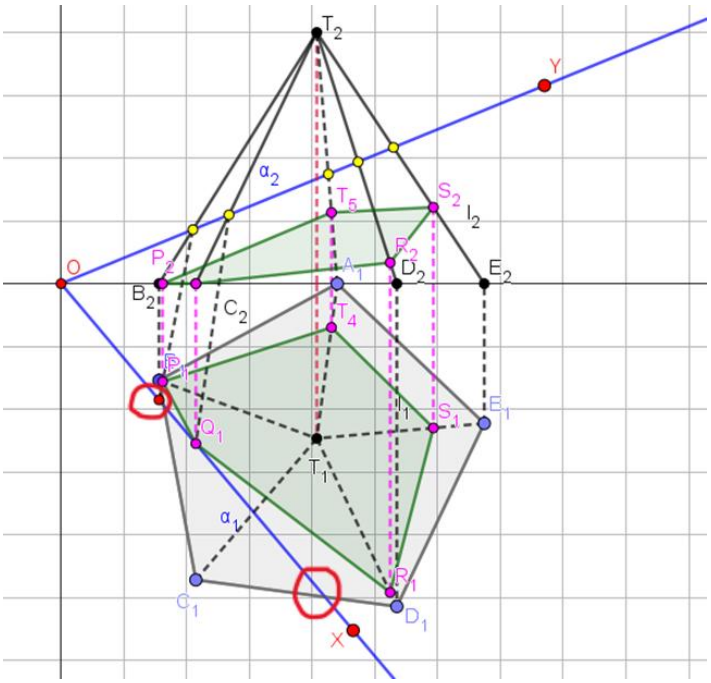

Figure 3. Answer to Question no. 3 from S10

Epistemological Analysis ("Floating Intersection"): S10 and nearly all other subjects failed to identify that the trace line α_1 cutting the pentagonal base of the pyramid produced two intersection points which are part of the intersection plane. Students tended to seek intersection points only on the upright edges of the pyramid (edges leading to apex T), as if the intersection occurred only in the "air" and did not touch the "ground" (base).

S10 expressed this exact difficulty during the interview: *"I was confused translating the 2D drawing instructions on paper into a 3D digital form"*. This demonstrates a serious cognitive gap between 3D and 2D representations. Students understood the concept of intersection as cutting a solid object but failed to realize that the pyramid base resting on the horizontal plane is also a "face" capable of being cut. This misconception indicates an incomplete understanding of the definition of a polyhedron and its interaction with a cutting plane (Aziiza et al., 2022; Sudirman et al., 2023).

The role of GeoGebra features in overcoming difficulties

Interview data confirmed that the use of GeoGebra helped students realize and (in some cases) correct the aforementioned errors, which might have gone undetected using manual methods.

1. Validation via Dragging: When asked, "Why did you try dragging the objects?", the majority of students responded: *"To ensure that the relationship between lines did not change (remained consistent)"*. This response is crucial. It proves that students adopted dragging as an instrument of logical verification. In paper drawings, lines that appear parallel may not actually be parallel if measured precisely. In GeoGebra, if a line is constructed using the Parallel Line feature, it will remain parallel regardless of how its

parent points are shifted. If the line "detaches" or changes properties upon dragging, students instantly know their construction is incorrect (instant feedback) (Akyüz, 2015).

2. Extreme Viewpoint Visualization (3D Rotation): S1, S4, S6, S7, S12, and S14 explicitly stated that GeoGebra *"Allowed me to see the object from angles impossible to achieve on paper"*. For S10, who struggled with the pyramid intersection, the 3D rotation feature (rotating the object to view from beneath the base) provided new insight that the cutting plane indeed penetrated the base. This triggered a cognitive conflict that forced a revision of their "floating intersection" concept.
3. Mental Bridges (The Aha! Moment): For S1, the "Aha!" moment occurred when *"The lecturer demonstrated a feature I didn't know before"* (e.g., animation). For S2, it occurred when *"The lecturer asked a prompting question"*. This indicates that technology alone is insufficient; pedagogical intervention by the lecturer (Instrumental Orchestration) is vital to transform software features into mathematical understanding (Rigopouli et al., 2025; Pfeiffer et al., 2025).

Discussion

Dynamics of instrumental genesis and student variation

The findings provide strong empirical evidence for the theory of Instrumental Genesis within the context of higher education in Indonesia. The integration of GeoGebra in the Descriptive Geometry course is not merely a substitution of tools from pencil to mouse, but a fundamental cognitive transformation. However, modifying assumptions from prior research, this study reveals that dynamic geometry software does not uniformly enable independent validation for all learners. Consistent with the Instrumental Genesis framework (Misfeldt, 2013), students who successfully transitioned the software from an artifact to an instrument (Type B and C profiles) demonstrated a shift from perceptually driven judgments to theoretically grounded verifications. They creatively modified tool usage, such as materializing abstract projector lines, to overcome visualization difficulties. Conversely, Type A students struggled significantly with instrumentation. This variation suggests that the capacity to utilize technology for independent exploration is heavily mediated by underlying cognitive and affective factors, such as emotional stability, mathematical anxiety, or weak foundational spatial knowledge. Students lacking these foundational competencies remain reliant on external validation, highlighting that technological access alone cannot override deep-seated learning dispositions.

Confronting epistemological obstacles through dynamic feedback

Rather than reiterating specific geometric errors, the broader theoretical implication of the results is that dynamic visualization serves as a powerful, yet conditional, catalyst for confronting epistemological obstacles. The empirical data support the assertions of Sudirman et al. (2023) and Modestou & Gagatsis (2007) that prior 2D knowledge often interferes with 3D reasoning. In manual drafting, visual ambiguities allow such misconstructions to remain hidden. In contrast, the rigid logical constraints of the GeoGebra environment force cognitive

conflicts when students attempt to construct geometrically impossible spatial relationships. This finding aligns with Parra Lara & Ospina Parra (2024), demonstrating that features like 3D rotation and dragging dismantle resistant spatial misconceptions by providing irrefutable visual feedback. Nevertheless, this study extends prior literature by showing that for highly dependent students, the cognitive load of navigating a novel 3D digital interface can initially exacerbate visualization challenges before conceptual resolution occurs (Sweller, 2020), necessitating carefully structured interventions.

Transformation of the lecturer's role: From instructor to orchestrator

The persistent reliance on instructional support among certain students underscores a critical boundary condition for Technology-Enhanced Learning. While previous studies often generalize the autonomous benefits of software, our findings clarify that GeoGebra facilitates independent exploration only for learners who have crossed a specific instrumental threshold. For others, the software remains an opaque artifact. This aligns with recent literature emphasizing that technology necessitates a shift in the lecturer's role from a knowledge transmitter to an "orchestrator" managing the interaction between students, tasks, and technology (Pfeiffer et al., 2025; Rigopouli et al., 2025; NCSM, 2024). The instructor's targeted interventions—such as prompting questions or demonstrating hidden software features—are essential to bridge the gap between students' visual perceptions and formal mathematical reasoning.

Limitations and future research directions

While this study provides in-depth insights into the cognitive processes of knowledge construction, several limitations must be acknowledged. The research was conducted with a small sample size within a single institutional context, which limits the generalizability of the identified exploration strategy profiles to broader populations. Additionally, despite the implementation of rigorous peer debriefing and reflexivity protocols, the dual role of the primary researcher as the course instructor introduces an inherent potential for positionality bias. Future research should involve larger, more diverse cohorts and incorporate quantitative measures of cognitive and affective variables, such as spatial visualization ability and mathematics anxiety, to further isolate the factors mediating instrumental genesis in digital environments.

Implications for mathematics education curricula

This research holds important implications for curricula in Teacher Education Institutions (LPTK) such as UNJ.

1. Integration of Digital Literacy: Proficiency in using Dynamic Geometry Software must be integrated early on, not just as an auxiliary tool but as a core competency.
2. Task Design: Geometry tasks must be redesigned. Questions should no longer merely ask "draw the projection...", but must demand exploration and justification, such as "construct the projection and prove via dragging that parallelism is maintained".

3. Focus on Concepts, Not Procedures: Since software handles the technical aspects of drawing, learning must shift focus to deep conceptual understanding (why does this line intersect that plane?) rather than procedural skills (how to hold the ruler straight) (Siregar, 2025; Shittu & Alex, 2025).

Conclusion

This study concludes that integrating GeoGebra into descriptive geometry instruction effectively transforms student knowledge construction by shifting their cognitive approach from static-procedural methods to dynamic-conceptual verification. By engaging in independent exploration, students successfully utilized dragging and 3D rotation to expose and dismantle persistent epistemological obstacles, such as dimensional transformation errors and planar intersection misconceptions. These findings hold significant practical implications for mathematics education, primarily highlighting the necessity for a differentiated pedagogical approach where lecturers transition into orchestrators who provide targeted scaffolding, while also underscoring the urgency to redesign curricula to prioritize digital exploration over manual drafting. However, the implications of this study are bounded by several limitations, specifically a small sample size restricted to a single institution, a relatively short six-week intervention period, and the potential for dual-role bias since the primary researcher also served as the course instructor. To build upon these findings, future research should address these constraints by employing longitudinal designs with larger, multi-institutional cohorts and by integrating quantitative measures of cognitive and affective variables, such as spatial reasoning and mathematics anxiety, to more comprehensively evaluate the factors mediating technology adaptation.

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Declarations

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Author Contributions	:	**Aris Hadiyan Wijaksana:** Conceptualization, Methodology, Data Curation, Formal Analysis, Investigation, Writing – Original Draft; **Yaya Sukjaya Kusumah:** Supervision and Validation; **Turmudi:** Supervision and Validation.

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