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Teacher Technological Pedagogical Content Knowledge and Skills (TPCK-S) and Student Cognitive Agency: Determinants of Deep Learning Outcomes in Immersive Geometry Instruction

Salmawati[1]*, Andi Kaharuddin[2], Nurfaidah Syam[3], [4]Vishal Gupta
[1*,2,3]Mathematics Education, Universitas Lakidende Unaaha, Indonesia.
[4]Mathematical Institute, University of Oxford, United Kingdom.
*Corresponding Author. Email: salmawati@unilaki.ac.id

Abstract: This study aims to investigates the determinants of student success in hologram-enhanced geometry classrooms by examining the mediating role of teachers' Technological Pedagogical Content Knowledge and Skills (TPCK-S). Employing a Sequential Explanatory Mixed-Methods Design, this research analyzed data from 12 secondary mathematics teachers (purposively sampled) and 248 Grade 8 students from four public schools implementing the national 'Kurikulum Merdeka' in a provincial capital city in Indonesia. Quantitative analysis utilizing Spearman's rank-order correlation revealed a robust positive revealed a robust positive relationship ($r = 0.78$, $p = 0.002$) between teacher performative skills and student deep learning achievement. To explain this statistical link, a qualitative phase involving classroom observations and semi-structured interviews was conducted with four teachers selected through extreme case sampling. The findings illuminate a "Flywheel Mechanism," demonstrating that high-TPCK-S teachers act as "Pedagogical Orchestrators" who effectively transfer "Cognitive Agency" to students. This agency characterized by student-led hypothesis testing and spatial reasoning is identified as the primary driver of deep conceptual understanding. Conversely, low TPCK-S results in passive student observation. These results suggest that educational development must shift focus from mere technology procurement to the cultivation of teachers' orchestration skills.

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Introduction

The challenge of enhancing student competency in Science, Technology, Engineering, and Mathematics (STEM) constitutes a global educational priority. Despite substantial investments in educational technology, international assessments such as PISA continue to reveal a persistent gap between students' procedural knowledge and their capacity for deep conceptual understanding in mathematics (OECD, 2023). This gap is particularly pronounced in geometry, a domain that remains a difficult area for secondary students due to the abstract nature of spatial concepts and the limitations of traditional two-dimensional instructional materials (Mullis & Martin, 2017; Cheng & Mix, 2014). This difficulty aligns with broader literature indicating that achieving deep learning involves the ability to link ideas, justify reasoning, and apply knowledge to non-routine problems (Danker, 2015; Ravenscroft & Boyle, 2010; Orhani, 2024). Such strategies are essential to bridge the persistent gap in mathematics achievement highlighted in recent practical research (Tian et al., 2022). These skills are especially crucial in geometry education, where students must advance through van

Hiele’s hierarchical levels of geometric thought (van Hiele, 1986, as cited in Sinclair et al., 2016).

In response to the challenge of fostering deeper conceptual understanding, immersive technologies such as Augmented Reality (AR), Virtual Reality (VR), and 3D holography have emerged as promising tools for supporting interactive and exploratory learning (Radianti et al., 2020; Fernandes et al., 2023; Avila-Garzon et al., 2021). In particular, recent reviews highlight the growing trends and potentials of holography in educational settings (Yoo et al., 2022). These tools enable learners to manipulate and visualise dynamic 3D objects from multiple perspectives (Lampropoulos et al., 2022), reducing cognitive load (Wu et al., 2024) and enhancing engagement, motivation, and conceptual understanding (Wang et al., 2025; Chen et al., 2024).

Hologram-based instruction, in particular, has demonstrated potential for improving conceptual comprehension of complex structures (Salloum et al., 2024) and supports constructivist processes such as hypothesis testing and spatial reasoning (Yoon & Wang, 2014). This affordance makes holograms especially relevant to advancing students toward higher levels of geometric reasoning. Compared to screen-based alternatives like PhET simulations or conventional augmented reality (AR), holograms offer unique pedagogical advantages for deep learning in geometry. While PhET simulations excel in procedural exploration, they remain constrained to 2D interfaces that require mental projection of 3D relationships, a known cognitive barrier in spatial learning. Similarly, conventional AR overlays digital content on 2D screens, creating device-mediated interactions that can distract from the learning task. In contrast, holograms provide glasses-free stereoscopic 3D visualization in shared physical space, allowing multiple students to simultaneously view and walk around virtual objects from different perspectives. This facilitates natural gestural interaction, reduces cognitive load in mental rotation tasks, and fosters collaborative sense-making, critical factors for developing deep geometric understanding that screen-based technologies may not fully support

However, educational literature consistently warns that advanced technology alone does not ensure improved learning outcomes (Ertmer & Newby, 2013; Chai et al., 2020). Often, there is a mismatch between teachers' online teaching expectations and reality (Van der Spoel et al., 2020), necessitating creative approaches like design-based learning to bridge this gap (Harriman, 2011). Effective outcomes depend heavily on teachers' ability to integrate technology meaningfully into their pedagogical practice. The influential TPACK framework (Mishra & Koehler, 2006) shaped research on technology integration for over a decade, supported by established assessment instruments (Schmidt et al., 2009), yet it faces criticism for relying largely on self-reported measures that capture perceived rather than enacted competence (Joshi, 2023; Tondeur et al., 2017; Graham, 2011; Abbitt, 2011; Tseng et al., 2022). However, as digital competence requirements for teachers evolve (Fernández-Batanero et al., 2022), systematic reviews suggest a need for continuous professional development beyond basic knowledge (Peters et al., 2022). Scholars argue that such measures risk overestimating teachers’ capabilities and fail to reflect the dynamic decision-making required in actual classroom settings (Harris et al., 2017; Koh & Chai, 2016; Voogt et al., 2013).

To address these limitations, the Technological Pedagogical Content Knowledge and Skills (TPCK-S) framework (Kaharuddin, Arsyad, & Asdar, 2023) extends TPACK by explicitly incorporating a skills dimension that captures teachers' observable practices. In the context of emerging technologies like holograms, this focus on skills is particularly critical because teachers' intentions (knowledge) are often misaligned with their actual execution due to unforeseen technical barriers and the dynamic complexities of classroom integration. This aligns with broader educational arguments for assessing performance-based competency requirements rather than solely relying on self-reports (Leijen et al., 2017). While literature acknowledges the importance of teacher knowledge (Joshi, 2023; Li et al., 2024) and has recently developed tools to measure performative skills, a critical empirical gap persists: existing studies have not examined whether teachers demonstrated TPCK-S proficiency translates into improved student learning outcomes, particularly deep learning in geometry. This gap is especially concerning given that even technology-rich classrooms often produce poor learning outcomes when teachers lack the skill to orchestrate learning effectively (Ruthven, 2009; Roschelle et al., 2013; Matsumoto-Royo & Ramírez-Montoya, 2021).

Accordingly, it remains unknown whether a teacher’s TPCK-S proficiency can predict students’ deep learning, especially within hologram-enhanced geometry instruction. Therefore, the novelty and primary contribution of this study lie in conducting the first empirical investigation linking teachers measured TPCK-S to students’ deep learning in geometry within a hologram-supported learning environment. This study seeks to provide empirical rather than theoretical insight into the impact of teachers’ performative skills. The research is guided by the objective to determine the proficiency level of secondary mathematics teachers’ TPCK-S, measure the level of student deep learning, and crucially, explain how differences in teachers’ TPCK-S proficiency relate to their pedagogical practices and student outcomes.

Research Method

This study employed a Sequential Explanatory Mixed-Methods Design (Creswell & Clark, 2017). This design was strategically chosen because a quantitative approach alone, while able to establish a correlational link, would be insufficient to explain the underlying pedagogical mechanisms driving this relationship. The subsequent qualitative phase was therefore essential to provide explanatory depth and contextual understanding of how specific teacher skills manifest in classroom practice and influence student learning. The QUAN→qual sequence allows for a more comprehensive understanding of how and why specific teacher competencies translate into observable student outcomes. The study was conducted in four public secondary schools in a provincial capital city in Indonesia, selected based on their implementation of the national 'Kurikulum Merdeka' curriculum.

The participants for the quantitative phase comprised 12 secondary mathematics teachers (8 female, 4 male) and their 248 Grade 8 students (average age = 13.6 years; 129 female, 119 male). All participants were drawn from public schools in Southeast Sulawesi Province, Indonesia. While the sample size (N=12 teachers) limits broad statistical generalization, it is explicitly aligned with the design of explanatory mixed-methods, where the priority is depth of understanding over breadth. The teachers were selected using purposive sampling, ensuring a range of teaching experience (from 5 to 22 years, M = 12.5). Prior to the study, the teachers’ general technology integration experience was varied, though all had received a mandatory 4-hour introductory training on the "Holometri" hologram system, a portable, glasses-free device that projects interactive 3D geometric models into physical space for classroom demonstration and manipulation. The system operates as a stand-alone unit, requiring only a power source, and is controlled via a touch interface or a wireless remote.

For the qualitative phase, an Extreme Case Sampling strategy was employed. Four teachers were selected from the initial cohort based on their TPCK-S scores: the two highest-scoring teachers and the two lowest-scoring teachers. This strategy was chosen to maximize the contrast in pedagogical enactment, facilitating a clearer analysis of the impact of teacher skills on student agency.

1) Teacher TPCK-S Scale: The primary instrument for measuring teacher competence was the 28-item TPCK-S scale developed and validated by Kaharuddin et al. (2025). This instrument uses a 5-point Likert scale (1 = Not Skilled at All, 5 = Highly Skilled) to assess skills across four factors: (1) Technological-Pedagogical Skills, (2) Technological-Content Skills, (3) Pedagogical-Content Skills in a Technological Context, and (4) Holistic Integration Skills. The instrument focuses on *performative competence* (e.g., 'I am skilled at managing classroom activities...') rather than abstract knowledge. The validation study reported excellent internal consistency (Cronbach’s α = 0.91) and strong construct validity confirmed through Confirmatory Factor Analysis (Chi-Square/df = 2.43, CFI = 0.948, RMSEA = 0.062).
2) Geometry Deep Learning Test (GDLT): A researcher-developed GDLT was designed to assess students' deep learning. The test design draws upon principles of constructive alignment to ensure teaching fosters quality learning outcomes (Biggs et al., 2022). The items were specifically designed to assess cognitive abilities across different levels of the van Hiele framework, with a focus on Analysis (Level 2) and Informal Deduction (Level 3). The final 10-item test demonstrated an overall Scale-Content Validity Index (S-CVI) of 0.92 based on review by a panel of four experts, comprising two mathematics education specialists, one educational technology researcher, and one expert in geometry curriculum development. The instrument also showed good internal consistency (α = 0.84) following a pilot test.
3) Qualitative Protocols: A semi-structured interview protocol and a classroom observation protocol based on the principle of 'classroom orchestration' (Ruthven, 2009) were used to document teacher and student actions.

The research was conducted in three chronological phases as outlined in Table 1. This structured approach ensured that the quantitative baseline was established before the qualitative inquiry provided explanatory depth.

Table 1. Research Procedure

Phase	Description
Pre-Intervention	All 12 teachers completed the TPCK-S instrument online. Informed consent was obtained from teachers, students, and their parents.
Intervention	All teachers conducted a four-week unit on 3D geometry using the Holometri system. They were provided with standardised learning objectives but were given autonomy in designing their specific lesson plans and activities. During this phase, the research team conducted two non-participant observations for each of the four purposively selected teachers for the qualitative follow-up.
Post-Intervention Data Collection	In the week following the intervention, the GDLT was administered to all 248 students. Subsequently, the four selected teachers participated in individual, 45-minute semi-structured interviews, which were audio-recorded and transcribed verbatim.

Quantitative data were analyzed using IBM SPSS Statistics (Version 26). Descriptive statistics were calculated for TPCK-S and GDLT scores. To explore the relationship between teacher skills and student achievement, a Spearman's rank-order correlation was conducted. This non-parametric test was chosen as it is more appropriate for the small teacher sample size (N = 12). Qualitative data (12 observation transcripts and 4 interview transcripts) were analyzed using Thematic Analysis following the six-phase process outlined by Braun and Clarke (2021). Two researchers independently coded the transcripts using NVivo 12 software (Cohen’s Kappa = 0.88). Crucially, data integration was performed using a Joint Display

Analysis technique, where quantitative scores were juxtaposed with qualitative themes to identify patterns of convergence and divergence, specifically examining how TPCK-S levels corresponded to observed pedagogical behaviors.

Results and Discussion

Quantitative Findings: Teacher TPCK-S and Student Outcomes

The descriptive statistics for the 12 teachers' scores on the TPCK-S instrument revealed an overall mean score of 3.82 (SD = 0.75), indicating a generally high level of self-reported skill but with notable variability. As detailed in Table 1, the subscale with the highest mean was Technological-Content Skills (M = 4.01), suggesting teachers felt most competent in the technical operation of the hologram to represent geometry concepts. Conversely, the lowest mean was observed in Holistic Integration Skills (M = 3.65), indicating that teachers felt less skilled in managing pedagogical problems and adapting to technical issues on the fly.

Table 2. Descriptive Statistics of Teacher TPCK-S Scores (N=12)

TPCK-S Factor	Mean	Std. Deviation	Min	Max
Technological-Pedagogical Skills	3.78	0.81	2.50	4.90
Technological-Content Skills	4.01	0.69	3.00	5.00
Pedagogical-Content Skills	3.85	0.74	2.80	4.85
Holistic Integration Skills	3.65	0.85	2.40	4.95
Overall TPCK-S Score	3.82	0.75	2.68	4.92

Regarding student outcomes, the mean score on the Geometry Deep Learning Test (GDLT) for the 248 students was 68.7 out of 100 (SD = 15.4). The scores ranged widely, from a low of 25 to a high of 98, indicating significant variation in students' deep learning achievement across the participating classrooms. The Spearman's correlation analysis revealed a strong, positive, and statistically significant correlation between teacher TPCK-S scores and mean student GDLT scores, $r_s(10) = 0.78$, $p = 0.002$. This relationship is visually summarized in Figure 2, which plots individual teachers' TPCK-S scores against the mean GDLT scores of their respective classes, confirming a clear positive trend. This result suggests that higher levels of teacher TPCK-S are strongly associated with higher levels of student deep learning.

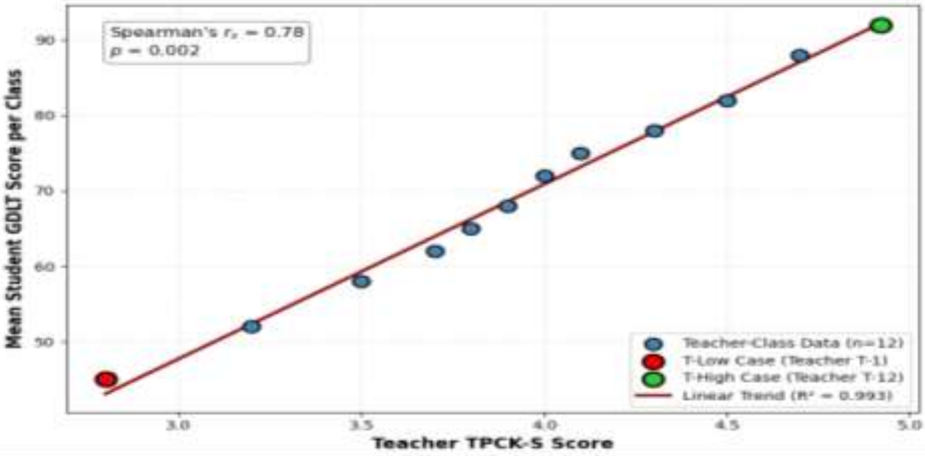

Figure 1. Scatter plot illustrating the relationship between teachers' TPCK-S scores and the mean deep learning outcomes (GDLT scores) of their students

Qualitative Findings: Pedagogical Orchestration and Cognitive Agency

The qualitative analysis of classroom observations and teacher interviews was integrated with quantitative scores to provide a comprehensive explanation of the statistical findings. This integration is summarized in Table 3, which highlights the distinct pedagogical differences between high-scoring teachers (referred to as T-High, e.g., T-12) and low-scoring teachers (referred to as T-Low, e.g., T-1)

Table 3. Integrated Matrix of TPCK-S Proficiency and Classroom Enactment

Teacher Profile	TPCK-S Score (Quant)	Dominant Observation Theme (Qual)	Deep Learning	Evidence Quote
T-High (T-12)	4.92 (High)	Pedagogical Orchestration	Reasoning: Students formulated and tested 3 distinct conjectures on cross-sections.	The hologram is a sandbox to test their hypotheses... it became our investigation.
T-Low (T-1)	2.80 (Low)	Technical Familiarization	Recall: Students focused on naming shapes correctly and watching passively.	"My main concern was making sure the hologram worked... and that every student could see it."

The detailed analysis yielded two overarching themes that explain the divergent outcomes shown in the matrix above.

A distinct difference was observed in how teachers conceptualized and utilized the hologram technology within the classroom ecosystem. The qualitative data revealed a fundamental bifurcation in teacher roles corresponding to their TPCK-S proficiency levels. Teachers in the T-Low group tended to operate at the *Technical Familiarization* stage, focusing primarily on the functional mechanics of the hardware rather than its pedagogical affordances. Classroom observations noted that their lessons were frequently structured as teacher-centric demonstrations. In these settings, the teacher retained exclusive control of the hologram while students remained seated, watching the projection passively. This approach was characterized in the field notes as "broadcast and awe," where the technology served as a centerpiece for display rather than a tool for inquiry. Teacher T-1, representative of this group, revealed a teaching orientation dominated by technical anxiety. During the interview, she frankly admitted:

> *"My main concern was making sure the hologram worked properly and that every student could see it... I felt it was a successful lesson if there were no technical glitches."* (Teacher T-1, Low TPCK-S)

This admission provides a clear window into the limitations of the "Operator" mindset. Here, the teacher's definition of success is strictly functional "the machine worked" rather than educational "the students learned." Because the teacher's cognitive load was monopolized by managing the device, there was little mental capacity left for responsive pedagogy. Consequently, the technology became a barrier to interaction rather than a bridge.

In stark contrast, T-High teachers operated at the *Seamless Integration* stage. For this group, the technology was rendered "invisible"; it was not the focus of the lesson but a tool strategically integrated into a larger constructivist design. These teachers acted as "Pedagogical Orchestrators," managing complex learning cycles involving prediction, experimentation, and confirmation. Teacher T-12, whose students achieved the highest deep learning scores, articulated this sophisticated approach during her interview:

> *"The hologram itself is not the lesson; rather, it serves as evidence that students use to construct their own arguments... the hologram becomes their sandbox to test their hypotheses."* (Teacher T-12, High TPCK-S)

This statement signifies a profound pedagogical shift. By metaphorically reframing the hologram as a "sandbox," Teacher T-12 explicitly shifts the locus of control from the teacher to the learner. The technology is no longer a screen for consuming information but a laboratory for generating it. This orchestration creates an environment conducive to deep learning, as it demands that students engage in active hypothesis testing, a cognitive process significantly more demanding than the passive observation found in T-Low classrooms.

The second theme delves into the critical issue of cognitive responsibility distribution, specifically, who holds the authority to generate mathematical knowledge in the classroom. The observational data highlighted a stark dichotomy in how this responsibility was managed. In T-Low classrooms, the teacher remained the sole "primary sense-maker." The flow of information was unidirectional: the teacher explained the geometric properties using the hologram, and students were expected to absorb this information. Interactions were predominantly teacher-centric and limited to lower-order cognitive tasks, such as recall questions (e.g., *"What is the name of this vertex?"*). In these environments, students were intellectually passive; their cognitive agency was restricted to validating the teacher's statements rather than constructing their own understanding.

Conversely, T-High teachers utilized the technology to deliberately transfer cognitive agency to the students. They recognized that for deep learning to occur, students must actively manipulate the object of study. This physical interaction reflects the critical role of embodiment and gestures in mathematics teaching and learning (Alibali & Nathan, 2012). A pivotal pedagogical maneuver observed across these classrooms was the "handing over of controls." This was often not a planned activity but a responsive pedagogical move designed to shift the lesson from instruction to inquiry. Teacher T-11 offered a profound reflection on one such moment that fundamentally altered the learning trajectory of her class:

> *"There was a moment when a student asked a 'what if' question... Spontaneously I said, 'Here, you try rotating it yourself.' That small moment changed the entire dynamic. It was no longer my lesson; it became our investigation. Once they had the controls, they started arguing about the angles and testing their own theories. I just stepped back and watched them learn."* (Teacher T-11, High TPCK-S)

This observed shift in agency directly catalyzed progression within the van Hiele geometric reasoning hierarchy. In T-Low classrooms, activities were confined to naming shapes and passive observation behaviors characteristic of van Hiele Level 1 (Visualization/Recognition). In stark contrast, the student-led hypothesis testing and logical argumentation fostered by T-High teachers, as seen in Teacher T-11's class, are hallmarks of the transition from Level 2 (Analysis) to Level 3 (Informal Deduction). Here, students moved beyond analyzing properties to making informal deductions based on them. Thus, effective teacher orchestration (high TPCK-S) did not merely increase engagement; it specifically enabled the cognitive leap from visual identification to deductive reasoning. Without it, students remained cognitively trapped at the basic visualization level.

This narrative illustrates a critical inflection point in the "Flywheel Mechanism." By physically transferring the control of the hologram to the student, the teacher symbolically and practically transferred the responsibility for learning. This act empowered students to explore the geometric space, formulate hypotheses, and crucially, make mistakes in a low-stakes environment. This shift fosters a robust constructivist atmosphere where students are not merely recipients of geometric facts but active architects of their own spatial understanding, a cognitive state that is essential for achieving deep learning outcomes.

Synthesising the quantitative and qualitative findings, this study proposes a "Flywheel Mechanism" to explain how teacher skills translate into deep learning. As illustrated in Figure 1, high TPCK-S acts as the external force or catalyst that initiates the momentum. It allows teachers to shift from technical management to Pedagogical Orchestration. This orchestration creates the necessary conditions for Student Cognitive Agency, where students actively manipulate holograms to test hypotheses. It is this agency that directly drives Deep Learning Outcomes. Crucially, the gray return arrow indicates a feedback loop: successful student outcomes reinforce the teacher's confidence and skills, sustaining the cycle.

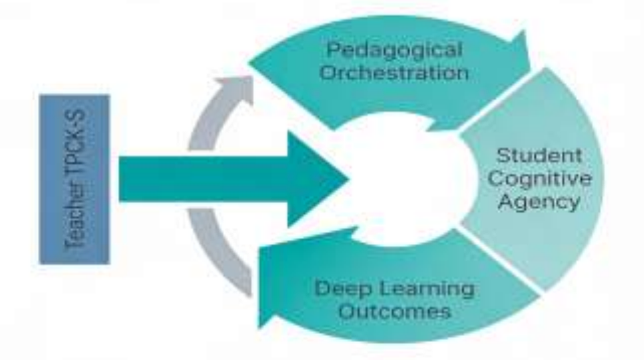

Figure 2. The 'Flywheel' Mechanism of Deep Learning illustrating the cyclic interaction between teacher orchestration and student agency.

The grey return arrow in Figure 1 represents this critical feedback loop, where strong student learning outcomes specifically enhance teachers’ TPCK-S through three reinforcing mechanisms. First, observing student success in deep reasoning tasks provides direct, positive evidence of one's instructional effectiveness, thereby boosting teachers' self-efficacy and confidence in using the technology (Bandura, 1997). Second, student inquiries and unexpected solutions during hypothesis-testing activities serve as powerful stimuli for teacher reflective practice, prompting educators to critically evaluate and refine their pedagogical approaches and task designs. Third, navigating the dynamic needs of an agentive classroom forces teachers to develop real-time technical and pedagogical adaptations, such as troubleshooting hologram manipulations on the spot or improvising questions that build on student conjectures, thereby expanding their repertoire of enacted skills. This completed cycle posits that TPCK-S is not a static input but a dynamic competency that is reciprocally developed through successful classroom enactment, creating a virtuous cycle of professional growth and student achievement.

The central finding of this study that a strong, positive correlation exists between teachers' TPCK-S scores and their students' deep learning achievement, makes a significant contribution to the field by empirically substantiating that it is the teacher's skillful *enactment* of knowledge, not merely their possession of it, that drives educational outcomes. While numerous studies have correlated teacher TPACK with student engagement (Panigrahi et al., 2021) or perceived learning (Zeng et al., 2022; Downie et al., 2021) , few have successfully linked a performance-based measure of teacher competence with an objective measure of deep student learning. The findings extend the work of Tondeur et al. (2017) by demonstrating that a skills-focused instrument can effectively capture the 'practice' dimension. The qualitative evidence of the "Pedagogical Orchestrator" aligns with Ruthven’s (2009) concept of classroom orchestration , showing that high TPCK-S teachers are not cognitively overloaded by the technology. This fluency allows them to create constructivist learning environments where students are empowered to take an active role in their own knowledge construction (Voogt et al., 2013). Facilitating this requires strong teacher agency to adapt performance-driven contexts (Lu et al., 2021), which in turn serves as a vital support mechanism for enhancing student engagement and self-directed learning (Mozammel et al., 2024). The "Flywheel Mechanism" implies that high Teacher TPCK-S does not directly impact learning but enables the critical shift in practice towards orchestration, which in turn creates the student agency required for deep learning.

Conclusion

This study concludes that teacher TPCK-S is a critical determinant of student deep learning in hologram-enhanced geometry instruction. The findings validate the "Flywheel Mechanism," positing that TPCK-S serves as the catalyst for Pedagogical Orchestration, which fosters Student Cognitive Agency the primary driver of deep learning. Therefore, this study provides the first empirical evidence that transitioning from perceived technological-pedagogical knowledge (TPACK) to enacted, observable skills (TPCK-S) is the key mechanism for resolving the persistent "rich-technology, poor-pedagogy" paradox in STEM education.

Recommendation

Based on the findings, it is recommended that professional development programmes adopt a practice-oriented approach, using frameworks like TPCK-S to diagnose needs and cultivate pedagogical orchestration skills. Crucially, training must move beyond technical familiarization (e.g., "how to operate the hologram") to focus on high-leverage orchestration strategies observed in this study. For example, training modules should include:

1) Designing and facilitating hypothesis-testing cycles: How to structure tasks where students formulate and test conjectures using technology (e.g., "What happens to the cross-section if we tilt the cube differently?").
2) Dynamic scaffolding during student inquiry: How to provide just-in-time support (e.g., strategic questioning, peer collaboration prompts) while students manipulate holograms, rather than providing direct answers.
3) Intentional transfer of cognitive agency: How to plan for and execute the "handing over of controls" to students, managing the classroom transition from teacher-led demonstration to student-led investigation.

This shift ensures training is aligned with the enacted skills that directly correlate with deep learning. Future research should expand upon these findings with larger samples and longitudinal designs to further explore the dynamics of teacher skill development. Furthermore, future studies should control for lesson planning autonomy to better disentangle the impact of in-class performative skills.

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