

Validating a TPCK-S Instrument for Hologram-Based Mathematics Teaching

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Abstract

The successful use of 3D holograms in teaching geometry depends greatly on teachers' practical skills. However, there remains a substantial gap in understanding how these skills are developed and how they can be reliably assessed. This study, carried out with mathematics teachers in Southeast Sulawesi, Indonesia, seeks to address this issue by (1) proposing a theoretical model for the development of Technological Pedagogical Content Knowledge and Skills (TPCK-S), and (2) creating and validating an instrument to measure this construct. Following a sequential exploratory mixed-methods design, a theoretical model was first built through a grounded theory study with six junior high school mathematics teachers. Building on this model, an instrument was then empirically validated with a sample of 112 junior high school teachers through the combined use of Exploratory Factor Analysis (EFA) and Confirmatory Factor Analysis (CFA). The findings revealed a three-stage TPCK-S development model consisting of Technical Familiarization, Pedagogical Experimentation, and Fluent Integration. In addition, the validated 28-item instrument demonstrated a solid four-factor structure, with confirmatory factor analysis (CFA) showing good model fit and internal consistency reliability reaching an excellent level ($\alpha = 0.91$). Overall, this study contributes a rigorously tested TPCK-S instrument that can serve as a valuable diagnostic tool to support and strengthen teacher professional development in the digital era.

Keywords: complex learning cycles, educational innovations, hologram technology, immersive technology in education, performative skill assessment, teacher pedagogical competence, technology integration.

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1. Introduction

The challenge of fostering effective geometry learning at the junior high school level is a global issue, widely recognized and documented across numerous studies in mathematics education (e.g., (Moore & Carlson, 2012; Mullis et al., 2021)). Research consistently shows that students struggle with the abstract nature of geometric concepts and with developing spatial visualization skills—both of which are

essential foundations for higher-order mathematical thinking. These difficulties are often intensified by traditional teaching methods that provide limited opportunities for exploring multimodal representations, such as the integration of diagrams, physical models, and interactive simulations. Yet, such representations play a crucial role in helping students build deeper and more meaningful conceptual understanding (Malhotra, 2021). A growing body of

research has demonstrated that training in spatial ability can lead to significant improvements in students' mathematics achievement (Cheng & Mix, 2014), underscoring the urgency of finding effective teaching aids.

In the Indonesian context, this challenge is further compounded by the reliance on traditional two-dimensional teaching media—such as blackboard drawings or static textbook images—that often fall short in supporting spatial reasoning. As a result, students' science process skills (SPS), including their ability to observe, formulate hypotheses, and interpret visual data, are not fully nurtured (Rusli Baharuddin et al., 2021). In response, the international educational research community has increasingly turned its attention to the potential of immersive technologies. Among these, 3D hologram technology—which projects virtual objects that appear strikingly real—has emerged as a promising medium for bridging the gap between abstract representations and concrete understanding Yoo et al. (2022). This technology goes beyond providing visualizations; it also fosters an interactive learning environment that encourages students to engage in independent exploration (Avila-Garzon et al., 2021). One of the key pedagogical strengths of this technology lies in its ability to make the invisible visible, a feature that is particularly valuable for teaching topics such as three-dimensional objects (Yoon & Wang, 2014; Khuluq et al., 2024).

Various studies have shown the positive impact of using holograms in improving understanding of 3D concepts (Khairunnisa Roslan & Ahmad, 2017; Salloum et al., 2024), triggering students' cognitive engagement (Yang & Lin, 2010), and even in analyzing teachers' thought processes when using them (Kosko, 2022).

Furthermore, other research has also confirmed the practicality of 3D hologram media in classroom geometry learning (Kaharuddin et al., 2023). Thus, the exploration of technology such as the "Holometri" system used in this research is in line with the global research trend of seeking innovative pedagogical solutions (Balalle, 2025).

However, the literature makes it clear that the mere presence of advanced technology does not guarantee successful learning; what truly determines its impact is the teacher's pedagogical competence in integrating it effectively (Ertmer & Newby, 2013). The Technological Pedagogical Content Knowledge (TPCK or TPACK) framework has long served as a foundation for understanding the complex interplay between technology, pedagogy, and content. Yet, it has often been criticized for its static nature and its limitations in addressing the gap between what teachers know and how effectively they can apply that knowledge in real classroom practice. This criticism highlights that many TPACK instruments measure self-perception rather than actual competence (Kadluba et al., 2025). To address this limitation, the author's earlier doctoral research developed an initial substantive theory of Technological Pedagogical Content Knowledge and Skills (TPCK-S) (Kaharuddin, 2024). This framework expands upon TPCK by introducing the additional 'S' dimension for Skills, referring to a set of observable, practical, and adaptive competencies that allow teachers to apply TPCK more dynamically in real classroom contexts.

Although TPCK-S has been introduced as a theoretical concept, a notable methodological gap remains. While several instruments have been developed to measure TPCK, none adequately capture the

expanded dimensions of TPCK-S (Li et al., 2024; Schmidt et al., 2009), but these instruments generally focus on the domains of knowledge and teacher self-perception. Studies show that there is often a gap between teachers' pedagogical beliefs and their actual practices in using technology (Tondeur et al., 2017), making the measurement of performative skill aspects crucial. A persistent challenge in the literature is how to measure the performative and practical skill aspects of technology integration in ways that are both valid and reliable (Angeli & Valanides, 2009). The need for measurement tools that are not only psychometrically valid but also relevant to the specific context of technology and subject matter continues to be voiced (Durdu & Dag, 2017). To date, no standardized instrument has been specifically designed to measure the TPCK-S construct in the context of using immersive technology like holograms.

To address this methodological gap, this study has two primary objectives. First, it aims to construct a theoretical process model

that explains how teachers' TPCK-S develops as they learn to integrate 3D hologram technology. Second, based on this foundational model, the study focuses on developing and validating a psychometric instrument designed to measure this construct. Through this sequential exploratory design (QUAL→quan), this research provides a key contribution by delivering the first TPCK-S instrument that is not only statistically robust but also substantively valid, as it is grounded in the authentic experiences of teachers in the field.

2. Method

This study employed a sequential exploratory mixed-methods design (QUAL→quan), where the findings from the qualitative phase provided the foundation for the quantitative phase (Creswel et al., 2017). The research flow integrating the qualitative and quantitative phases is visually illustrated in Figure 1.

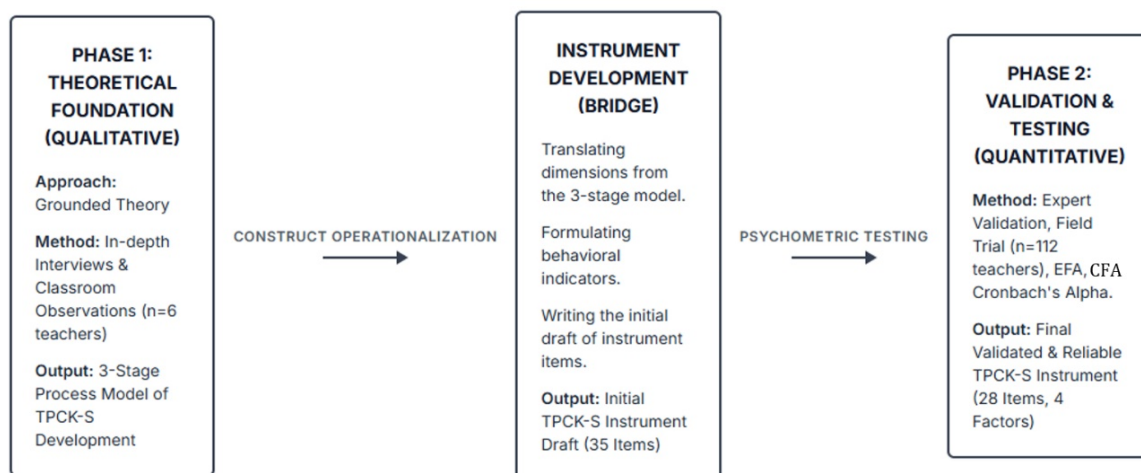


Figure 1. Conceptual Framework of the Research Flow

This study engaged two groups of participants aligned with its sequential research phases. In the initial qualitative, theory-building stage, six junior high school mathematics teachers from Southeast Sulawesi were purposively selected to

generate rich and in-depth data consistent with the grounded theory approach. The subsequent quantitative validation phase then encompassed the entire population of registered junior high school mathematics teachers in Southeast Sulawesi. From this population, 112 teachers were selected through stratified random sampling, ensuring representation across different regions and school accreditation levels. This approach strengthened the external validity of the research findings.

The research was carried out in two sequential phases. The initial phase centered on developing a theoretical model through a grounded theory approach (Corbin & Strauss, 2014; Kaharuddin, 2024). During the qualitative stage, data were gathered through classroom observations and semi-structured interviews with six junior high school mathematics teachers. Insights from this phase informed the subsequent quantitative stage, which focused on developing and validating the instrument. The draft items were constructed directly from the dimensions and indicators identified in the theoretical model. The draft instrument underwent content validation by a panel of five experts in mathematics education and technology. Following revisions based on their feedback, the finalized instrument was administered to a sample of 112 junior high school mathematics teachers.

Data analysis was carried out in two phases. For the qualitative phase, interview transcripts and field notes were examined using the grounded theory approach—through open, axial, and selective coding—with NVivo software support to identify core categories and construct the theoretical model. For instance, during open coding, a teacher's quote like, "Honestly, at first, I thought, 'is this just a gimmick?'" was assigned codes such as 'initial doubt' and

'tool-focused concern.' In axial coding, these codes were linked to others like 'technical burden' to form a broader category, such as 'Operational Hurdles.' In the final stage of qualitative analysis, selective coding integrated this category with related ones, yielding the core category Stage 1: Technical Familiarization—the first of three principal stages in the developed model. For the quantitative phase, data from the field trial involving 112 participants were analyzed with IBM SPSS Statistics (Version 26) and AMOS (Version 24).

- a. Content Validity: The degree of expert agreement was assessed quantitatively through Gregory's coefficient to confirm the relevance of each item.
- b. Exploratory Factor Analysis (EFA): The suitability of the data was assessed using the Kaiser-Meyer-Olkin (KMO) measure and Bartlett's Test of Sphericity. Exploratory Factor Analysis (EFA) was then conducted employing Principal Component Analysis with Varimax rotation to determine the factor structure. Items were retained if they demonstrated adequate factor loadings and did not exhibit high cross-loadings.
- c. Confirmatory Factor Analysis (CFA): The factor structure obtained from EFA was then tested for its fit using CFA. Several goodness-of-fit indices were used to evaluate the model, as recommended by (Byrne, 2001): Chi-square/degrees of freedom (χ^2/df), Root Mean Square Error of Approximation (RMSEA), Comparative Fit Index (CFI), and Tucker-Lewis Index (TLI).

Construct Validity and Reliability Analysis: To evaluate convergent validity, the Average Variance Extracted (AVE) and

Composite Reliability (CR) were computed. Internal consistency was further assessed using Cronbach's Alpha, calculated for the instrument as a whole as well as for each resulting factor.

3. Result and Discussion

The presentation of findings in this section follows a sequential order, starting with the qualitative phase that provided the foundation for instrument development, and continuing with the quantitative phase, which focused on psychometric analysis. The discussion is interwoven with the findings to provide a comprehensive interpretation.

An in-depth examination of interviews and classroom observations indicated that the development of teachers' TPCK-S competence follows three clear and sequential stages. These stages portray the teachers' transition from early hesitation toward achieving a fluid and confident integration of technology with pedagogy.

Stage 1: Technical Familiarization. At this stage, teachers primarily concentrate on the operational aspects of the technology, such as rotating or zooming the holographic object, selecting different shapes, or displaying a shape's net. Classroom interaction is largely one-directional—characterized as “broadcast and awe”—as the teacher's cognitive resources are focused on managing the technology's functionality. This condition is driven by a fundamental doubt about the pedagogical value of the technology, as expressed by one teacher: "Honestly, at first, I thought, 'is this just a gimmick?'... my initial concern was whether this was just a fancy toy or if it could actually teach them something".

Stage 2: Pedagogical Experimentation. As teachers gain greater technical confidence, they begin to transition into a

new stage characterized by spontaneous innovation. Here, teachers gradually shift responsibility to students, moving from the role of instructor toward that of facilitator. This crucial moment is captured in a teacher's reflection: "...spontaneously I said, 'Here, you try rotating it yourself.' That small moment, letting the student lead the exploration, changed the entire dynamic. It was no longer my lesson; it became our investigation."

Stage 3: Seamless Integration. As the culmination of this process, the technology is no longer the focus but has been strategically integrated with the learning objectives. The teacher skillfully designs complex learning cycles, such as "predict-experiment-confirm," where the hologram serves as a tool for students to test their hypotheses. This shift in strategic thinking was illustrated by one teacher who remarked, "I no longer view 'Holometry' as merely a technology. The hologram itself is not the lesson; rather, it serves as evidence that students use to construct their own arguments."

The three-stage model served as the foundation for constructing the statement items of the TPCK-S instrument. It highlights that TPCK-S mastery is not achieved in a single moment but unfolds as a predictable trajectory of professional growth (Utari et al., 2025). The first stage, Technical Familiarization, emphasizes that managing operational cognitive load is a necessary step before pedagogical innovation can take place. This result aligns with the Concerns-Based Adoption Model (CBAM), which posits that novice technology users typically experience personal concerns before progressing to task-related and impact-related concerns. It is further corroborated by research indicating that technological anxiety frequently serves as an initial barrier to

adopting educational innovations (Noroozi & Sahin, 2023).

Stage 2, Pedagogical Experimentation, marks a critical turning point in which teachers begin to transfer control to students. This shift emerges once the cognitive load of managing the technology has been overcome. With growing technical fluency, teachers redirect their attention from operating the tool to fostering student learning, enabling them to make spontaneous pedagogical choices such as encouraging student-led exploration (Ishartono et al., 2022). This stage signifies a movement from teacher-centered instruction to student-centered facilitation, a shift widely recognized as essential for effective technology integration (Harmadi et al., 2025). Such a transition fosters a constructivist learning environment in which students take an active role in constructing their own knowledge. (Voogt et al., 2013). In the final stage, Seamless Integration, teachers reach the peak of competence, where technology no longer stands out as a

separate element but blends naturally with pedagogical strategy. This stage underscores that advanced TPCK-S is less about simply “using technology” and more about “thinking pedagogically through technology.” At this level, teachers have achieved what is known as classroom 'orchestration,' where technology, pedagogy, and content are harmoniously coordinated to achieve learning goals (Ruthven, 2009).

The demographic profile of the 112 participating teachers reflected considerable variation: 65% were female and 35% male, with an average teaching experience of 11.5 years. In terms of educational background, 80% held a bachelor's degree and 20% a master's degree. Participants were drawn from five districts/cities across Southeast Sulawesi.

The initial draft of the instrument was reviewed by two experts. Agreement analysis using Gregory's formula produced a content validity coefficient of 0.94, reflecting a very high level of expert consensus. The results are summarized in Table 1.

Table 1. Summary of Content Validity Test Results with the Gregory Method.

Validator 1	Validator 2	
	Relevant	Not Relevant
Relevant	A = 32	B = 1
Not Relevant	C = 1	D = 1
Calculation: Content Validity = $A / (A + B + C) = 32 / (32 + 1 + 1) = 0.94$		

The Kaiser-Meyer-Olkin (KMO) test yielded a value of 0.87, confirming sampling adequacy. Exploratory Factor Analysis (EFA) identified four factors that accounted for 68.2% of the total variance, producing a final 28-item instrument. The factors were labeled as: (1) Technological-Pedagogical Skills, (2) Technological-Content Skills, (3)

Pedagogical-Content Skills in a Technological Context, and (4) Holistic Integration Skills. Reliability analysis demonstrated excellent internal consistency (Cronbach's Alpha = 0.91). The detailed factor structure and loadings of the final items are displayed in Table 2.

Table 2. Results of Exploratory Factor Analysis (EFA) of the TPCK-S Instrument

No.	Item Statement	Factor			
		1	2	3	4
1	I am skilled at using the zoom and rotation features of the hologram to show details of 3D shapes.	781			
2	I am able to guide students to discover geometric properties through hologram exploration.	755			
3	I can ask questions that trigger students' critical thinking based on the hologram display.	748			
4	I can create an interactive classroom atmosphere when using hologram media.	721			
5	I am skilled at integrating the use of holograms with group discussion activities.	705			
6	I am able to direct students' attention to specific parts of the hologram when explaining.	688			
7	I am able to manage time effectively during lessons using holograms.	657			
8	I can select the type of 3D shape in the hologram that is most appropriate for a specific learning objective.		802		
9	I can explain the concept of volume by illustrating it through hologram media.		763		
10	I am able to use the hologram to demonstrate the net of a 3D shape.		759		
11	I am skilled at using the hologram to visualize the concept of cross-sections.		741		
12	I can show the difference between a face diagonal and a space diagonal using a hologram.		733		
13	I am able to use the application's customization features to create my own hologram materials.		712		
14	I can effectively compare two 3D shapes using the hologram display.		695		
15	I am able to design a lesson plan (RPP) that integrates the hologram as the core of the learning activity.			815	
16	I can manage the class effectively when students are working in groups with the hologram.			790	
17	I can identify student misconceptions by observing how they interact with the hologram.			772	
18	I am able to connect the hologram visualization with formal mathematical formulas or definitions.			750	
19	I can design assessment tasks that utilize hologram media.			738	
20	I am skilled at providing feedback to students based on their hologram exploration.			715	
21	I can differentiate explanations for students with different levels of understanding when using the hologram.			699	
22	I am confident in combining knowledge of geometry, teaching methods, and the use of holograms simultaneously.				854
23	I can adapt quickly if technical problems with the hologram occur while teaching.				831
24	I feel comfortable and at ease when teaching using hologram media.				788
25	I can reflectively evaluate and improve the way I teach with holograms.				765
26	I am able to overcome pedagogical problems that arise (e.g., students focusing too much on the technology, not the concept).				740
27	Using the hologram feels like a natural part of my teaching, not an 'add-on'.				729
28	I can inspire students' mathematical curiosity through the use of holograms.				702

Confirmatory Factor Analysis (CFA) was subsequently performed to evaluate the fit of the four-factor model derived from the EFA. The results indicated a good model fit ($\chi^2/df = 2.43$; CFI = 0.948; TLI = 0.931;

RMSEA = 0.062). All indices satisfied the recommended thresholds, thereby supporting the validity of the four-factor structure of the TPCK-S instrument. A

summary of the fit indices is provided in Table 3.

Table 3. Goodness-of-Fit Indices of the TPCK-S Instrument CFA Model

Goodness-of-Fit Index	Criteria	Model Value	Evaluation
Chi-square/df	< 3.00	2.43	Good
CFI	> 0.90	948	Good
TLI	> 0.90	931	Good
RMSEA	< 0.08	62	Acceptable

The overall 28-item instrument demonstrated excellent internal consistency, with a Cronbach's Alpha of 0.91, which indicates that the items included in the measurement tool were highly reliable and consistently measured the intended constructs. Such a high value of Cronbach's Alpha reflects that the instrument can be confidently used in further analysis without significant concerns about measurement error or instability across items. Reliability analysis was also conducted for each factor individually, and the results, along with Composite Reliability (CR) and Average Variance Extracted (AVE), are presented in Table 4. The findings show that all CR values exceeded the recommended threshold

of 0.70, suggesting that the constructs demonstrated strong internal reliability and that the latent variables were well represented by their respective indicators. Furthermore, all AVE values were above 0.50, which provides evidence of good convergent validity, meaning that the items within each construct shared a substantial amount of variance and were strongly correlated with the underlying concept they were intended to measure. Collectively, these results confirm that the instrument not only possesses strong internal consistency but also demonstrates adequate psychometric properties, making it a valid and reliable tool for future research applications.

Table 4. Results of Reliability and Convergent Validity Test

Factor	Factor Name	Cronbach's Alpha	Composite Reliability (CR)	Average Variance Extracted (AVE)
1	Technological-Pedagogical Skills	0.88	0.91	0.63
2	Technological-Content Skills	0.85	0.89	0.59
3	Pedagogical-Content Skills (Technology Context)	0.87	0.90	0.62
4	Holistic Integration Skills	0.89	0.92	0.65

The factor analysis results offer compelling empirical support for the construct validity of TPCK-S as a multidimensional framework. This structure is consistent with prior research emphasizing that TPACK should be viewed as a complex, integrated model rather than a simple aggregation of distinct knowledge domains (Joshi, 2023).

The introduction and validation of TPCK-S represent more than a superficial extension of an acronym. They mark a deliberate conceptual shift—from assessing perceived knowledge (what teachers believe

they know) to evaluating performative competence (what teachers are able to demonstrate in classroom practice). Thus, this instrument is more than a tool for measurement it also advances a theoretical stance. It underscores that to truly grasp technology integration, the research community must move past merely cataloging knowledge and begin charting the observable, practical skills that teachers enact in real contexts (Budiningsih et al., 2022). This finding significantly extends the existing TPACK framework (Mishra & Koehler, 2006) by providing empirical

evidence of the importance of the 'Skills' (S) dimension.

This responds to the ongoing call in the literature to close the gap between what teachers believe about technology and how they actually use it in practice (Tondeur et al., 2017), as well as the need for more practice- and context-oriented measurement tools (Angeli & Valanides, 2009). The validation of an instrument focused on skills like this is very important for teacher professional development programs, as it allows for a more authentic evaluation of teacher competence (Koh & Chai, 2016).

4. Conclusion

This study achieved its twin goals. First, it introduced a three-stage model of how TPCK-S develops—beginning with Technical Familiarization, moving into Pedagogical Experimentation, and culminating in Seamless Integration. Second, it produced and validated a 28-item instrument designed to measure this construct. The findings show that the practice-oriented nature of TPCK-S is not only theoretical but can be empirically traced and reliably assessed through an instrument grounded in teachers' real classroom experiences. While this study recognizes its limitations—such as the reliance on data from a single province and the need for broader confirmatory validation—it nonetheless offers important contributions. On a practical level, the developed instrument serves as a valuable diagnostic tool that can guide the design of more targeted and effective teacher professional development programs. For the research community, this study creates new pathways for exploration. Future work could include testing measurement invariance with larger and more diverse samples, as well as conducting longitudinal studies to trace

teacher development across the proposed three-stage model.

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