Salud, Ciencia y Tecnología. 2025; 5:1943
doi: 10.56294/saludcyt20251943

ORIGINAL

Bridging technology and cognition: investigating augmented reality acceptance and thinking skill development using SEM-IPMA analysis

Conectando la tecnología y la cognición: investigación sobre la aceptación de la realidad aumentada y el desarrollo de habilidades de pensamiento mediante análisis SEM-IPMA

Fitrika Kumala Dewi[1], Hendra Hidayat[1], Ernawati[2], Hansi Effendi[1]

[1] Universitas Negeri Padang, Department of Electronics Engineering. Padang. Indonesia.
[2]Universitas Negeri Padang, Department of Family Welfare Science. Padang. Indonesia.

Cite as: Dewi FK, Hidayat H, Ernawati, Effendi H. Bridging technology and cognition: investigating augmented reality acceptance and thinking skill development using SEM-IPMA analysis. Salud, Ciencia y Tecnología. 2025; 5:1943. https://doi.org/10.56294/saludcyt20251943

Submitted: 09-01-2025 **Revised:** 22-04-2025 **Accepted:** 18-09-2025 **Published:** 19-09-2025

Editor: Prof. Dr. William Castillo-González

Corresponding author: Hendra Hidayat

ABSTRACT

Introduction: prior research has predominantly focused on dissecting the Technology Acceptance Model (TAM) to elucidate users' behavioral intentions toward adopting technology. Building upon this foundational scholarship, the present study advances the discourse by examining the cognitive ramifications associated with technology adoption. In particular, this investigation seeks to elucidate the interplay between perceived usefulness, perceived ease of use, and the actual utilization of augmented reality (AR) technologies, as they pertain to the cultivation of computational thinking and critical thinking competencies.
Method: this research adopts a quantitative approach, with an associative design. A sample of 141 vocational high school students from West Sumatera, Indonesia. The collected data were examined through Structural Equation Modeling (SEM) and Importance-Performance Map Analysis (IPMA).
Results: statistical analyses indicated that both perceived ease of use and actual AR utilization significantly enhanced students' computational and critical thinking skills. While perceived usefulness significantly influenced critical thinking, its effect on computational thinking was not statistically meaningful. IPMA results further highlighted that AR's ease of use performs strongly, whereas perceived usefulness remains an area for improvement.
Conclusions: the theoretical extension of the TAM into the domain of cognitive outcomes, moving beyond its traditional behavioral scope. They also establish a compelling platform for future scholarly inquiry and the formulation of strategic, evidence-based approaches to optimizing AR integration particularly in fostering higher-order thinking.

Keywords: Augmented Reality; Technology Acceptance Model; Computational Thinking Skills; Critical Thinking Skills.

RESUMEN

Introducción: investigaciones previas han analizado el Modelo de Aceptación Tecnológica para entender la adopción de tecnología. Este estudio amplía la discusión al explorar cómo la utilidad percibida, la facilidad de uso y el uso real de la realidad aumentada influyen en el desarrollo del pensamiento computacional y crítico.
Método: esta investigación adopta un enfoque cuantitativo con un diseño asociativo. La muestra estuvo compuesta por 141 estudiantes de secundaria vocacional de Sumatra Occidental, Indonesia. Los datos recopilados fueron analizados mediante Modelado de Ecuaciones Estructurales y Análisis de Mapa de Importancia-Desempeño.

Resultados: los análisis estadísticos indicaron que tanto la facilidad de uso percibida como la utilización real de la realidad aumentada mejoraron significativamente las habilidades de pensamiento computacional y crítico de los estudiantes. Mientras que la utilidad percibida influyó de manera significativa en el pensamiento crítico, su efecto sobre el pensamiento computacional no resultó estadísticamente relevante. Los resultados del IPMA destacaron además que la facilidad de uso de la AR presenta un buen desempeño, mientras que la utilidad percibida sigue siendo un área de mejora.
Conclusiones: la extensión teórica del Modelo de Aceptación Tecnológica hacia el ámbito de los resultados cognitivos va más allá de su enfoque conductual tradicional. Asimismo, establece una plataforma sólida para futuras investigaciones académicas y para la formulación de enfoques estratégicos, basados en evidencia, que optimicen la integración de la realidad aumentada, especialmente en el fomento del pensamiento de orden superior.

Palabras clave: Realidad Aumentada; Modelo de Aceptación de la Tecnología; Habilidades de Pensamiento Computacional; Habilidades de Pensamiento Crítico.

INTRODUCTION

Augmented reality (AR) has surged into the spotlight as a powerful educational tool in recent years.[1,2,3] This cutting-edge technology layers digital content seamlessly over the physical world, creating immersive, interactive experiences.[4] Originally conceptualized in the 1990s, AR has undergone a remarkable transformation.[5] Its mainstream breakthrough came with the global phenomenon Pokémon Go in 2016, which shifted public perception and opened the door for AR's expansion beyond gaming. Since then, it's found growing relevance in fields like education, healthcare, and engineering marking its evolution from novelty to necessity.

Globally, the integration of AR is increasingly asserting its prominence within the educational domain. Prior research has documented a remarkable surge in its adoption over the past decade, with publication rates escalating at an impressive annual pace of 21 %.[6] Nevertheless, the mere incorporation of AR into classrooms does not inherently translate into enhanced learning outcomes. To fully capitalize on its pedagogical potential, critical evaluations must be undertaken in advance. Chief among these is the assessment of how students embrace and operationalize the technology. This dimension of acceptance has long been illuminated within the framework of the Technology Acceptance Model (TAM). The model posits that individuals' perceptions of ease of use and usefulness exert a pivotal influence on their readiness to adopt emerging technologies. Actual usage, conversely, denotes the extent to which students embed and sustain AR within their learning practices.[7] When students internalize and endorse AR, it signifies that they are both willing and adequately prepared to engage with it in authentic learning environments. Regardless of how advanced a technological tool may be, if learners cannot comfortably appropriate and adapt it, its educational value will inevitably diminish.[8]

Beyond mere acceptance, the practical implementation of AR in education has been closely associated with advancing students' cognitive development.[9] AR does more than just capture attention it actively promotes the cultivation of advanced thinking skills. Research indicates that AR can enhance computational thinking abilities, including breaking down complex problems, spotting patterns, and engaging in logical, algorithm-based reasoning.[10,11,12] Simultaneously, AR serves as a catalyst for critical thinking by prompting learners to critically assess, interpret, and make well-informed decisions through dynamic, interactive visuals.[13,14,15] These benefits have been documented across a wide range of educational settings, including elementary, middle, and high schools, as well as university-level programs. Such findings are well-aligned with the foundational ideas of Bloom's Taxonomy and the constructivist model of education. Bloom's framework suggests that strategically using technology like AR can support the development of cognitive abilities at multiple levels, aiding in the achievement of meaningful learning outcomes.[16] AR's immersive and interactive visuals help learners retain and comprehend material more effectively than abstract mental imagery alone. In parallel, the constructivist perspective emphasizes the importance of rich, visually supported learning experiences.

Although numerous studies have been undertaken to explore the facts and phenomena surrounding the implementation of AR in educational settings, research that interrogates the acceptance and actual use of AR technology through the lens of the TAM theory while simultaneously incorporating students' computational and critical thinking skills into a unified investigation remains exceedingly rare, particularly within electronics education. This line of inquiry is, in fact, profoundly important, given that the field of electronics is intricately interwoven with the accelerating advances of digital technologies, and that these two cognitive competencies i.e. computational thinking and critical thinking are indispensable for vocational students. Previous studies have predominantly appraised AR's overall effectiveness.[17,18] However, they have seldom established a direct nexus to students' cognitive development. This shortfall generates a salient theoretical gap that necessitates rigorous scholarly procedures to be systematically unveiled.

Therefore, the objective of this study is to investigate the relationship between perceived usefulness, perceived ease of use, and actual use of AR technology and their impact on the development of computational thinking and critical thinking skills among vocational high school students specializing in electronics engineering. The aims of this research align with the conceptual framework illustrated in figure 1.

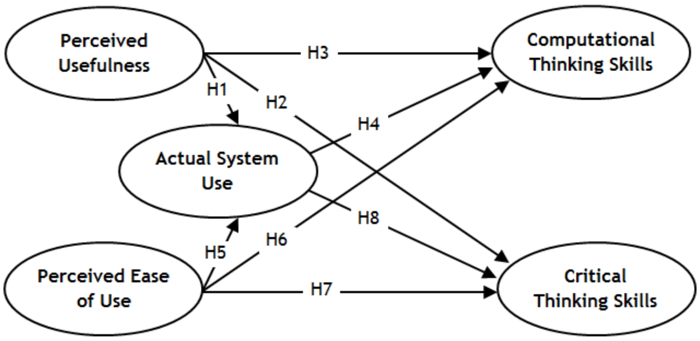

Figure 1. Research Framework

The conceptual framework underpinning this research posits eight direct hypotheses, which are formulated as follows:

- H1: perceived usefulness has a positive impact on actual system use.
- H2: perceived usefulness has a positive impact on critical-thinking skills.
- H3: perceived usefulness has a positive impact on computational thinking skills.
- H4: actual system use has a positive impact on computational thinking skills.
- H5: perceived ease of use has a positive impact on actual system use.
- H6: perceived ease of use has a positive impact on computational thinking skills.
- H7: perceived ease of use has a positive impact on critical thinking skills.
- H8: actual system use has a positive impact on critical thinking skills.

METHOD

Research Design

This study adopts a quantitative approach with an associative design, selected to suit the primary aim of the research. It focuses on identifying connections among variables and assessing the influence of perceived usefulness, perceived ease of use, and actual system use on computational thinking and critical thinking. The investigation also addresses assumptions or hypotheses outlined in the initial research structure.

Participants

The participants in this study consisted of 10th, 11th, and 12th-grade students enrolled in the Electronic Engineering program at a vocational high school located in West Sumatra, Indonesia. A total of 141 students took part in the research. The sample was selected through purposive sampling, as the AR content used in the study was specifically designed to align with the students' existing learning materials.[19] The implementation of AR is carried out across multiple learning sessions. Once students have completed all phases i.e., reviewing the provided learning materials, scanning markers to access 3D models and AR animations, and taking part in an evaluation quiz, they are invited to complete a research survey reflecting on their experience. An example of an AR-based learning scenario is shown in figure 2.

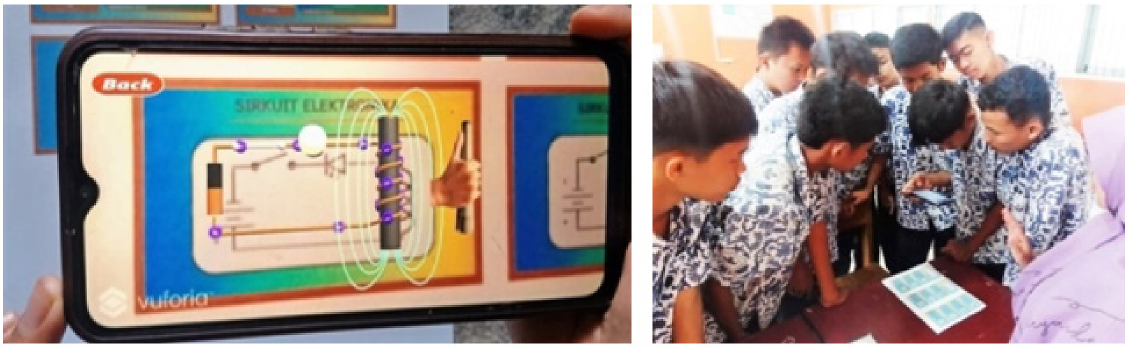

Figure 2. The Implementation of Augmented Reality in the Learning Process

All participating students had previously completed multiple AR-based learning sessions. The student profile details are summarized in table 1.

Table 1. Respondent Profile

Sample characteristics		Frequency	Percentage
Grade	10	62	44 %
	11	44	31,%
	12	35	248, %
	Total	141	100 %
Gender	Male	123	872, %
	Female	18	128, %
	Total	141	100 %
Age	15 - 16 years old	39	277, %
	17 - 18 years old	80	567, %
	19 - 20 years old	19	135, %
	> 20 years old	3	21, %
	Total	141	100 %

Measures

The measurement tools employed in this study were adapted from multiple prior studies. The construct of perceived usefulness of AR was measured using items adapted from a study that examined online tools for learning, which provided relevant measures for the educational context.[20] Perceived ease of use was assessed through an instrument adapted from a study on the use of AI in learning.[21] Actual use of AR was measured using items adapted from a study that examined real usage of blended learning in higher education.[22] Meanwhile, computational thinking and critical thinking skills were assessed using instruments developed in previous studies.[23,24]

Each of the referenced instruments had previously undergone statistical testing for validity and reliability, such as construct validity and reliability coefficients, in their original studies. Furthermore, these instruments have been cited and adopted in subsequent research, which supports their acceptance and recognition as appropriate and consistent measures for the present study. However, given that these tools were originally developed through various international studies involving diverse populations, required translation into the local language, and were designed around different types of technologies, an expert validation phase was first undertaken.[25] This entailed a comprehensive linguistic and content review by subject-matter experts to ensure that the adapted instruments were grammatically accurate, contextually relevant, and theoretically robust. Following expert validation, a pilot study was conducted with 38 students who were not part of the primary sample. The goal of this preliminary phase was to assess the practical usability of the revised instruments, ensuring they were clear in language, culturally appropriate, and methodologically sound before deployment in the main study.

The primary data for this research were collected through an online survey distributed via google forms. The instrument used was a structured questionnaire employing a 5-point Likert scale, ranging from 5 (strongly agree) to 1 (strongly disagree). The data collection process was carried out after students had completed a series of AR-driven simulation tasks. During these activities, students were tasked with customizing, experimenting with, and evaluating virtual electronic circuits, reinforcing key electronics principles as they engaged with the AR environment.

Data Analysis

The collected data were examined using Structural Equation Modeling (SEM) with the aid of SmartPLS 3. The analysis commenced with an evaluation of the outer model to confirm the reliability and validity of the measurement instruments. An indicator is considered valid when its outer loading exceeds 0,7, indicating that it effectively represents its corresponding latent construct. In addition to outer loadings, the Average Variance Extracted (AVE) serves as a complementary validity metric.[26] An AVE value above 0,5 implies that the construct accounts for more than half of the variance observed in its indicators.[27] Beyond assessing validity, the analysis also incorporated a reliability check to determine the internal consistency of each construct. Reliability captures the stability and coherence of respondents' responses to identical indicators across time or diverse groups. To assess this, Cronbach's alpha and Composite Reliability (CR) were employed, with both metrics expected to meet or surpass the recommended threshold of 0,7.[28] Table 2 provides a comprehensive summary of the validity and reliability evaluations conducted for each item within the research instrument.

Table 2. Instrument Validity and Reliability

Variable	Item	Outer loading	AVE	Cronbach's alpha	CR
Perceived Usefulness (PU)	PU1	0,839	0,660	0,829	0,886
	PU2	0,827			
	PU3	0,788			
	PU4	0,794			
Perceived Ease of Use (PEU)	PEU1	0,795	0,706	0,861	0,906
	PEU2	0,880			
	PEU3	0,821			
	PEU4	0,863			
Actual System Use (ASU)	ASU1	0,758	0,610	0,872	0,904
	ASU2	0,752			
	ASU3	0,785			
	ASU4	0,779			
	ASU5	0,801			
	ASU6	0,810			
Computational Thinking Skills (COTS)	COTS1	0,705	0,615	0,790	0,864
	COTS2	0,798			
	COTS3	0,799			
	COTS4	0,829			
Critical Thinking Skills (CITS)	CITS1	0,757	0,616	0,791	0,865
	CITS2	0,744			
	CITS3	0,817			
	CITS4	0,817			

As shown in table 2, all measurement items meet the required standards for validity. Each item reports an outer loading above 0,7, while all AVE scores exceed the 0,5 threshold. Furthermore, the instrument exhibits robust reliability, with both Cronbach's alpha and composite reliability values for every construct surpassing the recommended minimum of 0,7. These results affirm that the instrument is both precise and dependable, making it well-equipped for the subsequent structural analysis.

Following the outer model assessment, the inner model evaluation was carried out to test the structural relationships among the latent variables and to examine the proposed hypotheses. The decision to accept or reject a hypothesis was based on two statistical criteria, i.e. the t-statistic, where values equal to or greater than 1,96 indicate significance at the 95 % confidence level, and the p-value, where values less than or equal to 0,05 confirm significance.[29] To interpret the strength and direction of these relationships, the path coefficient (β) was analyzed, with values ranging from -1 to +1, where positive values indicate direct effects and negative values indicate inverse effects. Furthermore, an Importance-Performance Map Analysis (IPMA) was conducted to identify the constructs that most strongly influence students' computational and critical thinking skills, while also providing practical recommendations on which aspects should be prioritized, maintained, or left unchanged to optimize the effectiveness of augmented reality (AR) in enhancing cognitive development.

RESULTS

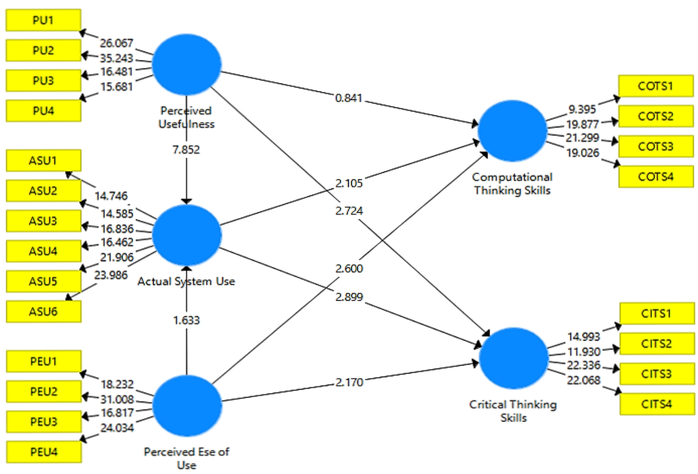

Figure 3. T-statistic Result

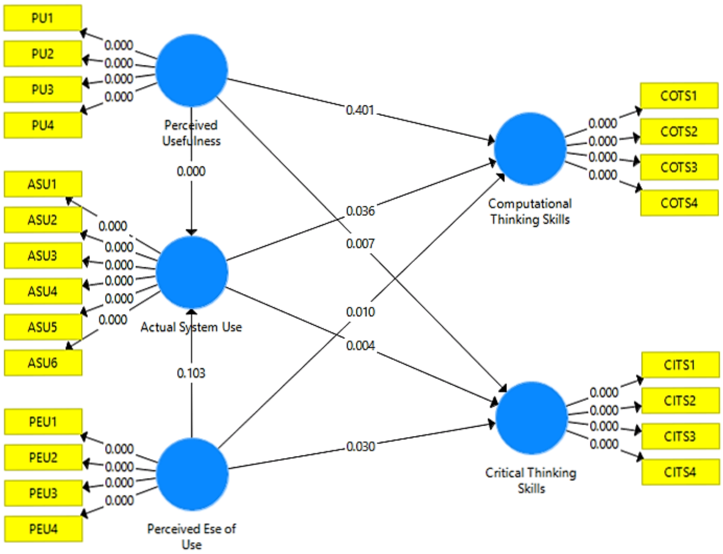

Figure 4. P-value Result

Hypothesis Result

A total of eight hypotheses within the structural model were statistically evaluated using SEM. This analysis examined both the magnitude and direction of the relationships among the latent constructs outlined in the research framework (figure 1). The full results of the inner model assessment including ß values, t-statistics, and p-values for each proposed relationship are detailed in figure 3, figure 4, and table 3.

Table 3. Direct Effect

Hypothesis		β	T-statistic	P-value	Result
H1	Perceived Usefulness -> Actual System Use	0,668	7,852	0,000	Supported
H2	Perceived Usefulness -> Critical Thinking Skills	0,350	2,724	0,007	Supported
H3	Perceived Usefulness -> Computational Thinking Skills	0,110	0,841	0,401	Unsupported
H4	Actual System Use -> Computational Thinking Skills	0,292	2,105	0,036	Supported
H5	Perceived Ease of Use -> Actual System Use	0,159	1,633	0,103	Unsupported
H6	Perceived Ease of Use -> Computational Thinking Skills	0,335	2,600	0,010	Supported
H7	Perceived Ease of Use -> Critical Thinking Skills	0,206	2,170	0,030	Supported
H8	Actual System Use -> Critical Thinking Skills	0,350	2,899	0,004	Supported

Based on the bootstrapping analysis, several hypotheses were validated, while others were not. Hypothesis 1 was statistically confirmed, revealing a positive and significant relationship between perceived usefulness and actual system use (ß = 0,668, t-statistic = 7,852, and p-value = 0,000). Similarly, hypothesis 2 was supported, showing a positive and significant association between perceived usefulness and critical thinking skills (ß = 0,350, t-statistic = 2,724, and p-value = 0,007). However, hypothesis 3 was not supported. Although the relationship between perceived usefulness and computational thinking skills was positive, it was not statistically significant (ß = 0,110, t-statistic = 0,841, and p-value = 0,401). Moving forward, hypothesis 4 was validated, indicating a positive and significant relationship between actual system use and computational thinking skills (ß = 0,292, t-statistic = 2,105, and p-value = 0,036).

Hypothesis 5, which proposed a positive relationship between perceived ease of use and actual system use, was not statistically significant (ß = 0,159, t-statistic = 1,633, and p-value = 0,103). Hypothesis 6 was supported, uncovering a positive and significant link between perceived ease of use and computational thinking skills (ß = 0,335, t-statistic = 2,600, and p-value = 0,010). Hypothesis 7 also gained support, showing a positive and significant impact between perceived ease of use on critical thinking skills (ß = 0,206, t-statistic = 2,170, and p-value = 0,030). Hypothesis 8 was confirmed, revealing a positive and significant relationship between actual system use and critical thinking skills (β = 0,350, t-statistic = 2,899, and p-value = 0,004).

The analysis went beyond assessing direct relationships by also investigating potential indirect effects. This approach aimed to uncover any mediating roles played by specific variables within the model. The results of this extended analysis are summarized in table 4.

Table 4. Indirect Effect

Hypothesis	β	T-statistic	P-value	Result
Perceived Usefulness -> Actual System Use -> Critical Thinking Skills	0,234	2,768	0,006	Supported
Perceived Usefulness -> Actual System Use -> Computational Thinking Skills	0,195	2,056	0,040	Supported
Perceived Ease of Use -> Actual System Use -> Computational Thinking Skills	0,047	1,217	0,224	Unsupported
Perceived Ease of Use -> Actual System Use -> Critical Thinking Skills	0,056	1,314	0,189	Unsupported

Based on the indirect effect analysis, two mediation pathways were found to be statistically significant, while the remaining two did not achieve significance. First, the pathway connecting perceived usefulness to critical thinking skills was mediated by actual system use. This pathway revealed a positive and significant indirect effect (β = 0,234, t-statistic = 2,768, p-value = 0,006). Similarly, perceived usefulness exerted a positive and significant indirect influence on computational thinking skills through actual system use (β = 0,195, t-statistic = 2,056, p-value = 0,040). In contrast, the other two mediation pathways did not yield statistically significant results. The pathway from perceived ease of use to computational thinking skills, with actual system use as a mediator, showed an insignificant indirect effect (β = 0,047, t-statistic = 1,217, p-value = 0,224). Likewise, the pathway from perceived ease of use to critical thinking skills also mediated by actual system use failed to reach significance (β = 0,056, t-statistic = 1,314, p-value = 0,189).

Importance-Performance Map Analysis (IPMA)

The IPMA delivers valuable insights by vividly illustrating how each variable influences the study, intertwining its significance with its effectiveness relative to the primary outcome measures. In this research, the focal constructs under scrutiny are computational thinking skills and critical thinking skills. This analysis illuminates the factors with the greatest potential to drive meaningful impact and steers targeted efforts toward areas most likely to enhance learning outcomes. The results of this analysis are depicted in figure 5 and figure 6.

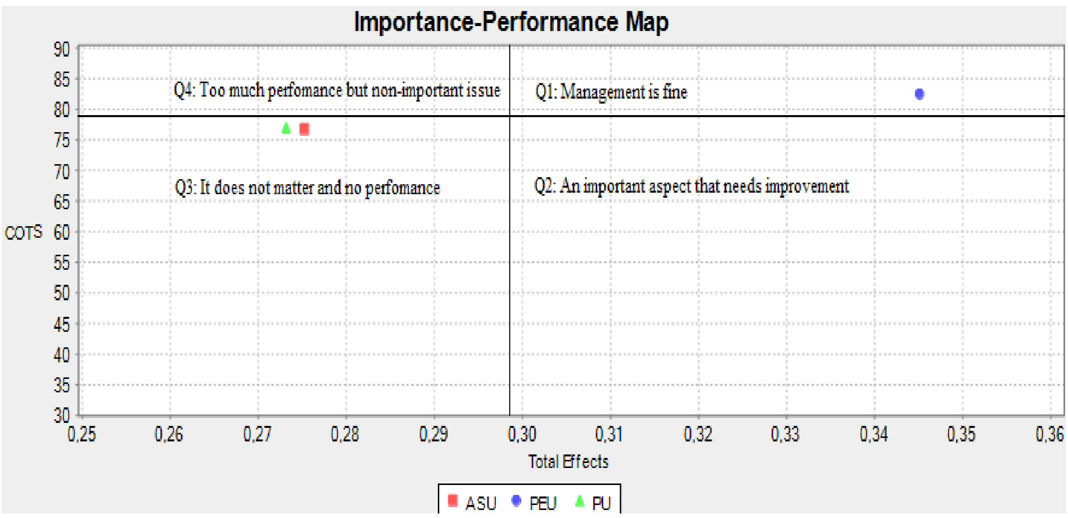

Figure 5. IPMA of Computational Thinking Skills

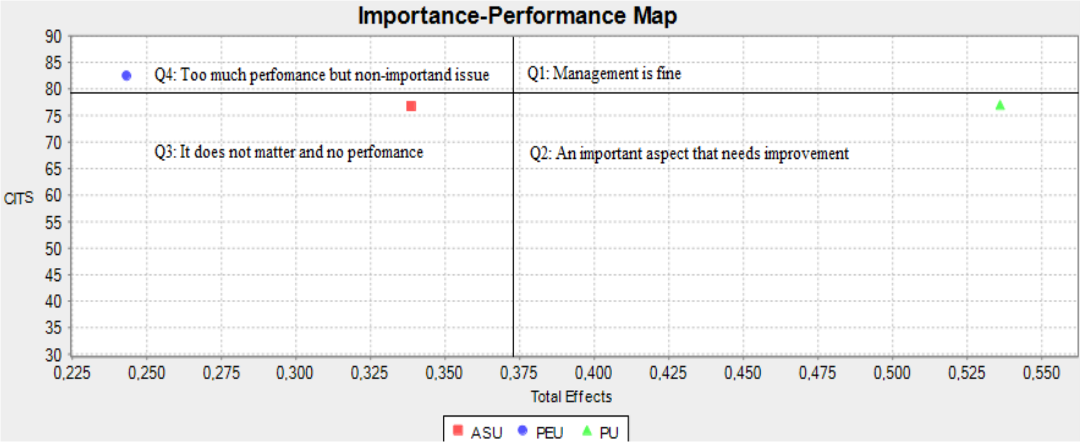

Figure 6. IPMA of Critical Thinking Skills

According to figure 5, the three principal TAM variables influence the first target construct, namely computational thinking skills. Perceived ease of use (PEU) is positioned in Quadrant 1, signifying that it ranks high in both importance and performance. Conversely, the other two variables i.e. perceived usefulness (PU) and actual system use (ASU) reside in Quadrant 3, which denotes relatively lower levels of both importance and performance.

Figure 6 illustrates the analysis of the second target construct, critical thinking skills. In this analysis, the variable perceived usefulness (PU) appears in Quadrant 2. This placement reveals that although students recognize the usefulness of AR as meaningful, its current performance lags behind expectations. In contrast, actual system use (ASU) settles in Quadrant 3, indicating it holds limited importance and underdelivers in performance, thereby not warranting immediate strategic intervention. Meanwhile, perceived ease of use (PEU) resides in Quadrant 4, demonstrating strong performance but offering minimal influence in advancing critical thinking skills.

DISCUSSION

The analysis revealed that perceived usefulness exerts a positive and significant influence on actual use (H1). Previous studies have also corroborated this relationship across diverse contexts, including e-learning, technology-supported learning environments, and health information systems.(30,31,32) In line with previous findings, perceived usefulness was also shown to have a positive effect on critical thinking skills (H2). This result echoes prior research,(33,34,35) which found that the perceived usefulness of generative AI significantly contributes to the enhancement of students' critical thinking abilities. In contrast to previous findings, perceived usefulness was not found to have a significant impact on computational thinking skills (H3). This outcome diverges from earlier studies that reported a positive and significant relationship between the perceived usefulness of AR technology and students' thinking abilities.(36,37) The divergence can be understood in light of the different educational contexts and learner characteristics. Prior studies were mostly conducted with students at school or general university students, who are in earlier stages of cognitive development and thus more likely to show measurable gains in thinking abilities when supported by useful technology. By contrast, the present research focuses on vocational students, who possess distinct learning orientations and practical skill emphases. Vocational education tends to prioritize applied competencies and hands-on skills over abstract or higher-order computational reasoning. Consequently, while vocational students may perceive AR technology as beneficial for improving task efficiency or practical performance, such perceptions do not automatically translate into enhanced computational thinking. Nevertheless, the results indicate that the actual use of AR significantly enhances students' computational thinking abilities (H4), in line with findings from previous studies.(38,39) This suggests that although perceived usefulness alone may not directly influence computational thinking among vocational students, active engagement with AR through consistent and effective use in instruction provides the necessary experiential learning to foster higher levels of computational reasoning.

The relationship between perceived ease of use and actual system use was positive yet statistically insignificant (H5), diverging from the expectations typically posited by the TAM framework.(40,41) The lack of empirical support for this hypothesis suggests that perceiving the AR system as easy to use does not substantially incentivize students to engage with it consistently. In this scenario, ease of use fails to serve as a decisive catalyst for actual usage. Even when AR is technically embedded within the classroom environment, students may still exhibit hesitation or grapple with unfamiliarity in interacting with it. Subsequently, a statistically significant link emerged between perceived ease of use and computational thinking skills (H6). This result resonates with the findings of study,(42,43) which underscore that when students regard a technology as intuitive, it dismantles barriers to effective learning. A positive and statistically significant association between perceived ease of use and critical thinking skills was also substantiated (H7). This result aligns with study,[33] which demonstrated that the perceived ease of use of generative AI engendered a meaningful enhancement in students' critical thinking capacities. Similarly, in the current study, the user-friendliness of AR technology is linked to improvements in students' analytical abilities. Lastly, a positive and statistically significant relationship surfaced between actual system use and critical thinking skills (H8). This outcome aligns with the tenets of experiential learning and constructivist theory, both of which emphasize that immersive participation amplifies understanding. By actively engaging with AR, students are encouraged to investigate, experiment, reflect, and interrogate information critically.

The indirect effect analysis revealed that perceived usefulness significantly enhanced both critical and computational thinking through actual system use, highlighting its central role in promoting cognitive development. In contrast, perceived ease of use did not show significant indirect effects, suggesting that ease alone may not directly drive meaningful AR engagement. Educational research consistently affirms that perceived usefulness outweighs ease of use in predicting technology adoption.[44,45,46] However, findings from the IPMA analysis indicate that both perceived usefulness and ease of use are equally important and should be prioritized in the development of AR for education. While perceived usefulness serves as the primary motivator for sustained use, ease of use ensures accessibility and reduces barriers to adoption. Together, these two factors form a complementary foundation for maximizing the educational impact of AR technology.

Practically, these findings highlight the need for educators and stakeholders to focus on developing AR applications that are both pedagogically beneficial and intuitively usable. Students are more likely to use AR meaningfully when they perceive clear learning benefits, and their cognitive skills improve most when AR tools are used consistently. Therefore, schools should not only ensure technical accessibility and ease of use but also design AR content that delivers clear educational value. Prioritizing both aspects can maximize AR's potential to foster their computational and critical thinking. This study has several limitations, including its focus on vocational students in electronics engineering, the use of AR only in basic electronics instruction, and a geographically limited sample from one province. Additionally, reliance on self-reported survey data may introduce response bias. Future research should expand participant diversity across disciplines and regions and adopt mixed methods such as observations, interviews, or qualitative studies to gain deeper, more reliable insights into AR's impact on cognitive development.

CONCLUSIONS

This study offers a strengthened perspective on how students' acceptance and utilization of augmented reality significantly contribute to the development of computational and critical thinking skills. Focusing on vocational high school students in electronics engineering, the study deliberately bridges the technology acceptance model theory with cognitive learning outcomes. Thus it addresses a critical gap in existing scholarship that often limits TAM to predicting usage behavior rather than educational impact. This integration is not only methodologically relevant but also pedagogically urgent, as it reflects the evolving demands of technology-enhanced learning. The results demonstrate that perceived usefulness and perceived ease of use are not merely peripheral attitudes but key enablers of sustained, meaningful engagement with AR. Furthermore, actual system use emerges as a critical mediating construct that effectively translates user perceptions into tangible cognitive development. These findings reinforce the theoretical extension of the TAM into the domain of cognitive outcomes, moving beyond its traditional behavioral scope. They also establish a compelling platform for future scholarly inquiry and the formulation of strategic, evidence-based approaches to optimizing AR integration particularly in fostering higher-order thinking within vocational education settings.

REFERENCES

1. Kusum JW, Akbar MR, Fitrah M. Dimensi Media Pembelajaran (Teori dan Penerapan Media Pembelajaran Pada Era Revolusi Industri 4.0 Menuju Era Society 5.0). PT. Sonpedia Publishing Indonesia; 2023.

2. Anwar M, Hendriyani Y, Zulwisli, Hidayat H, Sabrina E. Analyzing the Impact of Augmented Reality on Trait Thinking for Electronics Science Learning in Engineering Education. Int J Inf Educ Technol. 2024;14(11):1624–37.

3. Criollo-C S, Guerrero-Arias A, Arif YM, Samala AD, Jaramillo-Alcázar Á, Luján-Mora S. Usability Evaluation of a Mobile Augmented Reality App for PC Hardware Training: A Comparative Study in Three Countries. Emerg Sci J. 2025;9(2):977–94.

4. Nelson S, Darni R, Haris F, Ilham I, Ndayisenga J, Septri S, et al. The effectiveness of learning media based on digital augmented reality (AR) technology on the learning outcomes of martial arts. Retos. 2025;63:878–85.

5. Arena F, Collotta M, Pau G, Termine F. An Overview of Augmented Reality. Computers. 2022;11(2).

6. Garzón J. An overview of twenty-five years of augmented reality in education. Multimodal Technol Interact. 2021;5(7).

7. Mella-Norambuena J, Chiappe A, Badilla-Quintana MG. Theoretical and empirical models underlying the teaching use of LMS platforms in higher education: a systematic review. J Comput Educ. 2024;

8. Farell G, Latt CNZ, Jalinus N, Yulastri A, Wahyudi R. Analysis of Job Recommendations in Vocational Education Using the Intelligent Job Matching Model. Int J Informatics Vis. 2024;8(1):361–7.

9. Budayawan K, Ganefri G, Anwar M, Samala AD, Howard NJ, Sandra RP. Predicting Student Graduation Outcomes: An Evaluation of Project-Based Learning and Implementation of Naïve Bayes. TEM J. 2025;14(2):1586–601.

10. Huang S-Y, Tarng W, Ou K-L. Effectiveness of AR board game on computational thinking and programming skills for elementary school students. Systems. 2023;11(1):25.

11. Lin Y-S, Chen S-Y, Tsai C-W, Lai Y-H. Exploring computational thinking skills training through augmented reality and AIoT learning. Front Psychol. 2021;12:640115.

12. Abdul Hanid MF, Mohamad Said MNH, Yahaya N, Abdullah Z. Effects of augmented reality application integration with computational thinking in geometry topics. Educ Inf Technol. 2022;27(7):9485–521.

13. Faridi H, Tuli N, Mantri A, Singh G, Gargrish S. A framework utilizing augmented reality to improve critical thinking ability and learning gain of the students in Physics. Comput Appl Eng Educ. 2021;29(1):258–73.

14. Demircioglu T, Karakus M, Ucar S. Developing students' critical thinking skills and argumentation abilities through augmented reality–based argumentation activities in science classes. Sci Educ. 2023;32(4):1165–95.

15. Utami ANW, Rusnilawati R. Augmented Reality-based Discovery Learning: an Effective Strategy to Improve Critical Thinking in Sciences for Grade IV. Lect J Pendidik. 2025;16(1):293–306.

16. Nehru RSS, Paredes S, Roy SC, Cuong TQ, Huong BTT. Implementing the Revised Bloom's Taxonomy (2001) in AI-Digital and Online Learning Environments: A Strategic Approach. Indian J Educ Technol. 2025;7(1):173–89.

17. Fadillah R, Ganefri G, Yulastri A, Luthfi A, Hidayat H, Samala AD, et al. Digital Entrepreneurship Research for Learning and Teaching in Education: A Bibliometric Analysis. TEM J. 2024;(August):1997–2011.

18. Anwar M, Rahmawati Y, Yuniarti N, Hidayat H, Sabrina E. Leveraging Augmented Reality to Cultivate Higher-Order Thinking Skills and Enhance Students' Academic Performance. Int J Inf Educ Technol. 2024;14(10):1405–13.

19. Lenaini I. Teknik Pengambilan Sampel Purposive dan Snowball Sampling. Kajian, Penelit Pengemb Pendidik Sej. 2021;6(1):33–9.

20. Linus AA, Aladesusi GA, Monsur IA, Elizabeth FJ. Perceived Usefulness, Ease of Use, And Intention to Utilize Online Tools for Learning Among College of Education Students. Indones J Multidicipliner Res. 2025;5(1):41–52.

21. Yao N, Wang Q. Factors influencing pre-service special education teachers' intention toward AI in education: Digital literacy, teacher self-efficacy, perceived ease of use, and perceived usefulness. Heliyon. 2024;10(14):e34894. https://doi.org/10.1016/j.heliyon.2024.e34894

22. Anthony B, Kamaludin A, Romli A. Predicting Academic Staffs Behaviour Intention and Actual Use of Blended Learning in Higher Education: Model Development and Validation. Technology, Knowledge and Learning. Springer Netherlands; 2021;28:1223–1269. https://doi.org/10.1007/s10758-021-09579-2

23. Wardani SS, Susanti RD, Taufik M. Implementasi Pendekatan Computational Thinking Melalui Game Jungle Adventure Terhadap Kemampuan Problem Solving. SJME (Supremum J Math Educ. 2022;6(1):1–13.

24. Shin H, Park CG, Kim H. Validation of Yoon's Critical Thinking Disposition Instrument. Asian Nurs Res

(Korean Soc Nurs Sci). 2015;9(4):342-8. http://dx.doi.org/10.1016/j.anr.2015.10.004

25. Zohoorian Z, Matin Sadr N, Zeraatpisheh M. Development and validation of the language teachers' adaptive thinking scale. Think Ski Creat. 2023;48:101238. https://doi.org/10.1016/j.tsc.2023.101238

26. Ganefri, Nordin NM, Yulastri A, Hidayat H. The Analysis Factors Influencing the Implementation of Digital Social Entrepreneurship Application in Learning Engineering Education Using Structural Equation Modelling. Int J Informatics Vis. 2024;8(3):1344–51.

27. Hair JF, Ringle CM, Sarstedt M. PLS-SEM: Indeed a silver bullet. J Mark Theory Pract. 2011;19(2):139–52.

28. Hair JF, Risher JJ, Sarstedt M, Ringle CM. When to use and how to report the results of PLS-SEM. Eur Bus Rev. 2019;31(1):2–24.

29. Habibi DH, Firdaus MA, Agung S. Pengaruh Kompensasi dan Disiplin Kerja Terhadap Kinerja Karyawan PT. Canopus Konverta Industri. Indones J Innov Multidisipliner Res. 2023;1(3):155–64.

30. Hasan I, Permana B. Tools of Knowledge Sharing Dalam Kebijakan Teknologi E-Learning: Studi Kasus Tingkat Penerimaan Teknologi Pada Poltek Stia Lan Bandung. Kebijak J Ilmu Adm. 2022;13(2):154–70.

31. Luo J, Ahmad SF, Alyaemeni A, Ou Y, Irshad M, Alyafi-Alzahri R, et al. Role of perceived ease of use, usefulness, and financial strength on the adoption of health information systems: the moderating role of hospital size. Humanit Soc Sci Commun. 2024;11(1).

32. Al-Rayes S, Alumran A, Aljanoubi H, Alkaltham A, Alghamdi M, Aljabri D. Awareness and Use of Virtual Clinics following the COVID-19 Pandemic in Saudi Arabia. Healthc. 2022;10(10).

33. Zhou X, Teng D, Al-Samarraie H. The Mediating Role of Generative AI Self-Regulation on Students' Critical Thinking and Problem-Solving. Educ Sci. 2024;14(12).

34. Saidin NF, Halim NDA, Yahaya N, Zulkifli NN. Enhancing students' critical thinking and visualisation skills through mobile augmented reality. Knowl Manag E-Learning An Int J. 2024;16(1):1–41.

35. Hidayat H, Hidayah N, Rusmana N, Afdal, Hariko R, Tririzky R. The Effect of Using Smart Application on Critical Literacy of Engineering Education Students. Int J Inf Educ Technol. 2024;14(6):834–44.

36. Ou Yang FC, Lai HM, Wang YW. Effect of augmented reality-based virtual educational robotics on programming students' enjoyment of learning, computational thinking skills, and academic achievement. Comput Educ. 2023;195:104721. https://doi.org/10.1016/j.compedu.2022.104721

37. Hanid MFA, Mohamad Said MNH, Yahaya N, Abdullah Z. The Elements of Computational Thinking in Learning Geometry by Using Augmented Reality Application. Int J Interact Mob Technol. 2022;16(2):28–41.

38. Lin PH, Chen SY. Design and Evaluation of a Deep Learning Recommendation Based Augmented Reality System for Teaching Programming and Computational Thinking. IEEE Access. 2020;8:45689–99.

39. Angraini LM, Noto MS, Muhammad I. Augmented Reality–Based Learning Media on Mathematical Computational Thinking Ability. Int J Sci Math Technol Learn. 2024;31(2):89–118.

40. Davis FD, Bagozzi RP, Warshaw PR. User Acceptance of Computer Technology: A Comparison of Two Theoretical Models. Manage Sci. 1989;35:982–1003.

41. Davis FD, Venkatesh V. Toward preprototype user acceptance testing of new information systems: Implications for software project management. IEEE Trans Eng Manag. 2004;51(1):31–46.

42. Ling UL, Saibin TC, Labadin J, Aziz NA. Preliminary investigation: Teachers' perception on computational thinking concepts. J Telecommun Electron Comput Eng. 2017;9(2–9):23–9.

43. Thamrin, Giatman, Anwar M, Budayawan K, Faiza D, Kamarudin ND, et al. Fostering Critical Thinking Skills through Augmented Reality: Insights from Higher Education Engineering Students. Int J Inf Educ Technol. 2025;15(6):1122–33.

44. Tubaishat A. Perceived usefulness and perceived ease of use of electronic health records among nurses: Application of Technology Acceptance Model. Informatics Heal Soc Care. 2018;43(4):379–89.

45. Alassafi MO. E-learning intention material using TAM: A case study. Mater Today Proc. 2022;61:873–7.

46. Ganefri, Kamdi W, Makky M, Hidayat H, Rahmawati Y. Entrepreneurship Education and Entrepreneurial Intention among University Students: The Roles of Entrepreneurial Mindset, Digital Literacy, and Self-Efficacy. J Soc Stud Educ Res. 2019;10(3):364–86. https://www.learntechlib.org/p/224778/

FINANCING

This research was funded by the Ministry of Higher Education, Science, and Technology, through the Directorate General of Research and Development, Directorate of Research and Community Service under contract number 088/C3/DT.05.00/PL/2025 and derivative contract number: 2902/UN35.15/LT/2025.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHORSHIP CONTRIBUTION

Conceptualization: Fitrika Kumala Dewi, Hendra Hidayat.
Data curation: Hendra Hidayat, Ernawati.
Formal analysis: Hansi Effendi.
Research: Fitrika Kumala Dewi, Ernawati.
Methodology: Hendra Hidayat.
Project management: Hansi Effendi.
Resources: Hendra Hidayat.
Software: Fitrika Kumala Dewi.
Supervision: Hendra Hidayat, Hansi Effendi, Ernawati.
Validation: Ernawati.
Display: Fitrika Kumala Dewi.
Drafting - original draft: Fitrika Kumala Dewi.
Writing - proofreading and editing: Fitrika Kumala Dewi, Hendra Hidayat.