Architecture
Image Studies

Vol.7, Issue 1, pp.2205-2212, 2026
DOI: https://doi.org/10.62754/ais.v7i1.1198

https://journals.ap2.pt/index.php/ais/index

Technology-Integrated Flashcards and Critical Thinking: Evidence from a TPACK-Oriented Augmented Reality Intervention

Febrianti[1], Widya Karmila Sari Achmad[2], Faidah Yusuf[3]

Abstract

The rapid integration of digital technologies in classrooms has not automatically translated into the development of higher-order thinking skills. This study investigates the effectiveness of technology-integrated flashcards enhanced through augmented reality (AR) and designed within a Technological Pedagogical Content Knowledge (TPACK) framework to improve fourth-grade students' critical thinking skills in IPAS learning. A quantitative quasi-experimental design with a non-equivalent control group was employed. The participants consisted of 43 students from two primary schools in Bone Regency, Indonesia (23 in the experimental group and 20 in the control group). Data were collected through pretest and posttest critical thinking assessments and analyzed using descriptive statistics, independent-samples t-tests, and normalized gain (N-gain) analysis. The results revealed no significant difference in pretest scores between groups ($p = .893$), indicating comparable baseline ability. However, posttest results showed a statistically significant difference in favor of the experimental group ($t(41) = 6.82$, $p < .001$) with a large effect size ($d = 2.09$). The experimental group achieved a moderate N-gain (0.56), substantially higher than the control group. These findings suggest that AR flashcards, when pedagogically structured through TPACK principles, can effectively foster critical thinking in primary education. The study highlights the importance of purposeful technology integration in promoting meaningful cognitive engagement rather than superficial digital enhancement.

Keywords: *Augmented Reality, Technology-Integrated Flashcards, TPACK, Critical Thinking Skills, Primary Science Learning (IPAS).*

Introduction

Technology has saturated classrooms, but higher-order thinking has not automatically followed. While students can swipe, scan, and search faster than ever, many still struggle to justify claims, evaluate sources, or connect concepts beyond surface recall. This mismatch has pushed educators to look for learning designs that do more than "add apps," designs that turn tools into thinking partners. Research consistently shows that technology alone does not guarantee deeper learning unless it is pedagogically structured to promote reasoning (Tamim et al., 2011). One promising route is to reimagine a familiar micro-learning artifact—flashcards—so they do not merely test memory, but actively provoke reasoning. In this study, flashcards are treated not as old-school drills, but as a strategic interface where technology can amplify inquiry. The central premise is simple: when learning tools are designed to demand thinking, thinking becomes harder to avoid.

Critical thinking remains a cornerstone of contemporary education because it shapes how learners interpret information, analyze relationships, judge credibility, and make warranted decisions (Facione, 1990; Halpern, 2014). It is not a single skill but a disciplined pattern of reasoning—questioning assumptions, weighing evidence, and articulating conclusions with clarity. Yet in many instructional settings, "critical thinking" is invoked as a goal without being engineered into daily learning tasks. Students may be assessed on arguments they were never systematically taught to build. The result is a familiar paradox: curricula promise analytical learners, but activities reward compliance and

[1] Universitas Negeri Makassar , Email: febrianti.240014301040@student.unm.ac.id, (Corresponding Author)
[2] Universitas Negeri Makassar .
[3] Universitas Negeri Makassar

memorization. If critical thinking is the destination, instructional design is the vehicle—and the vehicle must be built for the terrain.

Flashcards, supported by retrieval practice and spaced learning, are powerful for strengthening memory and long-term retention (Roediger & Karpicke, 2006; Dunlosky et al., 2013). Retrieval-based learning has been shown to enhance durable understanding, yet traditional flashcards typically privilege recognition and recall, leaving limited space for evaluation, inference, or explanation. Technology-integrated flashcards can change that equation by embedding prompts for justification, counterexamples, evidence selection, and reflective self-checks—moving the learner from "What is it?" to "Why does it matter?" and "How do you know?". When flashcards become interactive, multimodal, and feedback-rich, they can function as micro-scenarios that require learners to reason in small but frequent doses. Despite their ubiquity, empirical work rarely treats flashcards as a deliberate vehicle for critical thinking development. This study positions flashcards as a design problem: the same tool can drill memory or cultivate judgment, depending on how it is built.

Augmented reality (AR) adds a distinctive affordance to this design space: it anchors abstract concepts in perceptible, situated experiences. By overlaying digital information onto physical objects, AR can convert a static card into an interactive encounter—where learners observe, manipulate, and interrogate representations rather than passively receive them. Empirical reviews suggest that AR can enhance conceptual understanding, spatial reasoning, and learner engagement when integrated with clear instructional goals (Bacca et al., 2014; Garzón & Acevedo, 2019). In principle, AR-enhanced flashcards can prompt learners to compare perspectives, test interpretations, and explain causal links as they engage with dynamic visualizations. But AR is not a pedagogical shortcut; novelty can entertain without deepening understanding if interaction is not tied to reasoning goals. The decisive factor is not the "wow," but the "why"—the extent to which AR interactions are structured to elicit analysis and evaluation.

This is why the Technological Pedagogical Content Knowledge (TPACK) framework is essential for studying AR interventions. TPACK emphasizes that meaningful technology integration emerges from the intersection of content knowledge, pedagogical knowledge, and technological knowledge—not from any one domain alone (Mishra & Koehler, 2006). Subsequent studies have confirmed that TPACK-oriented designs strengthen instructional coherence and student learning outcomes (Koehler et al., 2013; Schmid et al., 2021). An AR flashcard can be technologically impressive yet pedagogically thin; it can display content yet fail to cultivate reasoning. A TPACK-oriented approach forces design decisions to answer three questions simultaneously: What concepts matter most? What learning moves will make students think? What technology features best support those moves? Although AR in education has grown rapidly, fewer studies examine AR-enhanced micro-learning tools through an explicit TPACK lens while targeting critical thinking as a measurable outcome. This study addresses that gap by treating TPACK not as a background theory, but as the design engine of the intervention.

Accordingly, this research investigates whether technology-integrated flashcards, enhanced through a TPACK-oriented AR intervention, can produce credible gains in learners' critical thinking. The study examines not only whether students improve, but how the design features—prompting, feedback, interactivity, and content alignment—shape the reasoning processes students demonstrate. By combining an instructional design grounded in TPACK with an outcome focus on critical thinking, the study responds to calls for more evidence-based approaches to digital innovation in classrooms (Bond et al., 2020). The expected contribution is twofold: empirical support for AR flashcards as a serious learning tool, and design principles that help educators integrate AR with pedagogical purpose rather than technological enthusiasm. If critical thinking is a signature of educated minds, then the intervention tested here is an attempt to make that signature appear more often—on purpose, in real learning time.

Literature Review

Critical Thinking in Technology-Enhanced Learning Environments

Critical thinking has long been conceptualized as a core higher-order cognitive competence involving analysis, evaluation, inference, and reflective judgment (Facione, 1990; Halpern, 2014). Within contemporary educational discourse, it is increasingly framed as an essential 21st-century skill necessary for navigating complex information ecosystems (OECD, 2019). Rather than representing a discrete ability, critical thinking reflects a structured mode of reasoning through which learners examine evidence, question assumptions, and construct logically defensible conclusions. Consequently, instructional designs that aim to cultivate critical thinking must move beyond information delivery toward structured engagement with reasoning processes.

However, empirical studies indicate that digital technology alone does not automatically enhance critical thinking. Tamim et al. (2011) found that technology integration shows positive learning effects primarily when accompanied by strong pedagogical structuring. Similarly, Bond et al. (2020) emphasized that student engagement in digital environments must be cognitively activated to produce meaningful learning gains. This distinction is critical: exposure to digital content differs fundamentally from engagement in reasoning. Without deliberate scaffolding—such as prompting, justification tasks, and reflective feedback—technology risks reinforcing surface-level learning patterns.

Retrieval-based learning strategies, including flashcards and spaced practice, have demonstrated robust effects on retention and long-term memory consolidation (Roediger & Karpicke, 2006; Dunlosky et al., 2013). Yet, traditional flashcard use typically prioritizes recall over evaluation or inference. When redesigned to incorporate explanatory prompts, counterexample generation, and metacognitive reflection, flashcards can serve as micro-structures for reasoning practice. In this sense, technology-integrated flashcards represent a promising bridge between memory strengthening and critical thinking cultivation—provided their design embeds cognitive activation rather than simple repetition.

Thus, the literature suggests that fostering critical thinking in digital classrooms requires intentional alignment between learning objectives, cognitive demands, and technological affordances. The pedagogical challenge is not whether to use technology, but how to structure its use so that learners repeatedly engage in analysis, justification, and evidence-based reasoning within everyday learning tasks.

Augmented Reality, Flashcards, and the TPACK Framework

Augmented reality (AR) has emerged as a powerful instructional medium capable of overlaying digital information onto physical environments, thereby enhancing visualization and contextual understanding. Systematic reviews report that AR can improve conceptual understanding, spatial reasoning, and learner engagement when pedagogically integrated (Bacca et al., 2014; Garzón & Acevedo, 2019). Unlike static representations, AR enables dynamic interaction with three-dimensional objects, supporting exploratory learning and experiential cognition. These affordances are particularly relevant in subjects that require relational and causal reasoning.

When applied to flashcards, AR transforms a traditionally static retrieval tool into an interactive inquiry interface. Instead of merely revealing an answer, AR-enhanced flashcards can present manipulable models, layered explanations, or contextual simulations that prompt learners to compare, test, and interpret information. Such design shifts flashcards from memory drills to reasoning catalysts. However, research cautions that AR's novelty effect may temporarily boost engagement without guaranteeing deeper cognitive processing (Ibáñez & Delgado-Kloos, 2018). Therefore, instructional intentionality remains decisive.

The Technological Pedagogical Content Knowledge (TPACK) framework offers a theoretical structure for ensuring that AR integration supports rather than distracts from learning goals. According to Mishra and Koehler (2006), effective technology integration emerges from the intersection of technological knowledge, pedagogical knowledge, and content knowledge. Subsequent research affirms that TPACK-guided instructional design enhances coherence and learning outcomes by aligning technological features with pedagogical strategies and disciplinary demands (Koehler et al., 2013; Schmid et al., 2021). Within this framework, AR is not selected for its visual appeal, but for its capacity to facilitate specific cognitive operations aligned with content objectives.

Despite the expanding body of AR research, relatively few studies examine AR-enhanced micro-learning tools—such as flashcards—through an explicit TPACK lens while simultaneously targeting critical thinking as a measurable outcome. Most studies focus on engagement or conceptual understanding rather than structured reasoning development. This gap underscores the need for empirical investigation into how TPACK-oriented AR flashcards can be designed to systematically cultivate critical thinking in primary education contexts.

Methods

Research Design

This study employed a quantitative approach using a quasi-experimental design, specifically the non-equivalent control group design. This design was selected because full random assignment was not feasible in the school setting; therefore, intact classes were maintained to preserve instructional and administrative stability. Two groups were involved: an experimental group, which received instruction using augmented reality (AR)-based flashcards integrated with the Technological Pedagogical Content Knowledge (TPACK) framework, and a control group, which received conventional instruction.

Participants and Sampling

The population comprised all fourth-grade students in SD Gugus III, Amali District, Bone Regency, totaling 87 students across five primary schools. A purposive sampling technique was used to select participating schools based on predetermined criteria, including (1) comparable student characteristics, (2) technological readiness to support AR implementation, and (3) institutional willingness to support the research procedures. Based on these criteria, two schools were selected, resulting in 43 participants: 23 students in the experimental group and 20 students in the control group.

Variables and Operational Definitions

The independent variable was the implementation of TPACK-oriented AR flashcards as an instructional intervention. The dependent variable was students' critical thinking skills, operationalized as performance on a critical thinking test. The test was developed based on four indicators: problem clarification, observation and evaluation, inference, and advanced clarification. These indicators guided item construction to ensure that the instrument captured multiple dimensions of critical thinking relevant to primary-level IPAS learning contexts.

Instruments and Data Collection

Data were collected using a pretest–posttest procedure. The primary instrument was a critical thinking skills test administered before and after the intervention. In addition, an observation checklist was used to document (1) the fidelity of instructional implementation by teachers and (2) students' learning activities during classroom instruction. All instruments underwent expert validation (expert judgment) to establish content relevance and clarity. Prior to main data collection, the instruments were subjected to empirical try-out procedures. Instrument reliability was examined using Cronbach's alpha, and coefficients exceeding 0.70 indicated satisfactory internal consistency, supporting the reliability of the measurements.

Data Analysis

Data analysis was conducted using IBM SPSS Statistics version 29. Descriptive statistics (mean, standard deviation, minimum, maximum) were used to summarize students' critical thinking scores in both groups. Inferential analyses were performed to test group differences and intervention effects. Normality was assessed using the Shapiro–Wilk test, and homogeneity of variance was examined using Levene's test. To determine whether post-intervention differences between the experimental and control groups were statistically significant, an independent-samples t-test was applied. To quantify the magnitude of improvement attributable to the intervention, normalized gain (N-gain) scores were calculated based on pretest and posttest results, providing an interpretable index of learning improvement following TPACK-oriented AR flashcard instruction.

Result

Descriptive Results

Descriptive statistics indicate contrasting improvement trajectories between the control and experimental groups. In the control group (n = 20), the mean critical thinking score increased from M = 49.25 (SD = 7.66) at pretest to M = 56.75 (SD = 10.92) at posttest, reflecting a modest gain (Δ = 7.50 points). The increase in posttest variability (SD rising from 7.66 to 10.92) suggests that conventional instruction produced uneven progress across students, with achievement dispersion widening over time.

In contrast, the experimental group (n = 23) demonstrated a substantially larger improvement, increasing from M = 48.91 (SD = 8.52) at pretest to M = 76.96 (SD = 8.49) at posttest (Δ = 28.05 points). Notably, the standard deviation remained stable (8.52 → 8.49), indicating that gains were not only higher but also more consistently distributed among learners. Collectively, these descriptive patterns suggest that TPACK-oriented AR flashcards were associated with both stronger and more uniform enhancement of critical thinking skills compared with conventional instruction.

Table 1. Descriptive Statistics of Critical Thinking Scores (Pretest–Posttest)

	n	Pretest M	Pretest SD	Posttest M	Posttest SD	(Post–Pre)
Control	20	49.25	7.66	56.75	10.92	7.50
Experimental (TPACK–AR Flashcards)	23	48.91	8.52	76.96	8.49	28.05

Baseline Equivalence

An independent-samples *t*-test on pretest scores confirmed that the two groups were comparable prior to the intervention. The non-significant result (**p = .893**) indicates no meaningful difference in initial critical thinking ability between the experimental and control groups. This baseline equivalence strengthens the methodological basis for attributing posttest differences to the instructional treatment rather than pre-existing disparities.

Posttest Impact

Posttest comparison revealed a statistically significant difference favoring the experimental group. The independent-samples *t*-test showed $t(41) = 6.82$, $p < .001$, with a mean difference of 20.21 points (76.96 vs. 56.75). Importantly, the effect was not only statistically significant but also practically substantial, as indicated by a very large standardized effect size (Cohen's $d = 2.09$; Hedges' $g = 2.05$) and a robust 95% confidence interval for the mean difference (95% CI [14.23, 26.19]). These results provide strong evidence that AR flashcards designed through a TPACK lens can yield meaningful gains in students' critical thinking performance in the IPAS context.

Learning Gains

Learning improvement was further examined using normalized gain (N-gain). The experimental group achieved a moderate improvement level with an average N-gain = 0.56 (≈55.42%), indicating that the intervention was effective in producing realistic yet meaningful growth appropriate for primary learners, where higher-order thinking development is typically gradual. The improvement was most evident in core critical thinking components—such as problem clarification, inference, and evaluation—consistent with the premise that interactive visualization and structured prompting can shift students from factual recall toward evidence-based reasoning. Conceptually, these findings align with the view that technology becomes instructionally powerful when it is pedagogically orchestrated (TPACK) to activate reasoning processes rather than merely enhancing presentation.

Table 2. Independent-Samples T-Test Results

Comparison	t(df)	p	Mean difference	95% CI (difference)	Effect size
Pretest (Exp vs Ctrl)		.893			
Posttest (Exp vs Ctrl)	6.82 (41)	< .001	20.21	[14.23, 26.19]	d = 2.09 (g = 2.05)

Table 3. Normalized Gain (N-Gain) Summary

Group	n	N-gain (Mean)	Category
Experimental (TPACK–AR Flashcards)	23	0.56 (55.42%)	Moderate

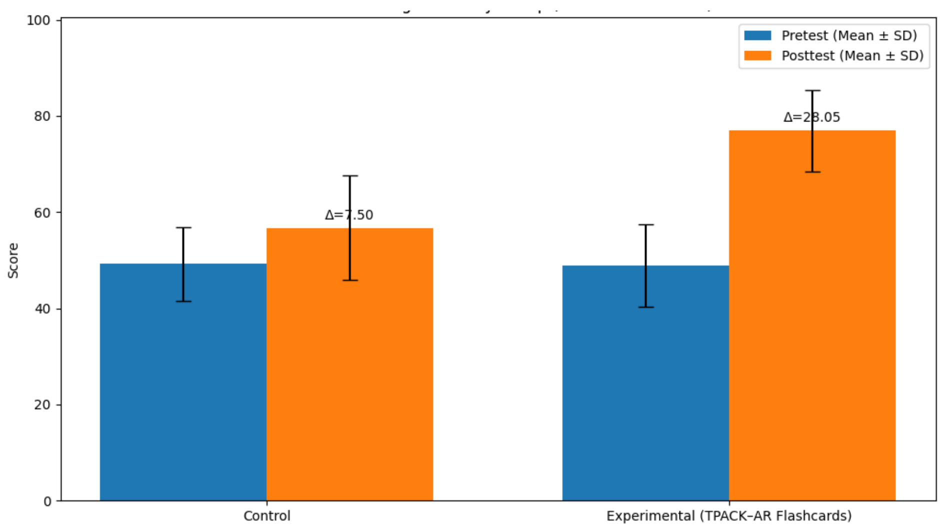

Figure 1. Pretest And Posttest Critical Thinking Scores by Group

Discussion

The findings from this study demonstrate that TPACK-oriented AR flashcards significantly enhanced students' critical thinking skills compared with conventional instruction. The experimental group's large gain in posttest scores (28.05) and moderate N-gain (0.56) underscore that well-designed technology integration can produce robust cognitive gains even in primary school contexts. The descriptive stability of scores in the experimental group (SD posttest ≈ SD pretest) further suggests that AR flashcards led to consistently distributed learning benefits, aligning with literature that identifies student-centered multimedia as a means to reduce inter-learner variance in outcomes (Setiawan et al., 2025; Setiawan et al., 2025).

This finding resonates with broader evidence that augmented reality learning media can support higher-order thinking when pedagogically anchored. Several recent studies indicate that AR-based flashcards not only improve content recall but can also support analytical and evaluative reasoning in elementary settings (Hidayat & Kena, 2025; Nina et al., 2023). Comparative research in high school contexts also reports moderate N-gain in critical thinking when AR flashcards are used to teach abstract concepts, reinforcing the notion that AR's dynamic visualizations help learners go beyond surface memorization toward interpretation and explanation (Anggraini et al., 2025).

The results also align with systematic literature on critical thinking instruction and technology use; reviews suggest that while technology can facilitate engagement, its impact on critical thinking depends on how it is embedded into learning tasks (Alsaleh, 2020; Rahmawati, 2025). Without deliberate cognitive activation, digital tools often reinforce surface learning rather than analytical processing. In this study, the AR flashcards were deliberately designed to elicit justification, comparison, and reasoning tasks, consistent with the principle that learning technologies must be instrumentalized toward pedagogical goals rather than implemented for novelty alone (Rahayu, 2025; Effendi, 2024).

A key mechanism through which AR seemed to foster critical thinking was its visual and interactive affordances. Research shows that AR can situate abstract content in perceptible contexts, thereby scaffolding conceptual reasoning and inference (Bower et al., 2014; Akçayır & Akçayır, 2017). For instance, when students manipulate virtual representations of scientific phenomena, they are more likely to engage in hypothesis testing and evidence evaluation, which are foundational aspects of critical thinking (Setiawan et al., 2025).

The integration of AR within a TPACK framework appears to be another critical factor in explaining the observed effects. TPACK highlights that technology should not merely augment instruction, but should transform pedagogical interactions by aligning technology, content, and pedagogy simultaneously (Mishra & Koehler, 2006; Rahayu, 2025). Prior research on TPACK-based learning has shown improvements in critical thinking through enriched instructional design that foregrounds inquiry and reflection rather than rote procedures (Nurtjahyani, 2022). The present study adds evidence to this line of research by demonstrating that AR, when integrated through TPACK principles, can operationalize such high-order thinking goals in real classrooms.

It is also notable that the intervention's positive impact occurred in routine science learning, which is typically dominated by low-order questioning. This supports broader calls for educational innovation in the 21st century, where learners must navigate complex information demands and apply reasoning skills across contexts (Daulika, 2025). Without such innovations, students are at risk of relying on technology as a substitute for thinking, a concern echoed in recent debates about artificial intelligence and critical cognition (Alsaleh, 2020; Daulika, 2025).

In sum, the evidence suggests that technology-mediated learning environments that are pedagogically robust can significantly support the development of critical thinking skills in primary students. The findings bridge a practical gap in the literature on AR flashcards—moving from feasibility and engagement studies to empirically grounded demonstrations of cognitive gain. They also bolster theoretical claims that technology's educational value depends not on its presence but on its purposeful integration within pedagogical ecosystems.

Conclusion

This study provides empirical evidence that TPACK-oriented augmented reality (AR) flashcards can significantly improve fourth-grade students' critical thinking skills in IPAS learning compared with conventional instruction. While both groups showed progress, the experimental group demonstrated a markedly larger increase from pretest to posttest (48.91 → 76.96) than the control group (49.25 → 56.75), supported by a statistically significant posttest difference (t = 6.820, p < .001) and a moderate normalized gain (N-gain = 0.56). These findings indicate that technology integration becomes instructionally meaningful when it is pedagogically designed—in this case, aligning AR affordances (visualization and interactivity) with TPACK-based learning moves that prompt clarification, inference, evaluation, and reflective reasoning. Practically, the results suggest that AR flashcards can function not merely as an engaging medium but as a structured scaffold for higher-order thinking in primary classrooms, helping students move beyond factual recall toward evidence-based reasoning. However, because the design was quasi-experimental with intact groups and a limited sample from one cluster of schools, future research should extend the intervention across broader settings, incorporate longer implementation periods, and include additional outcomes (e.g., retention, transfer tasks, and effect-size reporting across indicators) to strengthen generalizability and causal interpretation. Overall, the study strengthens the claim that TPACK-guided AR interventions can offer a viable pathway for developing critical thinking in elementary education when implemented with fidelity and clear cognitive targets.

References

[1] Akçayır, M., & Akçayır, G. (2017). Advantages and challenges associated with augmented reality for education: A systematic review of the literature. Educational Research Review, 20, 1–11. https://doi.org/10.1016/j.edurev.2016.11.002

[2] Alsaleh, N. J. (2020). Teaching critical thinking skills: Literature review. Turkish Online Journal of Educational Technology, 19(1), 21–39.

[3] Anggraini, R., Putri, D., & Sari, M. (2025). Augmented reality flashcards and critical thinking skills in science learning. International Science Education Journal, 7(1), 45–58.

[4] Bacca, J., Baldiris, S., Fabregat, R., Graf, S., & Kinshuk. (2014). Augmented reality trends in education: A systematic review of research and applications. Educational Technology & Society, 17(4), 133–149.

[5] Bond, M., Buntins, K., Bedenlier, S., Zawacki-Richter, O., & Kerres, M. (2020). Mapping research in student engagement and educational technology in higher education: A systematic evidence map. International Journal of Educational Technology in Higher Education, 17(2), 1–30. https://doi.org/10.1186/s41239-019-0176-8

[6] Bower, M., Howe, C., McCredie, N., Robinson, A., & Grover, D. (2014). Augmented reality in education—Cases, places, and potentials. Educational Media International, 51(1), 1–15. https://doi.org/10.1080/09523987.2014.889400

[7] Daulika, P. (2025). Educational innovation and critical thinking development in the 21st century. Eduvest – Journal of Universal Studies, 5(2), 211–220.

[8] Dunlosky, J., Rawson, K. A., Marsh, E. J., Nathan, M. J., & Willingham, D. T. (2013). Improving students' learning with effective learning techniques: Promising directions from cognitive and educational psychology. Psychological Science in the Public Interest, 14(1), 4–58. https://doi.org/10.1177/1529100612453266

[9] Effendi, R. (2024). Instrumentalizing educational technology for higher-order thinking skills. Journal of Educational Innovation, 12(3), 144–158.

[10] Facione, P. A. (1990). Critical thinking: A statement of expert consensus for purposes of educational assessment and instruction. The Delphi Report.

[11] Garzón, J., & Acevedo, J. (2019). Meta-analysis of the impact of augmented reality on students' learning outcomes. Educational Research Review, 27, 244–260. https://doi.org/10.1016/j.edurev.2019.04.001

[12] Halpern, D. F. (2014). Thought and knowledge: An introduction to critical thinking (5th ed.). Psychology Press.
[13] Hidayat, A., & Kena, L. (2025). The effectiveness of augmented reality flashcards in improving elementary students' higher-order thinking skills. Journal of Primary Education Research, 9(1), 33–47.
[14] Ibáñez, M. B., & Delgado-Kloos, C. (2018). Augmented reality for STEM learning: A systematic review. Computers & Education, 123, 109–123. https://doi.org/10.1016/j.compedu.2018.05.002
[15] Koehler, M. J., Mishra, P., Kereluik, K., Shin, T., & Graham, C. R. (2013). The technological pedagogical content knowledge framework. In J. M. Spector et al. (Eds.), Handbook of research on educational communications and technology (pp. 101–111). Springer.
[16] Mishra, P., & Koehler, M. J. (2006). Technological pedagogical content knowledge: A framework for teacher knowledge. Teachers College Record, 108(6), 1017–1054.
[17] Nina, S., Rahman, T., & Putra, A. (2023). Interactive flashcards and critical thinking in primary science classrooms. Journal of Science Education Studies, 15(2), 78–92.
[18] Nurtjahyani, R. (2022). TPACK-based learning and critical thinking skills development. Al-Ishlah: Jurnal Pendidikan, 14(4), 4125–4136.
[19] OECD. (2019). OECD future of education and skills 2030: OECD learning compass 2030. OECD Publishing.
[20] Rahmawati, D. (2025). Technology integration and cognitive activation in classroom learning. Educational Technology Perspectives, 18(1), 55–67.
[21] Rahayu, S. (2025). Transformative technology integration through TPACK-oriented pedagogy. Journal of Educational Practice, 20(1), 1–15.
[22] Roediger, H. L., III, & Karpicke, J. D. (2006). Test-enhanced learning: Taking memory tests improves long-term retention. Psychological Science, 17(3), 249–255. https://doi.org/10.1111/j.1467-9280.2006.01693.x
[23] Schmid, R., Brianza, E., & Petko, D. (2021). Developing a short assessment instrument for technological pedagogical content knowledge (TPACK.xs). Computers & Education, 157, 103967. https://doi.org/10.1016/j.compedu.2020.103967
[24] Setiawan, A., Lestari, R., & Pratama, Y. (2025). Student-centered multimedia and critical thinking performance in primary education. Pedagogia Journal of Education, 14(2), 87–99.
[25] Tamim, R. M., Bernard, R. M., Borokhovski, E., Abrami, P. C., & Schmid, R. F. (2011). What forty years of research says about the impact of technology on learning: A second-order meta-analysis. Review of Educational Research, 81(1), 4–28. https://doi.org/10.3102/0034654310393361.