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Research Article

Augmented Reality Comic-Based Learning: Its Impact on Student Learning Independence, Digital Literacy, and Literacy Achievement in Elementary Education

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Abstract: The rapid advancement of digital technology in the Industry 4.0 era necessitates innovative instructional media capable of fostering independent learning, digital literacy, and literacy achievement among elementary school students. This study examines the effectiveness of Augmented Reality (AR)-based comic learning media in enhancing learning independence, digital literacy, and literacy achievement. A quantitative descriptive research design was employed, involving 78 fifth-grade students from two elementary schools in Cirebon City selected through total sampling. Data were collected using closed-ended questionnaires to measure learning independence and digital literacy, along with essay tests to assess literacy achievement. Instrument validity and reliability were evaluated using Partial Least Squares Structural Equation Modeling (PLS-SEM), while Multivariate Analysis of Variance (MANOVA) was applied to examine the simultaneous effects of school differences on the three dependent variables. The results indicate a significant multivariate effect of school context on the combined variables. Post hoc analysis reveals that school differences significantly influence literacy achievement, whereas differences in digital literacy and learning independence are not statistically significant. Correlation analysis demonstrates a strong association between digital literacy and learning independence, but no direct relationship with literacy achievement. These findings suggest that AR-based comics effectively enhance students' literacy performance through immersive visualization and narrative engagement, while behavioral competencies such as learning independence and digital literacy require sustained implementation and pedagogical support. This study contributes an adaptable AR comic-based learning model suitable for elementary education, particularly in resource-limited schools, and provides empirical evidence of the integrated cognitive and behavioral impacts of immersive digital learning media.

Keywords: augmented reality, digital literacy, elementary education, learning independence, literacy achievement

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INTRODUCTION

The transformation brought by the Industry 4.0 era requires integrating innovative digital technologies to address the shortcomings of conventional instructional methods, particularly in fostering independent learning among elementary school students (Maulyda et al., 2025). Independent learning serves as a key foundation for academic success, as interactive technologies encourage students to take initiative in exploring learning materials with less dependence on teachers (Akhmetzhanova et al., 2025). National data from Indonesia show that only around 30% of students demonstrate autonomous learning behaviors in the post-pandemic digital context, indicating a substantial gap that needs attention (OECD, 2022). This condition highlights the need for instructional approaches that not only deliver academic content but also cultivate students' capacity to manage their own learning processes in technology-supported environments.

The success of independent learning is closely linked to digital literacy, especially students' ability to critically evaluate, interpret, and manage information within increasingly complex digital environments (Rakhimzhanova et al., 2025). Therefore, strengthening digital competence has become an essential step toward improving independent learning outcomes in contemporary education Despite ongoing efforts, Indonesia's national digital literacy index remains moderate, and limited technical and operational skills among young learners are a primary concern (Wijayanti et al., 2024). In this context, 'digital literacy' refers to the ability to find, evaluate, use, and create information using digital technologies, and 'technical and operational skills' describe the capacity to interact with and troubleshoot digital devices and software.

Technology-based visual media offer a practical strategy to reduce this gap while simultaneously supporting students' academic information literacy (Pratiwi et al., 2025). Augmented Reality (AR)-based comics, for instance, have demonstrated the potential to reduce cognitive load by presenting abstract concepts through dynamic, concrete visualizations (Siki & Leba, 2025). The three-dimensional, interactive features of AR create immersive experiences that align well with children's cognitive development (Mansour et al., 2025). Through this integration, AR media provide an effective means of enhancing both conceptual understanding and digital skills simultaneously.

The importance of such innovation becomes more evident in the Indonesian educational context, where limited access to engaging learning resources often reduces students' intrinsic motivation (Jumriani et al., 2025). Multisensory stimulation in AR environments has been shown to strengthen memory retention and promote deeper contextual understanding during reading (Rosita et al., 2025). Contemporary literacy development increasingly emphasizes active engagement with multimodal digital content rather than passive consumption of text (Kenedi et al., 2023). Empirical studies report higher literacy achievement when AR-based materials are used compared with traditional printed texts (Maulyda et al., 2025). These findings suggest that immersive digital media may contribute not only to motivational engagement but also to improved cognitive processing during literacy learning.

Recent PISA results reveal that Indonesian students' reading literacy performance remains below the global average, underscoring the urgent need for instructional innovation (OECD, 2022). Findings from the National Assessment further indicate that many elementary schools have yet to achieve minimum competency standards in reading literacy. However, one

persistent challenge lies in the fragmented implementation of independent learning strategies and digital literacy development, as these competencies are often addressed separately within classroom instruction (Forsström et al., 2025). As a result, students may develop digital operational skills without strengthening learning autonomy, or conversely engage in independent learning activities without meaningful interaction with digital information environments.

Previous studies on AR-based learning have largely focused on cognitive outcomes such as conceptual understanding, motivation, or academic achievement. Fewer studies have simultaneously examined how AR learning environments relate to both cognitive outcomes and behavioral learning competencies such as learning independence and digital literacy within the same instructional framework. This limitation creates a conceptual gap in understanding how immersive learning technologies shape students' broader learning profiles. In response to this gap, AR comic-based learning media offer a potentially integrative instructional approach. By combining narrative storytelling with interactive three-dimensional visualization, AR comics may create a learning environment that encourages students to actively explore information while interacting with digital content.

Interactive elements enable students to manipulate visual objects, access additional explanations, and engage with information in a multimodal format. Such characteristics align with principles of the Cognitive Theory of Multimedia Learning (CTML), which emphasize the role of integrated visual and verbal representations in supporting meaningful learning processes. At the same time, learning environments that encourage exploration and self-directed interaction may also support components of Self-Regulated Learning (SRL), particularly students' initiative in managing their own learning activities. From a social constructivist perspective, technology-supported learning environments may further facilitate active knowledge construction through meaningful interaction with learning materials. Consequently, AR-based comic media may provide a pedagogical context where cognitive processing, digital interaction, and learner autonomy develop simultaneously.

Nevertheless, empirical evidence examining these relationships remains limited, particularly in elementary education settings within developing digital infrastructures. Furthermore, many studies report positive learning outcomes from AR interventions without clearly distinguishing whether improvements result from the instructional media itself, the learning context, or differences between educational environments. Therefore, this study adopts a comparative quantitative design to examine differences in learning outcomes associated with the implementation of AR comic-based learning media across elementary school contexts. Rather than assuming direct causal effects, the study evaluates whether students exposed to AR comic-based learning demonstrate different levels of learning independence, digital literacy, and literacy achievement compared with students experiencing conventional instructional conditions.

This approach aims to provide a more methodologically cautious evaluation of the potential educational contribution of AR-supported learning environments. The main contribution of this research is the proposal of an adaptable AR comic-based learning model designed to support literacy learning while encouraging students' interaction with digital information environments. The study focuses on elementary education and acknowledges that the implementation of AR learning may depend on factors such as device availability, teacher facilitation, and school infrastructure.

The primary objective of this study is to examine whether differences in instructional context involving AR comic-based learning are associated with variations in students' learning independence, digital literacy, and literacy achievement. Quantitative evaluation procedures are used to analyze these outcomes simultaneously and to identify statistically significant differences between groups. By examining cognitive and behavioral learning indicators within a single analytical framework, the study aims to contribute to a deeper understanding of how immersive learning technologies may relate to multiple dimensions of student learning in elementary education.

THEORETICAL FRAMEWORK

The theoretical framework of this study is the Cognitive Theory of Multimedia Learning (CTML), which explains how students process visual and auditory information in their working memory during learning activities. This perspective emphasizes that effective integration of text and images reduces cognitive load by organizing information into structured mental representations (Mayer, 2024). Learning becomes more efficient when both processing channels in the brain operate simultaneously through complementary multimedia formats (Ljubojevi et al., 2025). Technology-based visual narratives, therefore, function as a bridge between sensory input and long-term memory, particularly for young learners who benefit from concrete and engaging representations (Gita et al., 2025). Well-structured multimedia integration ultimately improves comprehension efficiency and strengthens memory retention by optimizing students' cognitive resources.

Within the context of AR-supported learning environments, CTML provides a conceptual explanation of how multimodal representations-such as animated visual objects, narrative text, and interactive elements-may support students' comprehension processes. Rather than assuming a direct causal impact of AR technology, this study adopts CTML as a theoretical lens to interpret how differences in multimedia exposure across instructional contexts may relate to variations in students' literacy learning outcomes. This study also draws on Self-Regulated Learning (SRL) theory to explain how students develop independence in managing their own learning processes. SRL theory suggests that intrinsic motivation, metacognitive awareness, and behavioral regulation develop through continuous interaction with responsive learning environments (Fahrni et al., 2025).

Learning independence does not emerge automatically but is gradually formed through technological scaffolding that provides immediate feedback and encourages reflection (Zakir et al., 2025). In this regard, digital media play an important role in transforming learning behavior from passive reception into active exploration, which is essential for improving literacy competencies (Georgopoulou et al., 2025). From an SRL perspective, interactive digital media-such as AR-based comics-may provide learning environments that allow students to navigate content independently, revisit information, and interact with multimedia elements at their own pace. These characteristics may create conditions that support the development of learning independence, although behavioral competencies such as self-regulation often require longer periods of instructional exposure to demonstrate measurable change.

Digital literacy is positioned as a mediating variable that connects technical competence with the cognitive capacity to critically evaluate digital information. This view corresponds with the growing demand for twenty-first-century skills that require strong information literacy to sustain long-term academic achievement (Rakhimzhanova et al., 2025). The measurement of

digital literacy is grounded in functional literacy theory, which encompasses technical, cognitive, and ethical dimensions of using digital devices (Morfidi & Iatraki, 2025). Research instruments were therefore designed to align closely with both the theoretical framework and the practical challenges students encounter when navigating complex information environments (Nevrelova et al., 2024). Within the conceptual model of this study, digital literacy is examined as a competency that may coexist with literacy achievement and learning independence within technology-supported learning contexts. However, the study does not assume that improvements in digital literacy automatically translate into higher literacy achievement, as cognitive performance in reading may also depend on other instructional and contextual factors.

The integration of Augmented Reality (AR) technology with comic-based media provides a strong foundation for examining simultaneous improvements in literacy outcomes. Social Constructivism theory suggests that meaning is constructed through active interaction between learners and digital objects that represent narrative content (Bali et al., 2026). Interactive digital environments may therefore facilitate deeper engagement by enabling students to manipulate visual information and construct meaning through exploration. From a social constructivist perspective, AR-based comics function as interactive learning artifacts that combine storytelling with digital visualization, potentially encouraging students to actively interpret narrative content and relate it to prior knowledge. This perspective supports the investigation of how different instructional environments-such as classrooms using AR comic-based learning and those using conventional materials-may be associated with variations in students' cognitive and behavioral learning outcomes.

Based on the integration of CTML, SRL, and social constructivist perspectives, this study proposes a conceptual framework in which multimedia interaction (AR comic-based learning context) is associated with three key learning outcomes: learning independence, digital literacy, and literacy achievement. The framework does not assume a deterministic causal relationship but instead examines whether differences in instructional exposure correspond with measurable variations in these outcomes across school contexts. Through this theoretical integration, the study contributes to a broader understanding of how immersive learning environments may relate simultaneously to cognitive outcomes (literacy achievement) and behavioral competencies (learning independence and digital literacy) in elementary education. This multidimensional perspective extends prior AR learning research that has often focused primarily on academic achievement while giving less attention to students' learning behaviors and digital competencies.

METHODS

Research Design

This study employed a quantitative comparative inferential design with a quasi-experimental contextual comparison to examine differences in learning outcomes associated with the implementation of Augmented Reality (AR) comic-based learning. The investigation compared students' levels of learning independence, digital literacy, and literacy achievement across two elementary schools in Cirebon City. Unlike a purely descriptive design, this study incorporated hypothesis testing and multivariate statistical analysis (MANOVA) to identify statistically significant differences between groups. Therefore, the

research design is more appropriately positioned as a comparative inferential study rather than a descriptive survey.

The comparison between School A and School B does not represent a fully randomized experimental treatment. Instead, it reflects a quasi-experimental contextual condition in which AR comic-based learning was implemented within an authentic classroom environment. This approach enables the examination of how differences in instructional context may be associated with variations in students' cognitive and behavioral learning outcomes while maintaining ecological validity in real educational settings. The design was selected because it allows researchers to systematically evaluate patterns of learning outcomes using numerical data while examining potential differences between instructional environments. By applying comparative statistical analysis, the study aims to identify whether exposure to AR comic-based learning contexts corresponds with measurable differences in students' literacy achievement, digital literacy, and learning independence.

Sample

The participants were 78 fifth-grade students from two elementary schools, selected using a total sampling technique. School A contributed 38 students, while School B included 40 students. All members of the population were involved as research subjects to strengthen the validity and representativeness of the findings. Total sampling was applied to minimize sampling bias and ensure comprehensive representation of the study groups. Fifth-grade students were selected based on their cognitive readiness to operate AR technology and their ability to respond independently to research instruments. At this educational level, students generally possess sufficient digital familiarity and reading comprehension skills to interact with multimedia learning applications and complete structured questionnaires reliably. However, because the study involved only two schools within the same regional context, the findings should be interpreted as context-specific rather than broadly generalizable to all elementary school populations.

AR Comic-Based Learning Intervention Procedure

The AR comic-based learning intervention was implemented as part of regular classroom instruction during literacy learning activities. The intervention was conducted over a four-week period, with two learning sessions per week, resulting in a total of eight instructional sessions. Each session lasted approximately 60 minutes. The instructional procedure followed several structured stages: (1) Introduction Stage: the teacher introduced the learning objectives and provided a brief explanation of the narrative topic presented in the AR comic material. Students were also guided on how to access and operate the AR application. (2) Exploration Stage: students used mobile devices to scan specific markers printed in the comic pages. The AR application then displayed three-dimensional visual objects, animated scenes, and supplementary narrative information related to the story content. (3) Interactive Learning Stage: students interacted with the AR content by observing animations, reading narrative text, and discussing the storyline with peers. During this stage, students were encouraged to interpret information presented through both visual and textual elements. (4) Reflection and Discussion Stage: the teacher facilitated group discussions to encourage students to reflect on the story content, identify key information, and connect the narrative themes with literacy comprehension tasks. (5) Assessment Stage: students completed reading comprehension activities and responded to literacy questions designed to measure their understanding of the narrative content.

The teacher's role during the intervention was primarily as a facilitator who guided students in navigating the AR media, clarified instructions, and supported collaborative discussions. The AR comics were accessed using Android-based mobile devices equipped with an AR reader application specifically designed to recognize visual markers embedded in the printed comic pages. Through this system, students could interact with digital objects that appeared as three-dimensional overlays on the physical comic pages. Students' interaction with the AR media involved scanning markers, observing animated scenes, reading narrative explanations, and discussing story elements collaboratively. This interactive process allowed students to engage with multimodal learning content combining text, visual imagery, and digital animation.

Data Collection

Data were collected using closed-ended questionnaires and structured essay tests. Learning independence and digital literacy were measured using a 15-item, five-point Likert-scale instrument for each construct. The digital literacy questionnaire assessed five dimensions: Access to Digital Technology (ADT), Understanding Digital Information (UDI), Using Media for Learning (UML), Digital Communication (DC), and Evaluating Digital Information (EDI). The learning independence questionnaire evaluated five aspects: Initiative (I), Discipline and Responsibility (DR), Time Management (TM), Self-Confidence (SC), and Persistence and Perseverance (PP). Scoring was adjusted according to the direction of each statement, with positive and negative items receiving reversed values.

Table 1. Result of Questionnaire Scoring Criteria

Code	Response Option	Positive Statement Score	Negative Statement Score
SS	Strongly Agree	5	1
S	Agree	4	2
R	Undecited	3	3
KS	Partially Disagree	2	4
TS	Disagree	1	5

Literacy achievement was measured using an essay test comprising three analytical questions. This format was selected because it captures higher-order thinking skills, including comprehension, interpretation, and information synthesis, more effectively than objective tests. Student responses were evaluated using a structured rubric to ensure scoring consistency. The use of essay-based assessment enabled the evaluation of students' deeper reading comprehension and analytical reasoning related to narrative content presented in the learning materials.

Table 2. Result of Essay Test Scoring Rubric

Score	Scoring Criteria
5	The student provides a correct, complete answer that follows established linguistic conventions.
4	The student provides a correct answer but contains minor omissions or slight technical errors.
3	The answer is partially correct or incomplete but demonstrates fundamental understanding.
2	The answer is highly deficient, with only 1–2 correct components identified.
1	The answer is almost entirely incorrect but shows effort in attempting a response.
0	The student provides no response at all.

Although the questionnaire instruments provided systematic measurement of behavioral variables, it should be noted that self-reported responses may be influenced by students' subjective perceptions and response tendencies. Therefore, the behavioral data should be interpreted with appropriate methodological caution.

Data Analysis

Data analysis was conducted in two main stages: measurement model testing and comparative statistical analysis. Construct validity and reliability were examined using Partial Least Squares Structural Equation Modeling (PLS-SEM) with SmartPLS 3.0. Convergent validity was established when factor loadings exceeded 0.70, and the Average Variance Extracted (AVE) was above 0.50, indicating that each indicator adequately represented its construct. Reliability was assessed using Composite Reliability (CR), with a minimum criterion of 0.70 to ensure internal consistency of the instruments (Huang, 2021).

Table 3. Result of Convergent Validity and Construct Reliability

Variable	Aspect	Item	Outer Loading	Decision	Composite Reliability	Decision
Digital Literacy	ADT	P1	0.829	Valid	0,785	Reliable
		P2	0.714	Valid		
		P3	0.701	Valid		
	UDI	P4	0.742	Valid	0,781	Reliable
		P5	0.811	Valid		
		P6	0.701	Valid		
	UML	P7	0.823	Valid	0,818	Reliable
		P8	0.701	Valid		
		P9	0.796	Valid		
	DC	P10	0.719	Valid	0,815	Reliable
		P11	0.768	Valid		
		P12	0.825	Valid		
	EDI	P13	0.809	Valid	0,816	Reliable
		P14	0.834	Valid		
		P15	0.701	Valid		
Learning Independence	I	P16	0.741	Valid	0,813	Reliable
		P17	0.842	Valid		
		P18	0.722	Valid		
	DR	P19	0.836	Valid	0,850	Reliable
		P20	0.833	Valid		
		P21	0.756	Valid		
	TM	P22	0.817	Valid	0,894	Reliable
		P23	0.852	Valid		
		P24	0.904	Valid		
	SC	P25	0.784	Valid	0,776	Reliable
		P26	0.840	Valid		
		P27	0.556	Not Valid		
	PP	P28	0.819	Valid	0,834	Reliable
		P29	0.751	Valid		
		P30	0.802	Valid		

The results of the convergent validity and reliability tests indicate that the measurement models for digital literacy and learning independence met the required statistical standards. Most indicators showed factor loadings above the recommended threshold, confirming their adequacy in representing the intended constructs. Composite reliability values across all dimensions demonstrated strong internal consistency. One item within the self-confidence aspect did not meet the validity criterion and was therefore excluded from further analysis. The remaining indicators provided a stable and reliable basis for hypothesis testing. Further evaluation confirmed the test's validity and reliability. All items demonstrated outer loadings above 0.70, indicating strong correlations with the construct. Composite Reliability values exceeded 0.70, while AVE scores remained above 0.50, supporting the convergent validity and consistency of the assessment instrument.

The final stage employed Multivariate Analysis of Variance (MANOVA) using Jamovi to examine whether statistically significant differences existed between the two school contexts across the three dependent variables simultaneously. MANOVA was selected because it reduces the risk of Type I error when comparing multiple interrelated outcome variables in a single analytical model (Buditjahjanto & Irfansyah, 2023). Importantly, the analysis was designed to identify differences between instructional contexts rather than to establish direct causal effects of the AR intervention. Therefore, the interpretation of the results focuses on associative patterns between learning environments and student outcomes rather than definitive claims of causal effectiveness.

Methodological Considerations

Several methodological considerations should be acknowledged when interpreting the results of this study. First, the sample size was relatively small and limited to two elementary schools within a single regional context, which may restrict the generalizability of the findings. Second, the intervention period was relatively short, consisting of eight instructional sessions, which may not be sufficient to observe long-term changes in behavioral competencies such as learning independence and digital literacy. Third, the study employed a non-random group comparison, meaning that differences between schools may reflect contextual factors such as teaching practices, student characteristics, or technological familiarity. Finally, behavioral variables were measured using self-reported questionnaires, which may introduce response bias. These limitations should be considered when interpreting the observed differences in learning outcomes.

RESULT

Descriptive Statistics

Descriptive statistics were used to summarize students' performance in School A and School B across three variables: digital literacy, learning independence, and literacy achievement scores. This analysis provides an overview of central tendencies and score dispersion within each group while enabling comparisons between schools. The mean and median values represent the general level of student performance, whereas the standard deviation indicates the degree of variability among students. Minimum and maximum scores further illustrate the range of achievement across the measured domains, as presented in the table.

Table 4. Result of Data Description

Variable	School	N	Mean	Median	SD	Min	Max
Digital Literacy	School A	38	60.9	62.0	10.337	32	75

	School B	40	63.1	64.0	6.864	48	75
Learning Independence	School A	38	60.1	62.0	11.879	28	75
	School B	40	60.9	63.0	8.270	43	75
Literacy Achievement	School A	38	13.8	14.0	1.965	5	15
	School B	40	14.6	15.0	0.810	12	15

The results of the descriptive analysis indicate that students in both schools demonstrate relatively comparable performance patterns across the three measured variables. School B shows slightly higher mean scores in digital literacy, learning independence, and literacy achievement compared with School A; however, the differences observed at this stage represent descriptive tendencies rather than statistically confirmed effects. The variability of scores, reflected in the standard deviation values, indicates moderate dispersion within each group while remaining within a stable range suitable for further inferential analysis.

In addition, the distribution of minimum and maximum scores suggests that student responses span the full scale of measurement without extreme outliers that could substantially distort the statistical results. Because the study adopts a comparative inferential approach, the descriptive statistics primarily serve as an initial overview of student performance prior to conducting correlation and multivariate analyses. These preliminary patterns provide the empirical basis for examining relationships among variables and exploring whether statistically significant differences emerge between school contexts.

Correlation Analysis

Table 5 presents the Pearson correlation coefficients among digital literacy, learning independence, and literacy achievement.

Table 5. Result of Correlations

Variable	Measure	Digital Literacy	Learning Independence	Literacy Achievement
Digital Literacy	Pearson Correlation	1	.884**	-0.033
	Sig. (2-tailed)		.000	.777
	N	78	78	78
Learning Independence	Pearson Correlation	.884**	1	-0.035
	Sig. (2-tailed)	.000		.760
	N	78	78	78
Literacy Achievement	Pearson Correlation	-0.033	-0.035	1
	Sig. (2-tailed)	.777	.760	
	N	78	78	78

The correlation results indicate a very strong and statistically significant relationship between digital literacy and learning independence ($r = .884$, $p < .001$). This finding suggests that students who demonstrate higher levels of digital literacy tend to report stronger capacities for managing their own learning processes. In contrast, the correlations between digital literacy and literacy achievement ($r = -0.033$, $p = .777$) as well as between learning independence and literacy achievement ($r = -0.035$, $p = .760$) are not statistically significant.

These results indicate that neither digital literacy nor learning independence shows a direct linear association with students' literacy achievement scores within the observed sample.

Importantly, these correlations should be interpreted as associative relationships rather than causal connections. The absence of significant correlations with literacy achievement suggests that cognitive learning outcomes measured through essay-based literacy assessment may be influenced by additional factors beyond students' digital competencies or self-regulated learning behaviors. The correlation patterns therefore provide an empirical foundation for examining whether differences between school contexts are associated with variations across the combined dependent variables. To investigate this possibility, a multivariate analysis of variance (MANOVA) was conducted.

Multivariate Analysis of Variance (MANOVA)

Table 6 presents the results of the multivariate tests examining whether differences between School A and School B are associated with variations across the combined dependent variables: digital literacy, learning independence, and literacy achievement.

Table 6. Result of Multivariate Tests (MANOVA)

Effect	Test Statistic	Value	F	Hypothesis df	Error df	Sig.
Intercept	Pillai's Trace	0.994	3875.496[b]	3.000	73.000	0.000
	Wilks' Lambda	0.006	3875.496[b]	3.000	73.000	0.000
	Hotelling's Trace	159.267	3875.496[b]	3.000	73.000	0.000
	Roy's Largest Root	159.267	3875.496[b]	3.000	73.000	0.000
School	Pillai's Trace	0.108	2.945[b]	3.000	73.000	0.039
	Wilks' Lambda	0.892	2.945[b]	3.000	73.000	0.039
	Hotelling's Trace	0.121	2.945[b]	3.000	73.000	0.039
	Roy's Largest Root	0.121	2.945[b]	3.000	73.000	0.039

The multivariate test results indicate that the effect of school context on the combined dependent variables is statistically significant. The Pillai's Trace value of 0.108 with $F(3, 73) = 2.945$ and $p = 0.039$ suggests that the overall profiles of digital literacy, learning independence, and literacy achievement differ between the two school groups when considered simultaneously. These results should be interpreted within the framework of a contextual group comparison rather than as direct evidence of causal intervention effects. Because the study design involves a quasi-experimental comparison between two existing school environments rather than a randomized controlled experiment, the multivariate differences may reflect variations in instructional context, learning environment, or student characteristics.

Therefore, the significant MANOVA result indicates that the combination of learning variables differs across school contexts, but it does not independently establish that the AR comic-based learning media is the sole determining factor of those differences. To further examine which specific dependent variables contribute to the observed multivariate effect, follow-up univariate analyses were conducted.

Follow-Up Univariate Analysis

Table 7 presents the results of the follow-up analyses examining the effects of school context on each dependent variable separately.

Table 7. Result of Post Hoc

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	Digital Literacy	200.057[a]	1	200.057	2.710	0.104
	Learning Independence	76.365[b]	1	76.365	0.745	0.391
	Literacy Achievement	9.297[c]	1	9.297	4.498	0.037
Intercept	Literacy	294,747.589	1	294,747.589	3992.346	0.000
	Learning Independence	280,040.729	1	280,040.729	2731.743	0.000
	Literacy Achievement	15,616.154	1	15,616.154	7555.480	0.000
School	Digital Literacy	200.057	1	200.057	2.710	0.104
	Learning Independence	76.365	1	76.365	0.745	0.391
	Literacy Achievement	9.297	1	9.297	4.498	0.037
Error	Digital Literacy	5,537.112	75	73.828		
	Learning Independence	7,688.518	75	102.514		
	Literacy Achievement	155.015	75	2.067		
Total	Digital Literacy	300,734.000	77			
	Learning Independence	287,973.000	77			
	Literacy Achievement	15,793.000	77			
Corrected Total	Digital Literacy	5,737.169	76			
	Learning Independence	7,764.883	76			
	Literacy Achievement	164.312	76			

The follow-up analyses reveal that school differences are statistically significant for literacy achievement ($F = 4.498$, $p = 0.037$). This finding indicates that students' literacy achievement scores differ between School A and School B. In contrast, the differences between schools are not statistically significant for digital literacy ($p = 0.104$) and learning independence ($p = 0.391$). These results suggest that the levels of digital literacy and learning independence reported by students are relatively comparable across the two school contexts.

The pattern of results indicates that the multivariate difference identified in the MANOVA analysis is primarily associated with variations in literacy achievement rather than differences in the behavioral variables of digital literacy and learning independence. Because the analysis compares naturally occurring school contexts, the observed differences should be interpreted as contextual variations rather than definitive treatment effects. These findings therefore provide an empirical description of how student outcomes differ across learning environments, forming the basis for further theoretical interpretation in the discussion section.

DISCUSSION

The present study examined differences in students' learning independence, digital literacy, and literacy achievement across two elementary school contexts where AR-based comic learning media were introduced. The multivariate analysis indicated a statistically significant difference in the combined dependent variables between School A and School B ($p < 0.05$). Rather than representing a purely causal treatment effect, this result should be interpreted as evidence of contextual variation between the two learning environments in which the AR comic-based learning activities were implemented. This interpretation aligns with the comparative inferential nature of the research design, where the analysis evaluates differences between naturally existing school groups rather than outcomes from a fully randomized experimental intervention.

Although the statistical comparison was conducted at the school level, both groups were exposed to the same instructional media, namely AR-based educational comics designed to visualize narrative literacy content. The intervention was implemented during literacy learning sessions over several instructional meetings in which students accessed comic pages through mobile devices and scanned visual markers to activate AR animations. During the learning process, students read narrative segments, observed augmented visualizations, and discussed story elements with peers under teacher facilitation. Teachers guided the activity by introducing the learning objectives, demonstrating how to access the AR features, monitoring student interaction with the content, and facilitating reflective discussion after exploration. The learning scenario therefore combined reading activities, visual exploration, and guided reflection using commonly available smartphones and an AR application integrated into the comic media.

From a cognitive perspective, the observed differences in literacy achievement may be associated with the way AR visualization supports information processing. The Cognitive Theory of Multimedia Learning (CTML) suggests that presenting verbal and visual information simultaneously can reduce extraneous cognitive load and facilitate the integration of new knowledge within working memory. AR-supported visualizations embedded in the comic narrative may therefore assist students in transforming abstract textual descriptions into concrete mental representations, making the content easier to understand during reading activitie (Şimşek et al., 2025). This interpretation is consistent with previous studies indicating that immersive visualization can support comprehension and memory formation in multimedia learning environments (Sattar et al., 2025). Rather than demonstrating that AR alone determines learning outcomes, the findings suggest that interactive visualization may contribute to improved comprehension when integrated into structured literacy activities.

A comparison between School A and School B also indicates that differences in instructional context may influence the consistency of literacy outcomes. The results suggest that more structured and standardized learning environments tend to produce more stable literacy performance (Saavedra et al., 2025). The greater variability observed in School A implies that the effectiveness of digital learning media is influenced not only by the technology itself but also by contextual factors such as technical readiness, classroom management, and the quality of teacher facilitation (Maulyda et al., 2025). This observation supports the view that

educational technology should be interpreted as part of a broader pedagogical ecosystem rather than as an independent determinant of learning success.

The analysis further shows that significant differences were observed primarily in literacy achievement, while digital literacy and learning independence did not demonstrate statistically significant short-term differences between the two school groups. One possible explanation relates to the nature of digital literacy as a multidimensional competency. Digital literacy involves not only the ability to operate digital tools but also critical evaluation, information management, and reflective use of technology. These competencies typically develop gradually through repeated exposure to digital environments rather than through a short instructional intervention (Rakhimzhanova et al., 2025). Consequently, the brief exposure to AR-based learning activities may not have been sufficient to produce measurable differences in students' broader digital literacy competencies.

A similar interpretation can be applied to learning independence. Within the Self-Regulated Learning (SRL) framework, independent learning behaviors develop through cycles of planning, monitoring, and reflection that require sustained practice and structured scaffolding. The absence of significant short-term differences in learning independence may therefore indicate that the introduction of new technology does not automatically transform students' self-regulation strategies. Students frequently rely on teacher guidance when encountering unfamiliar digital tools, particularly in primary education settings (Sui et al., 2023). The transition from teacher-directed learning to autonomous learning requires continuous support and deliberate pedagogical design (Nevrelova et al., 2024).

Interestingly, this pattern also highlights a theoretical distinction between cognitive learning outcomes and behavioral learning competencies. While immersive visualization can support comprehension and knowledge retention relatively quickly, changes in learning behaviors such as self-regulation and independent learning typically emerge over longer instructional periods. This finding is consistent with research suggesting that behavioral competencies require repeated opportunities for practice and reflection before stable learning habits are formed (Tian & Ironsi, 2025)The novelty of AR technology may initially increase students' curiosity and engagement during learning activities. However, motivation triggered by technological novelty does not necessarily translate into long-term self-regulated learning behaviors (Nikou, 2025). For this reason, the integration of AR into literacy instruction should be accompanied by explicit pedagogical strategies aimed at fostering autonomy, such as reflective questioning, collaborative problem solving, and structured self-assessment tasks.

From a broader educational perspective, these findings contribute to the growing literature on immersive learning technologies in primary education. AR-based comic media appear to function effectively as a visual engagement tool that supports reading comprehension through dynamic storytelling and interactive visualization. Such characteristics are particularly relevant for Alpha Generation learners, who tend to respond positively to visually rich and interactive digital learning experiences (Morfidi & Iatraki, 2025). Nevertheless, the findings also highlight that technological engagement alone is insufficient to produce comprehensive learning development without supportive instructional strategies.

Future research should therefore investigate longitudinal implementations of AR-based learning to examine whether sustained exposure can gradually strengthen digital literacy and independent learning behaviors. Long-term studies may provide deeper insights into how immersive technology influences the development of self-regulated learning processes over

time (Şimşek et al., 2025). Further improvements in user-interface design are also recommended to reduce technological barriers and allow students to focus more fully on reflection, interpretation, and meaning-making during literacy learning activities (Rakhimzhanova et al., 2025).

Several methodological limitations should be acknowledged when interpreting the findings of this study. First, the research involved a relatively small sample drawn from only two elementary schools, which may limit the generalizability of the results to broader educational contexts. Second, the intervention period was relatively short, which may not have allowed sufficient time for behavioral competencies such as digital literacy and learning independence to develop measurably. Third, the comparison between School A and School B did not involve random assignment of participants, meaning that contextual differences between schools could act as confounding variables influencing the observed outcomes. Fourth, some variables were measured using self-reported questionnaire responses, which may be subject to response bias. Finally, the study focused primarily on short-term learning outcomes and did not examine longitudinal changes in students' learning behavior. Recognizing these limitations is important for maintaining analytical transparency and for guiding future studies that seek to examine the long-term educational potential of AR-supported learning environments.

CONCLUSION

The use of Augmented Reality (AR) comic-based media significantly improves elementary students' cognitive achievement, particularly in literacy performance, by transforming abstract concepts into concrete visual representations that reduce cognitive load and facilitate comprehension. However, its effects on learning independence and digital literacy remain limited, suggesting that these competencies require longer-term technological exposure and sustained teacher guidance to develop effectively. AR comics nevertheless show strong potential to increase reading interest among visually oriented Alpha Generation learners and may serve as an adaptive and practical instructional model, especially for schools with limited resources. Future research should therefore employ longer intervention periods and more intuitive interface designs to better examine the longitudinal development of independent learning habits and digital competencies.

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