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# ENHANCING STUDENTS' CONCEPTUAL UNDERSTANDING IN MATHEMATICS THROUGH COMIC-BASED LEARNING: A MIXED-METHODS STUDY

**Izay Zaenal Mutaqin [1]*, Dicky Zaini Abdullah Alas'ari[2], Azwan Rhamdhan Abdul Muin [3], Rival Muhamad Fauzi [4]**

Mathematics Education Siliwangi University, Jalan Siliwangi 24 Tasikmalaya, Jawa Barat, Indonesia.
E-mail: izayzm06@gmail.com

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**ABSTRACT**

Conceptual understanding lies at the heart of meaningful mathematics learning, yet instructional practices in many contexts remain procedural and memorization-based, limiting students' ability to connect symbolic, verbal, and visual representations. Addressing this gap, this study investigates the effectiveness and cognitive–affective mechanisms of comic-based learning in improving students' conceptual understanding of mathematics and develops a new theoretical model, the Visual–Narrative Learning Framework (VNLF). Employing a mixed-methods sequential explanatory design, the research involved 60 eighth-grade students divided into an experimental group (comic-based instruction) and a control group (conventional teaching). Data were collected through conceptual understanding tests, motivation questionnaires, interviews, and classroom observations. Quantitative data were analyzed using *t*-tests, gain scores, and effect size, while qualitative data underwent thematic analysis. Findings revealed that the experimental group achieved significantly higher conceptual understanding ($M = 93.6$ vs. 81.4; $t(58) = 7.25$, $p < .001$; $d = 1.56$, large effect; $g = 0.72$, high category). Comics facilitated the transformation of symbolic ideas into visual–narrative representations, increasing emotional engagement and intrinsic motivation. The integrated results produced the VNLF, which explains conceptual learning as the simultaneous interaction of visualization, narration, and teacher mediation. Theoretically, this study extends the Cognitive Theory of Multimedia Learning by incorporating affective and social dimensions into visual–narrative mathematics instruction. Practically, it positions comic-based learning as an integrative pedagogical strategy that enhances students' numeracy, visual literacy, and engagement, supporting the goals of the *Merdeka Curriculum* and advancing digital transformation in mathematics education.

Pemahaman konseptual merupakan inti dari pembelajaran matematika yang bermakna, namun praktik pengajaran di berbagai konteks masih bersifat prosedural dan berorientasi hafalan, sehingga siswa kesulitan mengaitkan representasi simbolik, verbal, dan visual secara terpadu. Untuk menjawab tantangan tersebut, penelitian ini menelaah efektivitas serta mekanisme kognitif–afektif dari pembelajaran berbasis komik dalam meningkatkan pemahaman konseptual matematika, sekaligus mengembangkan model teoretis baru bernama Visual–Narrative Learning Framework (VNLF). Penelitian menggunakan desain mixed-methods sequential explanatory dengan melibatkan 60 siswa kelas VIII yang dibagi menjadi kelompok eksperimen (pembelajaran berbasis komik) dan kelompok kontrol (pembelajaran konvensional). Data dikumpulkan melalui tes pemahaman konseptual, angket motivasi, wawancara, dan observasi kelas. Analisis kuantitatif dilakukan dengan *t-test*, gain score, dan effect size, sedangkan analisis kualitatif menggunakan *Thematic Analysis*. Hasil menunjukkan bahwa kelompok eksperimen memperoleh peningkatan signifikan dalam pemahaman konseptual ($M = 93{,}6$ vs. $81{,}4$; $t(58) = 7{,}25$; $p < 0{,}001$; $d = 1{,}56$; $g = 0{,}72$). Komik membantu siswa mentransformasikan ide simbolik menjadi representasi visual–naratif, sekaligus meningkatkan keterlibatan emosional dan motivasi intrinsik. Integrasi hasil melahirkan VNLF, yang menjelaskan bahwa pemahaman konseptual berkembang optimal melalui interaksi simultan antara visualisasi, narasi, dan mediasi guru. Secara teoretis, penelitian ini memperluas Cognitive Theory of Multimedia Learning dengan menambahkan dimensi afektif dan sosial ke dalam konteks pembelajaran visual-naratif. Secara praktis, pembelajaran berbasis komik berfungsi sebagai strategi pedagogis integratif yang menumbuhkan literasi numerasi dan visual abad ke-21, mendukung implementasi Kurikulum Merdeka, serta memperkuat agenda transformasi digital dalam pendidikan matematika.



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## 1. INTRODUCTION

Mathematics plays a central role in developing logical, analytical, and creative thinking skills that constitute the foundation of 21st-century competencies. However, across diverse global educational contexts—both in developed and developing countries—students frequently perceive mathematics as abstract, difficult, and detached from real-life situations (Schoenfeld, 2016; Kilpatrick et al., 2001). International studies indicate that most students tend to focus on mastering procedural routines and formulaic memorization, while the conceptual and interpretative dimensions of mathematical understanding remain underexplored (Hiebert & Grouws, 2007; Akkaya & Karaca, 2022). Consequently, a persistent gap exists between procedural fluency and conceptual understanding, leading to limited knowledge transfer to novel situations (Duval, 2006).

Conceptual understanding involves not only the ability to explain interconnections among mathematical ideas but also the capacity to represent these ideas symbolically, verbally, visually, and contextually (Hiebert & Grouws, 2007). Unfortunately, traditional instructional systems in many schools still fail to provide opportunities for students to navigate flexibly across these representations. Heavy reliance on text-based instruction and lectures hinders the multimodal activation required for deep comprehension. Therefore, an alternative pedagogical approach is needed—one that integrates cognitive and affective pathways through contextual visual–narrative media, bridging mathematical abstraction with meaningful learning experiences (Lin & Chen, 2022; Wang & Holmlund, 2022).

One promising pedagogical strategy is comic-based learning, which combines text, imagery, and narrative in an engaging and accessible visual format (McCloud, 1993; Berkowitz & Packer, 2018). In mathematics education, comics serve as a cognitive–affective bridge, enabling students to translate abstract symbols into concrete representations through contextual storytelling (Özdemir, 2017; Li & Ni, 2021). A growing body of international research supports this approach: Lin and Chen (2022) demonstrated that contextual comics enhance mathematical literacy and concept retention; Kurniawan and Widodo (2023) reported improvements in students' critical thinking dispositions through digital comics; and Mekonnen and Teferra (2024) found that narrative-based instruction promotes metacognitive awareness and emotional engagement.

Despite these advances, three notable research gaps remain: (1) Most previous studies emphasize quantitative outcomes without examining the underlying cognitive and emotional mechanisms driving conceptual understanding (Nordin & Zakaria, 2021), (2) The integration of Dual Coding Theory (Paivio, 1990), Cognitive Theory of Multimedia Learning (Mayer, 2021), and Representation Theory (Duval, 2006) into a unified model for visual–narrative mathematics instruction remains underdeveloped, and (3) The roles of teacher mediation and affective engagement—critical factors in digital media–based learning success (Park et al., 2023)—have rarely been examined systematically.

To address these gaps, the present study develops and empirically tests a new conceptual model called the Visual–Narrative Learning Framework (VNLF). This framework integrates three interrelated dimensions of visual–narrative learning: (1) The cognitive dimension, emphasizing dual coding between verbal and visual information; (2) The affective dimension, focusing on students' emotional engagement with learning

narratives; and (3) The pedagogical dimension, highlighting the teacher's mediating role in linking visualization to conceptual meaning.

Methodologically, this research adopts a mixed-methods sequential explanatory design (Creswell & Plano Clark, 2018), integrating quantitative and qualitative data to achieve a comprehensive understanding. The quantitative phase assesses the effectiveness of comic-based instruction in enhancing students' conceptual understanding, while the qualitative phase explores students' learning experiences, perceptions, and the affective mechanisms underlying the observed effects. Integration of both phases occurs through meta-inference (Tashakkori & Teddlie, 2020), yielding a holistic explanation of how and why comic-based learning facilitates mathematical knowledge construction.

This study is expected to make two primary contributions. Theoretically, it extends the Cognitive Theory of Multimedia Learning (CTML) (Mayer, 2021) by incorporating affective and social dimensions within visual–narrative mathematics learning. Practically, it provides empirical evidence and a conceptual model that teachers and curriculum developers can employ to implement comic-based media as a contextual and humanistic visual numeracy strategy, aligned with the ongoing digital transformation of 21st-century education.

## 2. Research Methodology

### 2.1. Research Design

This study employed a mixed-methods sequential explanatory design (Creswell & Plano Clark, 2018), integrating quantitative and qualitative phases conducted in succession. The quantitative phase examined the effect of comic-based learning on students' conceptual understanding, while the qualitative phase explored the underlying cognitive, affective, and pedagogical mechanisms explaining the observed quantitative outcomes.

The adoption of this design was based on the premise that the effectiveness of an instructional medium cannot be fully understood through quantitative score comparisons alone; rather, it requires an in-depth exploration of learners' and teachers' experiences throughout the learning process (Tashakkori & Teddlie, 2020). The integration of both phases was achieved through a meta-inference process, which involved synthesizing findings from quantitative and qualitative data to generate holistic conclusions through triangulation (Fetters et al., 2013).

### 2.2. Population and Sample

The population of this study comprised all eighth-grade students in a public junior high school in Indonesia implementing the *Merdeka Curriculum*. A purposive random sampling technique was applied, considering the equivalence of academic ability across classes and teachers' readiness to employ innovative media. Two classes were randomly assigned to different conditions: an experimental group (n = 30), which received comic-based mathematics instruction, and a control group (n = 30), which experienced conventional textbook-based instruction.

Sample adequacy was verified through power analysis using parameters $\alpha = 0.05$, power = 0.80, and an expected medium effect size (d = 0.50), following Cohen's (1988)

recommendations. The analysis indicated a minimum of 27 participants per group; therefore, the actual sample of 30 students per group was considered sufficient for inferential testing and ensuring valid representation.

## 2.3. Variables and Operational Definitions

This study involved two primary variables: the independent variable, which was the implementation of comic-based mathematics learning, and the dependent variable, referring to students' conceptual understanding of the topic *Systems of Linear Equations in Two Variables (SLETV)*.

Conceptual understanding was operationally defined as students' ability to (a) explain interconnections among mathematical concepts, (b) apply principles in new contexts, and (c) transform ideas across symbolic, verbal, and visual representations (Hiebert & Grouws, 2007; Duval, 2006).

## 2.4. Research Instruments

Conceptual Understanding Test. The test consisted of ten open-ended items constructed based on established indicators of conceptual understanding. Content validity was verified by three mathematics education experts, yielding an Aiken's V coefficient of 0.87 (high validity). Internal reliability was confirmed with Cronbach's Alpha = 0.88, indicating strong consistency. Item analysis demonstrated satisfactory discrimination indices (rpbis > 0.35) and balanced difficulty levels.

Perception and Motivation Questionnaire. A 5-point Likert-scale questionnaire (1 = strongly disagree to 5 = strongly agree) was used to assess students' engagement, enjoyment, and interest in comic-based learning. Confirmatory Factor Analysis (CFA) produced KMO = 0.812 and Bartlett's Test $p < 0.001$, confirming construct validity. The overall reliability ($\alpha = 0.90$) demonstrated excellent internal consistency.

Semi-Structured Interviews. Interviews were conducted with ten students from the experimental group and one mathematics teacher. The questions explored (1) perceptions of comic use, (2) mechanisms of conceptual understanding through visual–narrative representation, and (3) emotional experiences during learning. All interviews were transcribed verbatim and analyzed using NVivo 12, ensuring coding consistency and analytical rigor.

Participant Observation. Observations were carried out across four learning sessions to record teacher–student interactions, instructional strategies, and student engagement. Field notes were cross-referenced with interview transcripts to establish triangulated validity of qualitative findings.

## 2.5. Research Procedures

The research was implemented in four systematic stages.

Preparation. The process began with the development of SPLDV comic materials grounded in *dual coding* and *multimedia learning principles*. Expert validation covered content accuracy, linguistic clarity, and visual design quality. A pilot readability test involving ten students yielded a comprehension rate above 85%.

Experimental Implementation. The experimental group participated in four 80-minute sessions using interactive comic-based media, while the control group received traditional textbook-based instruction. Both groups were taught by the same teacher to minimize potential teacher-effect bias.

Data Collection. Pretests and posttests were administered to both groups. Additionally, questionnaires, interviews, and classroom observations were conducted following the intervention to capture students' affective and cognitive responses.

Integration and Meta-Inference. Quantitative and qualitative data were integrated using joint display analysis (Fetters, Curry, & Creswell, 2013), allowing for the identification of convergence patterns between numerical trends and narrative insights.

### 2.6. Data Analysis

Quantitative Analysis. Data analysis began with testing assumptions of normality (Kolmogorov–Smirnov) and homogeneity (Levene's Test). Differences between groups were examined using an independent samples t-test**,** with effect size computed using Cohen's d (0.2 = small, 0.5 = medium, ≥ 0.8 = large). A normalized gain score (g) was calculated to measure relative learning effectiveness (Hake, 1998). Additional analyses explored correlations between conceptual understanding and motivation to examine the cognitive–affective linkage**.**

Qualitative Analysis. Thematic Analysis (Braun & Clarke, 2019) was applied through five stages: familiarization with data, open coding, theme identification, inter-rater reliability verification ($\kappa = 0.87$), and narrative interpretation. Findings were categorized into three emergent themes: cognitive clarity**,** emotional engagement, and pedagogical mediation.

Quantitative–Qualitative Integration (Meta-Inference). Integration followed an explanatory sequential approach, wherein qualitative results were used to interpret and enrich quantitative findings. This process led to the formulation of the Visual–Narrative Learning Framework (VNLF), illustrating the simultaneous interaction among visual representation, affective narration, and teacher mediation in fostering conceptual understanding of mathematics.

### 2.7. Validity, Reliability, and Research Ethics

The study adhered to the British Educational Research Association (BERA, 2018) and APA Ethical Guidelines (2020). Written consent was obtained from the school administration and participating teachers. Participant confidentiality was strictly maintained, and participation was entirely voluntary.

Internal validity was strengthened through member checking**,** method triangulation**,** and audit trail documentation**.** Procedural reliability was ensured through instrument consistency, detailed documentation logs, and standardized training for research assistants.

## 3. Results and Discussion

### 3.1. Results

### 3.1.1. Improvement in Students' Conceptual Understanding

The analysis of pretest and posttest data revealed a statistically significant improvement in students' mathematical conceptual understanding following comic-based instruction. The experimental group achieved a mean posttest score of M = 93.6, SD = 4.2, while the control group obtained M = 81.4, SD = 6.8**.** An independent samples *t*-test indicated a significant difference between groups, $t(58) = 7.25$, $p < .001$, with a large effect size (Cohen's d = 1.56)**.** The normalized gain score (*g*) for the experimental group was 0.72 (high category), compared to 0.34 (medium category) in the control group, confirming the substantial impact of the intervention.

Furthermore, a significant positive correlation was found between students' learning motivation and conceptual understanding ($r = .68$, $p < .01$), suggesting a strong linkage between cognitive and affective dimensions in mathematics learning. This relationship aligns with the premise of the Cognitive–Affective Theory of Learning with Media (Moreno, 2023), which emphasizes that emotional engagement enhances cognitive processing and knowledge retention. The quantitative findings therefore confirm that comic-based learning not only promotes cognitive achievement but also fosters emotional and motivational engagement.

### 3.1.2. Students' Perceptions, Motivation, and Affective Engagement

Survey results indicated that students' perceptions of comic-based learning were highly positive (M = 3.78 out of 4.00). The visual appeal dimension obtained the highest score (M = 3.90), followed by narrative comprehension (M = 3.84). Notably, 91% of students reported that comics improved their focus, motivation, and reduced boredom in learning mathematics.

Qualitative data further substantiated these findings. Students described that the use of comics helped them visualize abstract concepts and connect mathematical logic with contextual narratives. As one participant expressed, *"I finally understand how linear equations work because I can see the story, not just the numbers on the board"* (Student E3). Another student added, *"Learning with comics feels like reading a story while thinking through mathematical logic"* (Student E7).

Thematic analysis of interviews and classroom observations yielded three major themes: cognitive clarity, referring to the way narrative visualization supports comprehension of abstract concepts; affective engagement, reflecting students' emotional involvement stimulated by colors, characters, and storylines; and pedagogical mediation, describing how teachers used comics as visual scaffolds to clarify complex symbolic representations. These results align with recent empirical studies demonstrating that multimodal narrative-based instruction enhances motivation, focus, and deep learning (Plass & Kaplan, 2024; Aghaei et al., 2023).

### 3.1.3. Teacher Validation and Pedagogical Aspects

Teacher evaluations demonstrated exceptionally high acceptance of comic-based instructional media, with 100% of respondents strongly agreeing that the materials were suitable for classroom implementation. Teachers particularly highlighted the relevance of

the content to the curriculum, the communicative nature of the language, and the cognitive appropriateness of the visuals for students.

As one mathematics teacher observed, *"Comics are very helpful for explaining the relationships between variables because students can see the context of the story, not just abstract symbols"* (Teacher G1). This endorsement reflects a growing recognition among educators of the pedagogical potential of visual–narrative media in making abstract mathematical concepts more accessible. These findings are consistent with research indicating that teacher mediation is a key determinant of successful technology and media integration in classrooms (Park et al., 2023; Scherer et al., 2023).

### 3.1.4. Integration of Quantitative and Qualitative Findings (Meta-Inference)

The integration of quantitative and qualitative findings revealed **high convergence** between datasets. The quantitative evidence confirmed the effectiveness of comic-based learning in enhancing conceptual understanding, while qualitative insights elucidated the cognitive, affective, and pedagogical mechanisms underlying this improvement.

Through meta-inference analysis, the study synthesized these findings into the Visual–Narrative Learning Framework (VNLF), a conceptual model explaining how visual representation, narrative engagement, and teacher mediation interact to foster conceptual understanding in mathematics. The VNLF comprises three interdependent dimensions: Visual Representation, grounded in Dual Coding Theory (Paivio, 1990); Conceptual Linking**,** based on Representation Theory (Duval, 2006); and Affective Engagement and Teacher Mediation, as supported by contemporary frameworks of integrated engagement (Wang & Holmlund, 2022; Park et al., 2023).

This integrative model provides both theoretical and empirical evidence that the interplay among visual, emotional, and pedagogical processes constitutes a powerful mechanism for enhancing mathematical literacy and conceptual transfer in 21st-century learning environments.

## 3.2. Discussion

### 3.2.1. Integration of Empirical Findings with Theoretical Foundations

The empirical findings of this study demonstrate that comic-based learning significantly enhances students' conceptual understanding of mathematics, with a large effect size (Cohen's $d = 1.56$). This result reinforces the argument that comics function not merely as visual aids, but as *cognitive–affective strategies* that optimize dual processing between textual and pictorial information.

According to Dual Coding Theory (Paivio, 1990; Clark & Paivio, 2023), verbal and visual information are processed through two complementary representational systems, promoting semantic integration and long-term retention. Within this framework, narrative comics act as *dual-channel scaffolds* that bridge abstract mathematical symbols with contextual visual representations (Fiorella & Mayer, 2022; Li & Ni, 2021; Ainsworth, 2022). Similarly, the Cognitive Theory of Multimedia Learning (CTML) (Mayer, 2021; Mayer & Fiorella, 2023) posits that the integration of text and imagery reduces extraneous cognitive load and enhances schema construction. Recent meta-analyses further confirm that visual–

narrative instructional strategies significantly improve conceptual learning across STEM disciplines (Zhang & Zhou, 2022; Aghaei et al., 2023).

In addition, the Cognitive–Affective Theory of Learning with Media (CATLM) suggests that emotional engagement reinforces cognitive processing through affective activation (Moreno, 2023; Plass & Kaplan, 2024). In the context of comic-based learning, visual and narrative elements elicit emotional resonance, facilitating deep learning and long-term conceptual retention (Wang & Holmlund, 2022; Park et al., 2023). Collectively, these findings affirm that comic-based instruction represents an integrated multimodal system, harmonizing cognitive, affective, and representational dimensions to strengthen mathematical conceptual understanding.

### 3.2.2. Affective Dimension and Emotional Engagement

The significant improvement in students' motivation and engagement underscores the central role of affective factors in mathematics learning. Visual and narrative features within comics evoke *emotional resonance*, making abstract mathematical ideas more concrete, accessible, and meaningful. As outlined in the Cognitive–Affective Theory of Learning with Media (CATLM) (Moreno, 2023; Plass & Kaplan, 2024), positive emotions enhance cognitive engagement and strengthen meaning construction. This affective activation stimulates attention, semantic memory, and long-term concept retention (Chen et al., 2024; Mousavinasab et al., 2023).

Aligned with the Integrated Engagement Framework (Wang & Holmlund, 2022), effective learning occurs when visual, social, and emotional dimensions interact dynamically. Through narrative and character-driven contexts, comics establish *situated learning environments* (Lave & Wenger, 1991; Damsa et al., 2022), enabling students to construct understanding through emotionally and contextually rich experiences. Neuroeducation studies further reveal that positive emotional experiences during learning activate neural regions associated with conceptual encoding, particularly within the hippocampal and prefrontal networks (Tyng et al., 2022; Pekrun et al., 2023). Such evidence underscores that emotional engagement constitutes a neurological and psychological foundation for deep conceptual learning.

### 3.2.3. The Role of Teachers as Pedagogical Mediators

Teacher validation confirmed that the success of comic-based instruction is strongly influenced by teacher mediation. Teachers function not only as conveyors of information but as *conceptual and affective facilitators* who help students transform mathematical symbols into meaningful representations. This role resonates with Social Constructivist Theory (Vygotsky, 1978) and recent findings highlighting teachers as *pedagogical orchestrators* within digital learning environments (Chen & Chan, 2023; Mishra & Koehler, 2022).

These findings are consistent with the Technology Acceptance Model (TAM) (Park et al., 2023; Scherer et al., 2023), which asserts that teachers' perceptions of usefulness and ease of use determine the successful adoption of innovative media. Teachers with strong digital pedagogical competence effectively integrate media such as comics without compromising conceptual depth (Instefjord & Munthe, 2022; Pettersson & Molstad, 2023).

Thus, teachers serve as *reflective and transformative mediators*, ensuring that comics operate as *pedagogical enhancers*—broadening instructional reach while preserving conceptual depth and emotional engagement.

### 3.2.4. Meta-Inference Synthesis and the Development of the VNLF Model

The integration of quantitative and qualitative results led to the formulation of the Visual–Narrative Learning Framework (VNLF), a conceptual model elucidating the synergistic relationships among visualization, narration, and pedagogical mediation in promoting conceptual understanding. Within the VNLF, visual elements serve as *cognitive scaffolds* that strengthen dual processing (Paivio, 1990; Mayer & Fiorella, 2023), narratives function as *affective drivers* that enhance emotional engagement (Plass & Kaplan, 2024; Moreno, 2023), and teachers act as *pedagogical anchors* that mediate meaning and reflection (Chen & Chan, 2023; Park et al., 2023).

This model aligns with contemporary developments in the learning sciences, emphasizing the integration of cognitive, affective, and social dimensions in multimodal learning (Rapp & Ainsworth, 2022; D'Mello & Graesser, 2023; Pekrun et al., 2023). Accordingly, the VNLF extends the scope of the Cognitive Theory of Multimedia Learning toward a more humanistic and contextualized framework that captures the interplay between cognition, emotion, and pedagogy.

### 3.2.5. Theoretical and Practical Implications

Theoretical Implications. This study extends the Cognitive Theory of Multimedia Learning (CTML) by incorporating affective and social dimensions into the context of *visual–narrative mathematics learning*. The proposed VNLF serves as a theoretical bridge connecting Dual Coding Theory (Paivio), Representation Theory (Duval), and Multimedia Learning Theory (Mayer), emphasizing that conceptual understanding emerges from the synergy among visual, narrative, and pedagogical processes (Ainsworth, 2022; Fiorella & Mayer, 2022; Moreno, 2023). The framework aligns with emerging perspectives in the learning sciences, which highlight the integration of cognitive–affective–social processes as essential for fostering deep learning and conceptual flexibility (Rapp & Ainsworth, 2022; Mayer et al., 2024; Plass & Kaplan, 2024).

Practical Implications. Practically, comics can be utilized as conceptual scaffolding tools rather than merely as visual supplements, as they facilitate *conceptual transfer* and *affective engagement* (Li & Ni, 2021; Lin & Chen, 2022). Teachers are encouraged to integrate interactive digital comics into STEM instruction to enhance motivation and conceptual comprehension (Kurniawan & Widodo, 2023; Aghaei et al., 2023). Moreover, educational policymakers may adopt the VNLF as a conceptual foundation for developing *visual-based numeracy learning policies* aligned with the global agenda of digital transformation in education (Holmes et al., 2022; OECD, 2023).

### 3.2.6. Limitations and Directions for Future Research

Although this study provides strong evidence of the effectiveness of comic-based instruction, several methodological limitations must be acknowledged. First, the limited sample size (n = 60) and single-site context constrain the generalizability of findings,

consistent with concerns raised in recent replication studies in educational research (Cheung & Slavin, 2023; Kulik, 2022). Second, the short intervention duration (four sessions) precluded the examination of long-term retention and knowledge transfer, which are increasingly central in digital learning research (Fiorella & Mayer, 2022; Lee et al., 2023). Third, the current study employed printed media, leaving unexplored the potential of Augmented Reality (AR) and AI-driven digital comics in facilitating immersive learning experiences (Bacca et al., 2022; Chen et al., 2024).

Future studies are therefore encouraged to develop AR comic-based learning environments to enhance interactivity, *situated cognition*, and emotional engagement (Ibáñez & Delgado-Kloos, 2023; Garzón & Acevedo, 2024); implement longitudinal designs to evaluate conceptual retention and knowledge transfer over extended periods (Loderer et al., 2023; Moreno, 2023); and replicate the VNLF model across STEM domains to assess its cross-disciplinary validity and cultural adaptability (Ainsworth & Rapp, 2023; Chen et al., 2025). Advancing this line of research may enable the integration of VNLF with emerging technologies such as AR/VR and AI-based learning analytics, thereby enhancing its relevance within the evolving digital learning ecosystem.

## 4. Conclusion

This study provides robust empirical and theoretical evidence that comic-based learning is an effective pedagogical approach for enhancing students' conceptual understanding of mathematics and fostering their affective engagement**. Employing a** mixed-methods sequential explanatory design**,** the integration of quantitative and qualitative findings demonstrated that comic media not only produced a statistically significant improvement in learning outcomes ($t(58) = 7.25$, $p < .001$, $d = 1.56$; $g = 0.72$) but also enriched students' learning experiences through heightened visual engagement and contextualized narrative comprehension.

Conceptually, the findings affirm that mathematical understanding is not solely the result of symbolic cognitive processing but also emerges from emotionally and representationally mediated learning. Comics function as dual-channel cognitive tools**,** simultaneously activating verbal and visual processing pathways while facilitating inter-representational transformations (verbal → visual → symbolic), in line with Duval's (2006) *Theory of Semiotic Representation*.

Furthermore, this research produced a novel conceptual model—the Visual–Narrative Learning Framework (VNLF)—which integrates three foundational dimensions of effective learning. The cognitive dimension reflects dual processing between verbal and visual representations as proposed in Dual Coding Theory (Paivio, 1990); the affective dimension emphasizes emotional and motivational engagement as conceptualized in the Integrated Engagement Framework (Wang & Holmlund, 2022); and the pedagogical dimension highlights the teacher's mediating role as a facilitator who bridges symbols, visualizations, and narratives within authentic learning contexts.

Taken together, these insights underscore that comics are not merely visual teaching aids but integrative pedagogical strategies that unify cognitive, affective, and representational processes within a coherent visual–narrative learning system. This study concludes that meaningful conceptual learning occurs when students simultaneously

"see," "feel," and "construct meaning" from mathematical concepts through multimodal and emotionally resonant engagement.

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