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Integrating Augmented Reality Based Comics into Chemical Bonding Instruction to Enhance Students' Thinking Skills

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Abstract: This study aims to investigate the effectiveness of integrating Augmented Reality (AR)-based comics into chemical bonding instruction to enhance students' critical thinking skills. A quasi-experimental design with a non-equivalent control group was employed, involving 40 eleventh-grade students divided into an experimental group and a control group. The experimental group was taught using AR-based comics within a project-based learning framework, while the control group received conventional instruction without AR support. Data were collected through essay tests, observation sheets, and documentation, and analyzed using descriptive statistics, N-gain, and an independent sample t-test. The results indicate that the experimental group achieved a higher post-test mean score (75.75) compared to the control group (65.30). The N-gain score of the experimental group (0.49) was categorized as moderate, exceeding that of the control group (0.29), which was classified as low. Statistical analysis revealed a significant difference between the two groups ($p < 0.05$). These findings suggest that the integration of AR-based comics effectively enhances students' critical thinking skills by facilitating visualization, engagement, and conceptual understanding. Therefore, this approach can serve as an innovative instructional strategy to improve the quality of chemistry learning.

Keywords: Augmented reality; Chemical bonding; Comics-based learning; Critical thinking skills; Project-based learning

Introduction

Chemical bonding occupies a pivotal position in the chemistry curriculum because it provides the conceptual foundation for explaining a wide range of chemical structures, properties, and transformations (Dulmen et al., 2023). Mastery of this topic requires students to engage in sophisticated cognitive processes, including constructing mental representations of atomic interactions, coordinating symbolic notations with particulate-level models, and interpreting dynamic phenomena that are fundamentally invisible (Hamerská et al., 2024). These demands often exceed students' representational fluency, resulting in persistent misconceptions, fragmented understanding, and limited capacity to reason across multiple representational domains (Lang-Raad, 2025). Such challenges suggest that chemical bonding remains a persistent barrier to the development of comprehensive chemical literacy, thereby necessitating pedagogical innovations that more effectively cultivate students' thinking skills (Qi et al., 2024).

The urgency of addressing these learning difficulties is underscored by evidence from classroom

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performance trends, diagnostic assessments, and teachers' observations, all of which consistently reveal that many students exhibit misconceptions about bonding types, electron distribution, and molecular formation mechanisms (Grigorenko et al., 2020). Students' difficulties are rooted not merely in content complexity but also in the cognitive load imposed by traditional instructional materials, which typically rely on static representations incapable of capturing the dynamic nature of bonding processes (Skulmowski & Xu, 2022). In the context of contemporary educational expectations—where analytical reasoning, visual–spatial thinking, and scientific problem-solving are increasingly emphasized—there is a compelling need to implement instructional media that promote deeper cognitive engagement and enhance representational competence (Chisunum & Nwadiokwu, 2024).

Technological advancements have introduced Augmented Reality (AR) as a powerful medium capable of addressing these pedagogical challenges (Shihab et al., 2023). AR provides interactive three-dimensional visualizations that allow learners to manipulate molecular structures, observe bonding interactions in real time, and bridge the gap between abstract theoretical constructs and tangible perceptual experiences (Abdinejad et al., 2021; Khairani & Prodjosantoso, 2023). This multimodal representational affordance has the potential to support more coherent mental model formation and reduce the intrinsic cognitive load associated with complex chemical concepts (Reyes & Villanueva, 2024). Meanwhile, narrative-based comics have gained recognition as pedagogical tools that facilitate conceptual understanding through storytelling, sequential visualization, and contextualization (Fitriani & Leton, 2024). Comics offer an accessible narrative structure that can guide learners through complex reasoning pathways, enhance their engagement, and promote cognitive coherence by integrating affective and cognitive dimensions of learning (Rasmet et al., 2025).

The integration of AR into comic-based instructional materials represents an emerging pedagogical innovation that capitalizes on the strengths of both media (Kasman, 2025). Whereas AR provides dynamic, immersive visualizations, comics offer narrative continuity and scaffolding that help students connect representational forms and sustain cognitive engagement (Calvert & Hume, 2022). This combination presents a theoretically grounded approach to learning design, where multimodality, interactivity, and narrative structure converge to support students' higher-order thinking skills (Zhou & Qu, 2024; Prananta et al., 2024). Preliminary findings from exploratory classroom trials of AR-based comic prototypes indicate promising outcomes: students demonstrate heightened engagement, improved clarity in visualizing bonding events, and early signs of enhanced analytical reasoning regarding molecular interactions (Volioti et al., 2022). Although preliminary, these observations provide a credible rationale for investigating the effectiveness of this integrated medium through more systematic empirical inquiry (Lewis et al., 2020).

Despite the growing body of literature examining AR or comics as individual tools in science education, a clear gap remains (Akcanca, 2020). Existing studies predominantly isolate these media rather than exploring how their integration may produce synergistic cognitive benefits (Zou et al., 2025). Moreover, research focusing on chemical bonding frequently centers on conceptual acquisition alone, with limited attention to the attainment of broader cognitive outcomes such as visual–spatial reasoning, integrative thinking, and scientific explanation skills (Kuit & Osman, 2021). The scarcity of studies examining AR-based comics as a unified intervention—particularly in the context of fostering students' thinking skills—reveals a theoretical and practical gap that warrants systematic exploration (Lampropoulos et al., 2022). This gap not only delineates the novelty of the present research but also highlights the need to reconceptualize chemistry instruction through multimodal, cognition-oriented learning environments.

In situating itself within previous scholarship, this research acknowledges and supports earlier claims regarding the pedagogical strengths of AR and narrative-based media (Aura et al., 2021). At the same time, it extends and refines prior work by integrating both modalities into a cohesive instructional design grounded in cognitive principles (Caskurlu et al., 2021). The present study adopts a research stance that builds upon existing findings while simultaneously challenging the implicit assumption that AR or comics alone are sufficient to enhance higher-order cognitive outcomes (O'Sullivan, 2023). By merging immersive visualizations with narrative scaffolding, this research proposes a more comprehensive instructional model that may address limitations observed in earlier approaches (Beck et al., 2023).

Based on this identified gap and theoretical rationale, the purpose of this study is to integrate AR-based comics into chemical bonding instruction and examine their potential to enhance students' thinking skills. The investigation aims to advance theoretical perspectives on representational competence in chemistry education while also providing practical implications for the development of multimodal instructional materials that align with the cognitive demands of contemporary science learning.

Method

This study employed a quantitative method with a quasi-experimental design of the Non-Equivalent Control Group type. The research subjects were 40 eleventh-grade students of MA DDI Padaelo. The sample was divided into two groups: 20 students from class XI-1 as the experimental group, who received treatment through the use of an Augmented Reality (AR) application in a Comics (PjBL) model, and 20 students from class XI-2 as the control group, who were taught using the PjBL model without AR media.

The independent variable in this study was the use of AR application media, while the dependent variable was students' critical thinking skills. Data were collected using three main instruments: An essay test consisting of 12 questions developed based on critical thinking skill indicators; An observation sheet with an assessment rubric based on Bloom's Taxonomy; and Documentation of learning activities.

The research instruments were validated by two experts in chemistry education and subsequently tested for reliability using Cronbach's Alpha. Data were analyzed using descriptive statistics (mean and standard deviation), prerequisite tests including the Shapiro–Wilk normality test and Levene's homogeneity test, N-Gain calculations, and an Independent Sample t-test to determine differences in critical thinking skills between the two groups. All data analysis procedures were performed using SPSS 25 for Windows.

Result and Discussion

The critical thinking skills pre-test was administered to students prior to the learning process in order to identify their initial ability in critical thinking. The pre-test results are presented in Table 1.

Table 1. Pre-test results of critical thinking skills

Data	Control Group Interval	Experiment Class
N	20	20
Highest Score	64	67
Lowest Score	26	33
Average	47.35	50.00
Standard Deviation	10.85	10.55

The pre-test results of critical thinking skills indicate that the initial abilities of both classes were relatively balanced. The experimental class had an average score of 50.00, while the control class achieved an average of 47.35, indicating a difference that was not statistically significant. Table 1 presents the initial condition of students' critical thinking skills based on the pre-test results. The experimental class demonstrated a slightly higher mean score than the control class. In addition, the highest and lowest scores in both classes showed similar distributions, as did the standard deviations. These findings indicate that the critical thinking abilities of students in both classes prior to the treatment can be considered equivalent.

After the learning process was carried out in each class, students were given a post-test to determine their critical thinking skills after receiving the treatment. The post-test results are presented in Table 2.

Table 2. Critical thinking skills post-test results

Data	Control Group Interval	Experiment Class
N	20	20
Highest Score	88	88
Lowest Score	50	50
Average	65.30	75.75
Standard Deviation	13.07	10.12

A significant improvement was observed in the experimental class. The average post-test score for critical thinking skills reached 75.75, which was higher than that of the control class, which only achieved an average score of 65.30. These findings indicate that AR- and PjBL-based learning is more effective in stimulating students' analytical, evaluative, and reflective abilities. As shown in Table 2, the improvement in post-test results for critical thinking skills was greater in the experimental class, with an average score of 75.75, compared to the control class, which only reached 65.30. The lower standard deviation in the experimental class (10.12) suggests a more even distribution of learning outcomes. This condition indicates that all students experienced a more consistent improvement in critical thinking skills after the implementation of AR-based learning. Thus, the effectiveness of this approach is reflected not only in the higher average scores but also in the more uniform distribution of values, as indicated by the lower standard deviation. This demonstrates that the learning method is capable of accommodating diverse student learning characteristics.

Before conducting the hypothesis testing, a normality test was performed on the pre-test and post-test data of critical thinking skills in both the control and experimental classes to ensure that the data were normally distributed. The normality test used the Shapiro–Wilk method, and the significance values are presented in Table 3.

Table 3. N-Gain value data for critical thinking skills

Data	Control Group Interval	Experiment Class
N	20	20
Highest Score	0.53	0.73
Lowest Score	0.18	0.36
Average	0.29	0.49
Category	Low	Medium

The average N-Gain value of questioning skills in the experimental class reached 0.49, which falls into the moderate category, while the control class only achieved 0.29, classified as low. This result indicates that the AR-PjBL approach is effective in enhancing students' cognitive participation. Table 3 presents the N-Gain values of students' critical thinking skills after the learning intervention. The experimental class obtained an average N-Gain of 0.49 (moderate category), whereas the control class reached only 0.29 and was categorized as low. This difference further confirms previous findings that the AR-PjBL approach is more effective in improving students' critical thinking skills. In addition, the highest N-Gain value in the experimental class (0.73) indicates that some students experienced a substantial improvement. Prior to hypothesis testing, normality tests were conducted on the pre-test and post-test data of questioning skills in both the control and experimental classes to ensure that the data were normally distributed. Subsequently, normality tests were also performed on the pre-test and post-test data of critical thinking skills for both classes. The results of the Shapiro–Wilk test are presented in Table 4.

Table 4. Normality test

Control Class		Experiment Class		Explanation
Pre-Test	Post-Test	Pre-Test	Post-Test	
0.13	0.79	0.48	0.10	Normally Distributed

Since all significance values are greater than 0.05, the pre-test and post-test data on critical thinking skills in both classes are normally distributed. Therefore, the data meet the normality assumption required for subsequent parametric statistical analysis. Levene's Test shows a significance value greater than 0.05, indicating that the variances of the data between the two classes are homogeneous, as presented in Table 5.

Table 5. Homogeneity test

Test	Leven's Statistic	df1	df2	significance	Explanation
Pre-test	0.032	1	38	0.860	Homogen
Post-test	1.251	1	38	0.270	Homogen

Since the significance values of the pre-test and post-test are greater than 0.05, the variance of the pre-test and post-test data on critical thinking skills can be considered homogeneous. The analysis results indicate a very significant difference in critical thinking skills between the control class and the experimental class (p-value < 0.05), demonstrating the effectiveness of the Augmented Reality–based Comics model, as shown in Table 6.

Table 6. Significance test

Hipotesis test	t	df	Sig. (2-tailed)
0.768	3.519	38	0.001

A significance value of 0.001< 0.05 indicates that there is a significant difference between the control class and the experimental class in students' critical thinking skills after the learning treatment was implemented. In addition to analyzing the overall results, this study also examines students' achievement based on each indicator of critical thinking skills. The evaluation of these indicators includes five main aspects, namely: providing simple explanations; building basic skills; drawing conclusions; providing further explanations; and organizing strategies and tactics. All of these aspects are interrelated in assessing students' ability to understand problems, identify relevant information, and draw logical conclusions. Pre-test and post-test data from the control class and the experimental class are presented to identify differences in improvement for each indicator, as shown in Table 7.

Table 7. Percentage of pre-test results for critical thinking skills indicators

Indicator	Control Class		Experiment Class	
	Percentage (%)	Category	Percentage (%)	Category
Interpretation	31.25	Less	46.25	Rather
Analysis	27.5	Less	40	Less
Inference	22.5	Less	38.75	Less
Evaluation	40	Rather	43.75	Rather
Eksplanation	28.75	Less	35	Less
Self-regulation	35	Less	36.25	Less

The average level of students' critical thinking skills in the pre-test indicated that the control class achieved 30.83% and the experimental class 40%, with both results still categorized as low. When examined by individual indicators, the experimental class demonstrated higher performance in almost all aspects, namely: interpretation, with the control class at 31.25% (low) and the experimental class at 46.25% (moderate); analysis, with the control class at 27.5% (low) and the experimental class at 40% (low); inference, with the control class at 22.5% (low) and the experimental class at 38.75% (low); evaluation, with the control class at 40% (moderate) and the experimental class at 43.75% (moderate); explanation, with the control class at 28.75% (low) and the experimental class at 35% (low); and self-regulation, with the control class at 35% (low) and the experimental class at 36.25% (low). Nevertheless, these findings indicate that students' critical thinking skills in both classes still require improvement. Although differences exist between the control and experimental classes, the pre-test results generally show that students' critical thinking skills remain at a low level. This suggests that both the conventional instructional method applied in the control class and the initial approach used in the experimental class had not yet produced a significant impact on the development of students' critical thinking skills.

The percentage of each critical thinking skills indicator in the post-test scores for the control class and the experimental class is presented as shown in Table 8.

Table 8. Percentage of post-test results for critical thinking skills indicators

Questioning Skill Indicator	Control Class		Experiment Class	
	Percentage (%)	Category	Percentage (%)	Category
Interpretation	77.5	Great	82.5	Rather
Analysis	67.5	Great	88.75	Less
Inference	70	Great	77.5	Less
Evaluation	77.5	Great	87.5	Rather
Eksplanation	61.25	Great	83.75	Less
Self-regulation	58.75	Rather	77.5	Less
Average	68.75	Great	82.91	Excelent

Overall, the experimental class achieved an average score of 82.91%, which falls into the very good category, whereas the control class obtained an average of 68.75%, categorized as good. These results indicate that the learning process implemented in the experimental class was more effective in enhancing students' critical thinking skills. When examined in detail across individual indicators, the experimental class demonstrated higher performance on all aspects, namely: interpretation, with 82.5% in the experimental class and 77.5% in the control class; analysis, with 88.75% in the experimental class and 67.5% in the control class; inference, with 77.5% in the experimental class and 70% in the control class; evaluation, with 87.5% in the experimental class and 77.5% in the control class; explanation, with 83.75% in the experimental class and 61.25% in the control class; and self-regulation, with 77.5% in the experimental class and 58.75% in the control class. All indicators exhibited more substantial improvement in the experimental class, suggesting that the Augmented Reality–based comic was more effective in optimally developing students' critical thinking skills. These findings further support the assumption that the integration of innovative technologies, such as Augmented Reality, within the Comics framework not only enhances student engagement but also deepens students' conceptual understanding (Hidayat et al., 2024).

Overall, the findings indicate that the integration of comic-based Augmented Reality technology makes a positive contribution to the learning of chemical bonding, particularly in enhancing students' critical thinking skills (Tanjung & Louise, 2024; Kasman et al., 2025). These results are consistent with the studies by Kuswinardi et al. (2023), which demonstrate the effectiveness of AR media in increasing student engagement and understanding. Augmented Reality facilitates conceptual understanding through three-dimensional visualizations that support meaningful learning, while also providing opportunities for active exploration and student reflection. Project-based learning supported by interactive media offers a more holistic and in-depth learning experience and encourages students to collaborate and construct knowledge independently. Thus, the integration of comic-based AR serves as a strategic alternative for improving the quality of learning in the digital era (Jannah & Putra, 2024).

Conclusion

The findings of this study demonstrate that integrating Augmented Reality–based comics into chemical bonding instruction effectively strengthens students' critical thinking skills. The intervention promotes deeper cognitive engagement by enabling learners to visualize abstract molecular interactions through immersive three-dimensional representations while simultaneously benefiting from the narrative scaffolding provided by comics. This multimodal learning environment supports the development of higher-order thinking processes, as reflected in the experimental group's significantly higher post-test performance, superior N-Gain scores, and more consistent improvement across all indicators of critical thinking. Conceptually, the study underscores the pedagogical value of combining interactive visualization technologies with structured narrative media to reduce cognitive load, enhance representational competence, and foster analytical reasoning in complex chemistry topics. The research contributes to the growing discourse on innovative digital learning tools by offering empirical evidence that AR-based comics can serve as a transformative instructional model capable of elevating students' cognitive outcomes. The impact of this study lies in its potential to guide the design of future multimodal learning resources and inform educational practices that seek to improve the quality of science learning in increasingly digital classrooms.

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Author Contributions

Conceptualization, Risqah Amaliah Kasman and Muhammad Fuad; methodology, formal analysis, writing—original draft

preparation, project administration, funding acquisition, Risqah Amaliah Kasman; software, visualization, Muhamad Fadli; validation, Risqah Amaliah Kasman, Muhammad Fuad and Hastuti Agussalim; investigation, Risqah Amaliah Kasman, Nudia Tuljannah and Siti Yasya Ey Fathanah; resources, Imranah; data curation, Nudia Tuljannah; writing—review and editing, Muhammad Fuad and Hastuti Agussalim; supervision, Muhammad Fuad. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

There is no conflict of interest.

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