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# Development of AR Comics for Differentiated Chemistry Learning: Catalyzing Students' Critical Thinking

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**ABSTRACT:** To bridge the gap in visualization and interactivity found in traditional chemistry tools, this study developed an AR-powered comic using differentiated instruction to help students navigate the spatial complexities of molecular geometry while sharpening their critical thinking.The product was developed using the 4D model (Define, Design, Develop, Disseminate) and integrated visual storytelling, interactive 3D molecular visualisations, and an instructional song to support multimodal learning. Five experts validated the media and content, indicating high validity (media = 89.5%; content = 91%). Effectiveness was examined using a one-group pretest-posttest design with 30 Grade 11 students. Shapiro–Wilk results confirmed normal distributions for pretest and posttest scores ($p = 0.278$; $p = 0.324$). A paired-samples *t*-test showed a significant improvement in students' critical thinking after the intervention ($t(29) = -11.524$, $p < 0.001$). Learning gains were moderate (n-gain = 0.40), with the strongest improvements in supposition and integration but inference and decision-making require further reinforcement through targeted scaffolding, such as the inclusion of guided inquiry prompts or interactive decision-making tasks within the AR interface that direct students to evaluate electron pair repulsions and conclude molecular properties based on their 3D observations. Overall, the AR differentiated comic is a promising medium for strengthening critical thinking in chemistry differentiated learning.

**Keywords:** development, comics, augmented reality, differentiated learning, critical thinking

## INTRODUCTION

Critical thinking is widely recognised as a core competency essential for students to navigate the complexities of the 21st century, particularly in chemistry education, where learners are expected to analyse data, interpret abstract concepts, and solve scientific problems through logical reasoning [1, 2]. Despite its recognised importance, research consistently reports low levels of critical thinking among high school students, which is often attributed to traditional instructional approaches that prioritise memorisation over conceptual reasoning [3, 4, 5].Teaching practices that rely on passive learning activities, such as note copying and factual recall, limit students' opportunities to engage in cognitive processes such as critical thinking [6, 7]. Calls for pedagogical reform have highlighted the need for more innovative approaches, including Differentiated instruction, Augmented Reality and Comics media, which have been shown to improve student engagement and critical thinking outcomes [8, 9, 10]. By shifting the focus from rote learning to active exploration, these innovative tools provide the necessary cognitive stimulus for students to practice evaluative and analytical skills, which are the hallmarks of critical thinking development [11, 12, 13].

Differentiated instruction, which involves modifying content, processes, and learning outcomes based on students' readiness levels, learning profiles, and interests, has emerged as a promising approach to address the lack of critical thinking in science education [14, 15, 16]. This pedagogical model encourages meaningful engagement by allowing students to access material suited to their cognitive needs, which can enhance deeper learning and promote analytical thinking. Despite its potential, implementing differentiated instruction in topics that are highly abstract, such as molecular geometry, presents considerable challenges. Students often struggle to understand molecular shape and spatial arrangement due to the invisible and conceptual nature of the subject matter. A study by

Setianingsih [17] revealed that only 2.78% of students exhibited very high levels of critical thinking when learning molecular geometry, while the majority demonstrated poor conceptual mastery. This difficulty suggests that differentiated instruction alone may be insufficient unless supported by appropriate visual and interactive learning media. Recent research has called for innovative tools that complement instructional strategies with concrete visual representations of abstract scientific phenomena [18]. Differentiated instruction facilitates critical thinking by ensuring that every student operates within their Zone of Proximal Development, allowing them to engage in complex logical reasoning that is tailored to their specific readiness level.

The subject of molecular geometry demands students to synthesise information from multiple representational levels, including macroscopic observations, submicroscopic particle models, and symbolic notation. These cognitive tasks become more complex when learners are required to comprehend theories such as the Valence Shell Electron Pair Repulsion (VSEPR) and hybridisation, which are both highly abstract and non-observable [18]. Misconceptions are common, particularly among students who lack spatial reasoning or the ability to mentally visualise three-dimensional molecular structures. Instructional limitations, including the continued use of traditional, text-based resources, often exacerbate students' difficulties in grasping the multidimensional nature of these concepts [6, 7]. To overcome these barriers, instructional strategies must integrate dynamic and visual media that can make invisible chemical structures tangible. Pedagogical tools that enable interactive exploration of molecular forms are critical for scaffolding students' conceptual development. Educators require both content expertise and technological fluency to deploy such tools effectively, particularly in the context of differentiated instruction [11, 12, 13]. By providing concrete visuals, these tools reduce the extraneous cognitive load associated with mental rotation, thereby freeing up cognitive resources for higher-order analysis and the evaluation of scientific arguments.

Augmented Reality (AR) offers significant potential in enhancing chemistry learning, particularly in visualising molecular structures through interactive three-dimensional models. Tools like MoleculAR allow students to manipulate and observe virtual molecules in real-time, facilitating spatial understanding and increasing engagement [19]. Although AR effectively supports visual learning, its impact may be limited without narrative or emotional components that sustain student motivation and cognitive involvement [20]. Comics, which incorporate sequential storytelling and simplified visuals, have been shown to improve content retention and clarify complex concepts [21]. The integration of AR and comics into a single instructional medium termed augmented reality comics has the potential to address both the cognitive and affective dimensions of science learning. This approach aligns with the principles of differentiated instruction by supporting various learning modalities and offering personalised entry points to content [22]. An instructional framework that merges technological interactivity with narrative structure can therefore provide a more holistic learning experience, particularly in complex chemistry topics like molecular geometry. This multimodal synergy fosters critical thinking by providing diverse entry points to content such as the AR components allow for empirical observation and 3D analysis, the comic provides a narrative context for logical inference, and the instructional audio reinforces clarity of VSEPR rules, allowing students to focus more on analytical application rather than basic terminology recall.

Existing studies have explored the impact of AR and comics individually, but few have investigated their integration within a differentiated instruction model for chemistry education. Most available research remains fragmented, lacking comprehensive insight into how the combination of these media could enhance critical thinking, especially in abstract domains such as molecular geometry [18, 21]. Addressing this gap requires the development and empirical evaluation of adaptive instructional tools that not only visualise scientific concepts but also foster reasoning and analysis. Combining AR and comics in a differentiated learning environment could provide a strategic means of bridging conceptual gaps while supporting students' individual cognitive profiles. This study aims to design and test the effectiveness of augmented reality comics integrated with differentiated instruction for improving critical thinking among senior high school students learning molecular geometry. The proposed instructional model is expected to contribute to the advancement of chemistry education by introducing an innovative, research-informed solution to persistent conceptual and pedagogical challenges. A stronger emphasis on integrating technology and pedagogy is crucial for equipping students with the skills necessary for success in a complex scientific world [8, 10].

## RESEARCH METHODS

### Materials and Tools

This research was conducted during the second semester of the 2024/2025 academic year in two senior high school classrooms located in Semarang, Central Java, Indonesia. The study involved both expert validation and trials. The research subjects consisted of:

1. 30 students from Grade XI
2. 5 experts for media and content validation
3. 2 chemistry teacher

The following revisions were to measure cognitive gains using validated critical thinking instruments. Due to the specific sample size and geographical focus in Semarang, this study is positioned as a pilot project aimed at providing a research-informed foundation for broader implementation of AR-integrated differentiated instruction in chemistry education. Meanwhile, the instruments used in this research included:

1. Questionnaires for measuring the students' learning style and interest
2. Validation sheets for media and content experts, which focused on two main aspects:
   a. Content validity: Content Alignment, Arrangement, and Linguistics
   b. Media validity: Presentation, Overall Appearance, Media Impact on Learning Strategy

   The scores from expert validation were analyzed using a 4-point Likert scale (1–4). Equation (1) was used to determine the validity percentage.

$$P = \frac{\Sigma x}{\Sigma xi} 100\% \quad (1)$$

Within the context of this formula, the variable *P* represents the validity percentage, while Σx and Σxi denote the sum of the obtained scores and the total possible scores, respectively.

**TABLE 1**. Category of Expert Validation

| Percentage Range | Category |
|---|---|
| 0 < P ≤ 20% | Very Inappropriate |
| 20% < P ≤ 40% | Inappropriate |
| 40 % < P ≤ 60% | Fairly Appropriate |
| 60 % < P ≤ 80 % | Appropriate |
| 80% < P ≤ 100% | Very Appropriate |

(Source: Ernawati [26])

3. Pre-test and post-test instruments for assessing students' critical thinking.

   Following expert validation, field testing was conducted through trials. A one-group pretest-posttest design was employed to examine the effectiveness of the developed media in improving students' critical thinking [27]. Pretest and posttest data were analysed using statistics software. Prior to hypothesis testing, a normality test was conducted using the Shapiro-Wilk procedure (α = 0.05) to confirm that the score distributions met the assumptions for parametric analysis. After the normality assumption was satisfied, a paired-samples *t*-test was performed to determine whether there was a statistically significant difference between pretest and posttest critical thinking scores. In addition to significance testing, learning improvement was quantified using the normalised gain (n-gain) formula proposed by Hake [28], with the calculation and interpretation presented in equation (2) and Table 2.

$$\text{n} - \text{gain} = \frac{\text{score posttest} - \text{score pretest}}{\text{max score} - \text{score pretest}} \quad (2)$$

**TABLE 2**. n-gain Category

| n-gain Range | Category |
|---|---|
| g ≥ 0,7 | High |
| 0,3 ≤ g ≤ 0,7 | Medium |
| g < 0,3 | Low |

(Source: Hake [28])

**Data Collection Techniques**

1. Interview

   Interviews were conducted with 2 chemistry teachers to gain insight into instructional challenges, student learning needs, and classroom conditions. These were used during the Define stage to inform the design of the media.

2. Non-Test Instruments
Non-test instruments included learning style questionnaires forms using a 1-4 point Likert scale. The learning style questionnaire consisted of three indicators: auditory, visual, and kinesthetic preferences.
3. Test Instruments
Tests were designed to measure students' critical thinking before and after the intervention. Instruments consisted of open-ended questions and were validated by two chemistry lecturers and one high school teacher. The effectiveness of the media was measured using pretest-posttest scores analysed via saphiro wilk normality test, partial t-test and n-gain.
4. Documentation
Class data (student lists), student work, photos, and video documentation were collected during the trials to support analysis.

**Method**

This study employed a Research and Development (R&D) methodology with the objective of producing a valid, effective, and practical instructional media product in the form of augmented reality (AR) comics integrated with differentiated instruction. The research design followed the 4D model, comprising four systematic stages: Define, Design, Develop, and DisseminateThis study utilized the 4D model due to its comprehensive framework, which is ideal for the iterative nature of developing educational media. We measured the success of the final product through a combination of professional expert validation and hands-on testing in actual classrooms. Figure 1 provides a visual breakdown of how the research procedure was carried out through each of the four stages.

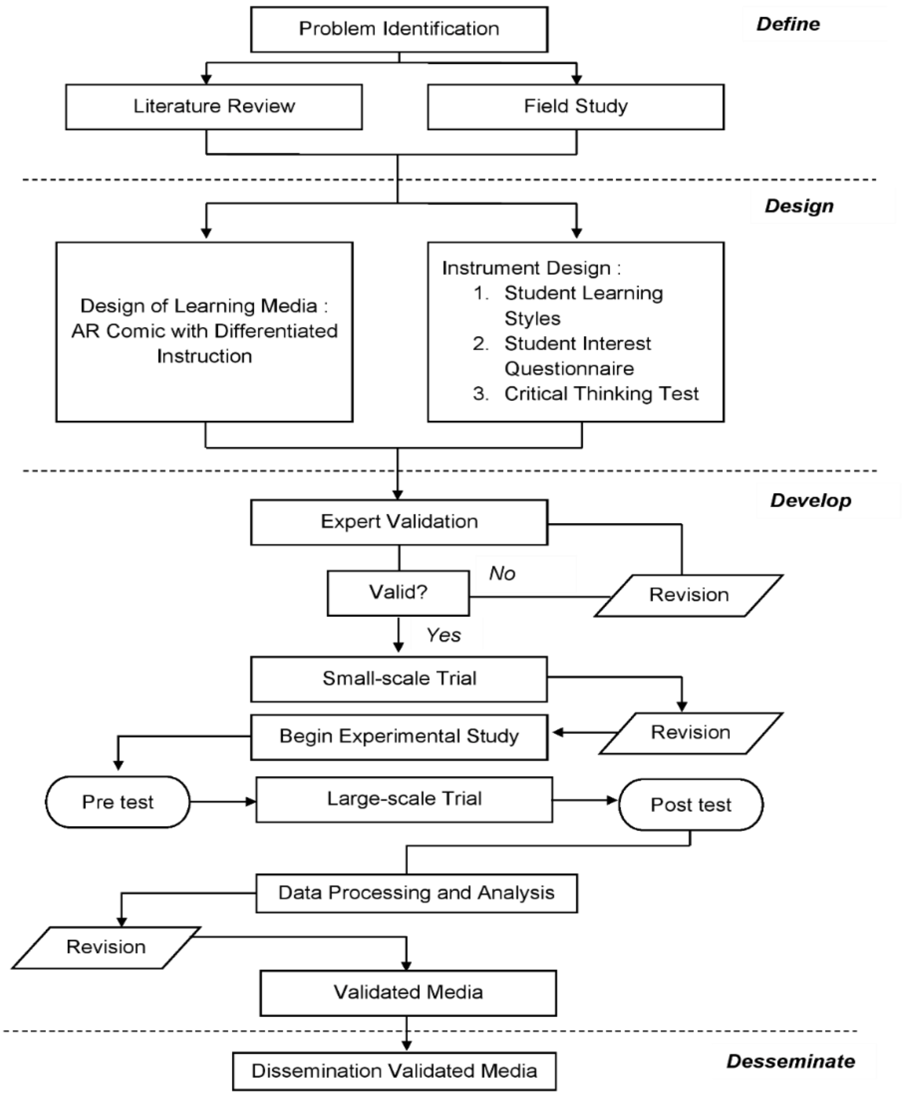


**FIGURE 1.** Research Workflow

The research followed the 4D model, beginning with the Define stage where we identified specific learning hurdles through curriculum analysis and direct interviews with chemistry teachers. Moving into Design, we crafted an initial AR comic prototype that integrated storyboarding and visual elements with tailored tools like learning style inventories and readability questionnaires. During the Develop phase, a panel of five experts (including chemistry education and visual arts expert) validated the prototype before we tested its impact on students' critical thinking using a pretest-posttest design supported by normality, t-test, and n-gain assessments. Finally, in the Disseminate stage, we secured the product's intellectual property through copyright registration and shared our results via academic publications to help other educators integrate AR and differentiated instruction into their own science classrooms.

## RESULT AND DISCUSSION

### Result

This research aimed to develop an augmented reality comic on the topic of molecular geometry, designed to support differentiated instruction in senior high school chemistry. The development process, as outlined in the 4D model, consists of four stages: Define, Design, Develop, and Disseminate

**Define**

Our research found that students often struggled with critical thinking because they were stuck in passive learning environments with very few interactive tools. We chose a research site that follows the Merdeka Curriculum's focus on differentiated instruction, yet we discovered that even though the school was trying to use these strategies, they didn't have any engaging media to actually meet their students' diverse needs. This gap highlighted the urgent need for a more creative solution, an instructional tool that could bring abstract chemistry concepts to life while fully supporting personalized learning across content, process, and product dimensions.

**Design**

We brought the project to life during the design phase by balancing several core tasks: creating a storyboard, illustrating the comic panels, and setting the layouts, while also integrating AR components and educational audio alongside our research media. To keep the story flowing naturally, we used a storyboard to align the visuals and text into a coherent sequence. This study highlights two main parts of that creative process. On one hand, we used IbisPaint to draft detailed digital illustrations, using its layering system to keep the dialogue bubbles and artwork organized for a clearer narrative. On the other hand, we developed 3D molecular structures based on VSEPR theory through Assemblr Studio. By embedding these models into the comic with AR-QR codes, students can simply use their smartphones to jump from the printed page into an interactive 3D world, as illustrated in Figure 2.

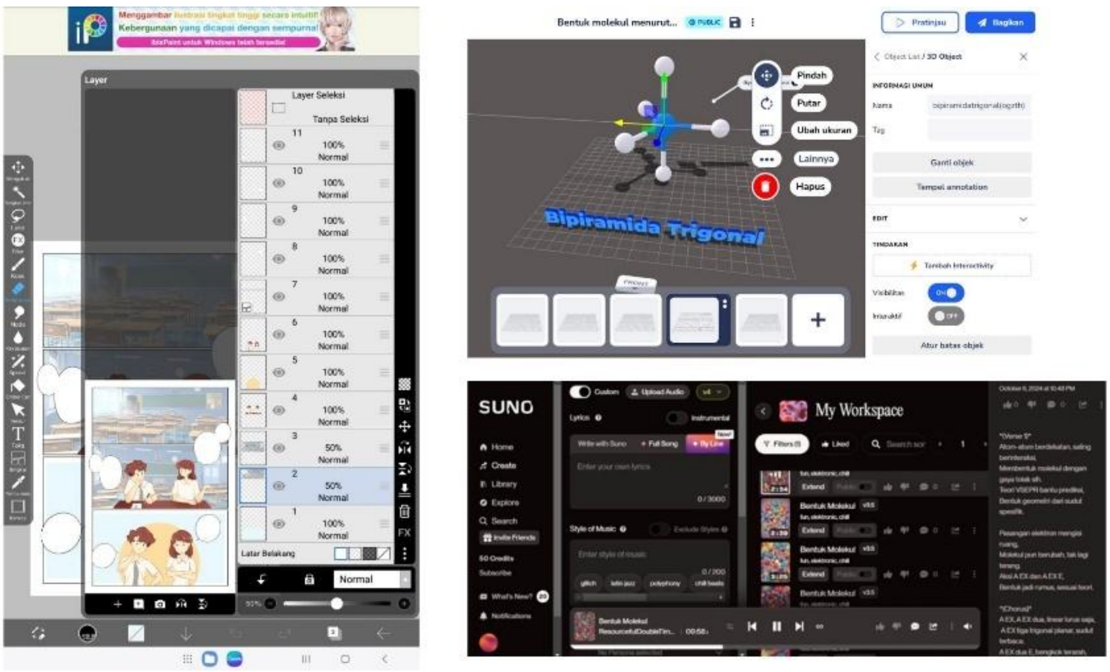


**FIGURE 2.** Design of Digital Illustration, Augmented Reality, and Educational Song

To make the experience more inclusive for auditory learners, we used Suno AI to create a custom educational song about molecular shapes and integrated it directly into the AR scenes. This combination of AI-generated audio, 3D models, and narrative visuals creates a truly multimodal environment that supports differentiated instruction. By offering these various ways to interact with the material, we can help students wrap their heads around abstract chemistry concepts while ensuring that every learner, regardless of their preferred style, feels supported.

**Develop**

We built this AR comic to be more than just a textbook, it's designed to be visually inviting and educationally structured specifically for learning molecular geometry. The book is a complete package, featuring clear instructions for both reading and launching the AR scenes, alongside character bios and the main story. On the cover, we've included everything from the title and institutional branding to the characters and molecular illustrations that lead the way. By using these character-driven narratives, we can take abstract scientific concepts and ground them in learning scenarios that students can relate to. As shown in Figure 3, every part of the design follows the principles of differentiated instruction to ensure the material is engaging and accessible for every type of learner.

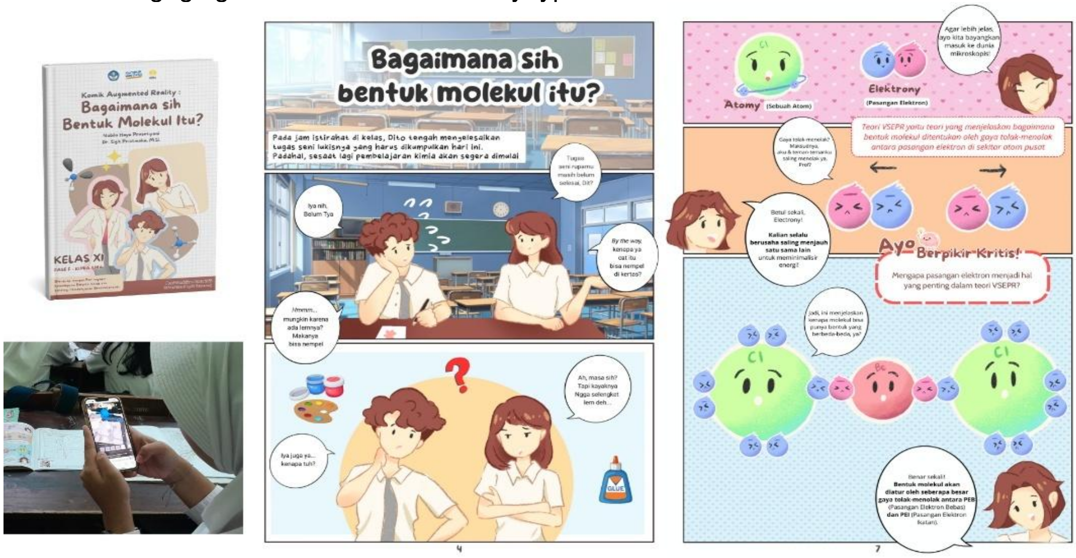


**FIGURE 3.** AR Comic for Differentiated Chemistry Learning

The differentiated instruction implemented in this study focused on content differentiation based on students' learning styles, which was embedded in the various features of the AR comic. For instance, visual learners benefited from conceptual diagrams and dialogues that emphasized spatial geometry [29], while auditory learners engaged with a molecular shape song designed to reinforce the VSEPR theory through rhythm and language [30]. Kinesthetic learners interacted directly with 3D rotatable molecular models, aligning with findings that physical interaction enhances conceptual retention [10]. Although all students accessed the full range of features, this inclusive strategy was intended to activate both dominant and non-dominant modalities simultaneously, maximizing cognitive flexibility. Research has shown that such multimodal differentiation not only supports academic gains but also nurtures metacognitive awareness and engagement in science learning environments [31].

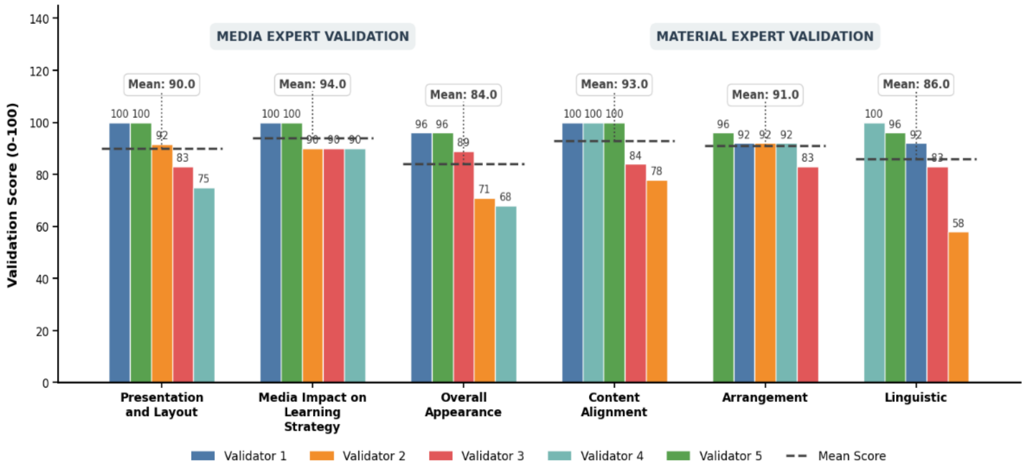


**FIGURE 4.** Media Expert Validation

The validation of the Augmented Reality (AR) comic development was conducted by five experts, comprising three chemistry lecturers, one fine arts lecturer, and one chemistry teacher. The assessment utilized a 1-4 Likert-scale rubric, covering both media and material aspects as illustrated in Figure 4. The media validation results reached an overall average score of 89.5%, placing it in the "very valid" category. While instructional impact and linguistic clarity received high consensus across validators (75%-100%), aspects of visual presentation and layout exhibited greater variability (68%-96%). This indicates a specific need for refinements in font size, layout consistency, and visual contrast to maintain both aesthetic appeal and functional accessibility. These findings align with Atong [32], and Ningrum [33] who also reported high media validity in AR comic-based instructional products.

The overall average percentage score reached 89.5%, which falls into the "very appropriate" category. Among the evaluated aspects, the media's linguistic clarity and instructional impact received the highest consensus across validators, with scores ranging from 75% to 100%, indicating that the AR comic was effective in delivering content and supporting instructional strategies. However, the presentation and overall appearance aspects showed greater variability (especially in the range of 68% to 96%), suggesting a need for visual refinement, particularly in font size, layout consistency, and storyline flow. These findings align with Atong [32] and Ningrum [34], who also reported high media validity in AR comic-based instructional products. Validator feedback recommended specific revisions, such as improving character design onomatopoeia, adding academic identity on the cover, and enhancing visual contrast on key elements to increase clarity and engagement, enhancements that are essential in maintaining both aesthetic appeal and functional accessibility in AR-based learning media as shows in Table 3 [35].

**TABLE 2**. Revision made after expert feedback

| No | Suggestions and Feedback | Before Revision | After Revision |
|---|---|---|---|
| 1 | Enhancement of colour contrast for key points conveyed to students |  |  |
| 2 | Improvement of reading flow |  |  |

<table>
<tr><th>No</th><th>Suggestions and Feedback</th><th>Before Revision</th><th>After Revision</th></tr>
<tr><td>3</td><td>Improvement of consistency in font size and speech balloon size</td><td>
</td><td>
</td></tr>
<tr><td>4</td><td>Improvement of writing conventions in accordance with standard Indonesian orthography</td><td></td><td></td></tr>
<tr><td>5</td><td>Addition of sound effect (SFX) text or onomatopoeia in the comic</td><td>
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</table>

Following the revisions based on expert validation feedback, the data were further analysed to determine whether the statistical assumptions were met prior to hypothesis testing. The normality of the pretest and posttest scores was examined using the Shapiro-Wilk test, as the sample size was fewer than 50 students (n = 30). The results, presented in Table 3, indicate that the pretest scores obtained a significance value of 0.278, while the posttest scores showed a significance value of 0.324. Both significance values exceeded the threshold of 0.05, indicating that the data were normally distributed. These findings confirm that the assumption of normality was satisfied, thereby justifying the use of parametric statistical analysis, specifically the paired-samples *t*-test, to evaluate the effectiveness of the AR comic in improving students' critical thinking skills.

**TABLE 3**. Normality Test Shapiro-Wilk

| Test | Statistics | dF | Sig. | Criteria |
|---|---|---|---|---|
| Pretest Critical Thinking | 0.958 | 30 | 0.278 | Normal |
| Posttest Critical Thinking | 0.961 | 30 | 0.324 | Normal |

**TABLE 4**. Paired t-Test

| Pair | t | dF | Sig. | Criteria |
|---|---|---|---|---|
| Pretest-Posttest Critical Thinking | -11.524 | 29 | <0.001 | Significant |

These findings confirm that the assumption of normality was satisfied, thereby justifying the use of parametric statistical analysis, specifically the paired-samples *t*-test, to evaluate the effectiveness of the AR comic in improving students' critical thinking skills. The paired-samples *t*-test results (Table 4) showed a statistically significant difference between the pretest and posttest scores, $t(29) = -11.524$, $p < 0.001$, indicating that students' critical thinking performance improved after using the AR comic. The negative *t* value reflects the direction of computation (pretest − posttest), suggesting that posttest scores were higher than pretest scores. Overall, this result provides inferential evidence that the developed AR comic contributed to meaningful gains in students' critical thinking within the one-group pretest-posttest scheme.

**TABLE 5**. N-gain Test

| Pair | Min | Max | STD | Mean | Criteria |
|---|---|---|---|---|---|
| N-gain Critical Thinking | 0.10 | 0.68 | 0.172 | 0.40 | Moderate |

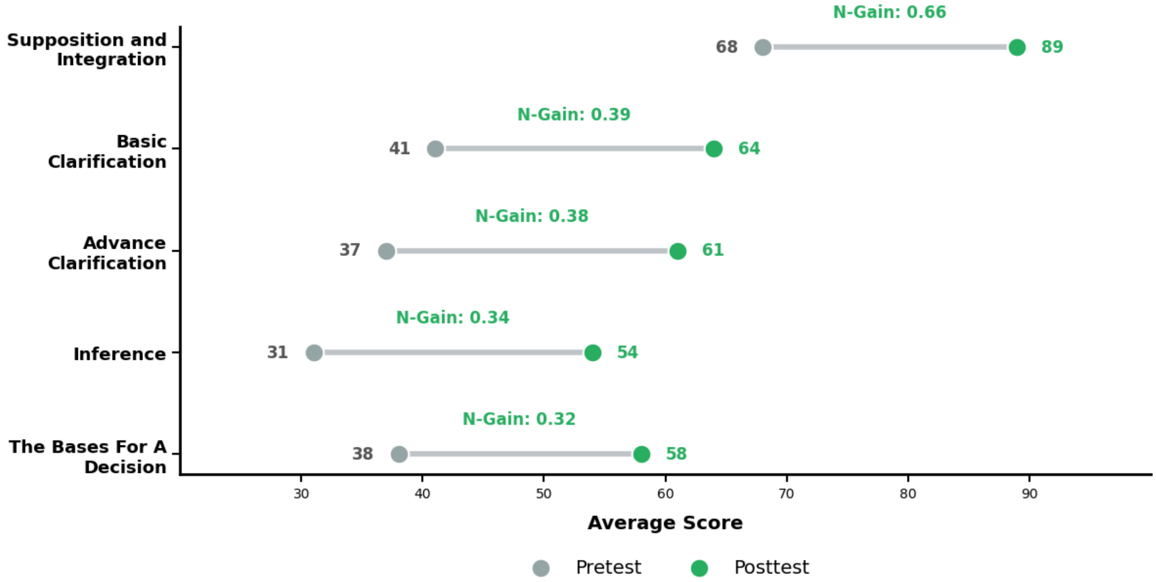


**FIGURE 5.** Dumbbell Plot Analysis on Pretest, Posttest and n-gain scores per Aspect of Critical Thinking

Table 5 and Figure 7 is a visual representation of the effectiveness of the differentiated and multimodal features in the AR comic, which shows the pretest and posttest scores across five indicators of critical thinking, along with their respective n-gain values. The highest gain occurred in supposition and integration, indicating improved reasoning and the ability to combine ideas when making decisions. Moderate gains in clarification suggest better skills in identifying issues and analysing arguments, while lower gains in inference and decision-making show continued difficulties in drawing conclusions and evaluating information. These areas typically require more structured and repeated practice [36] . These results align with findings by Saidin [10], who reported improved critical thinking and visualisation when using AR in chemistry learning. The multimodal design of the AR comic likely played a key role in engaging students cognitively. Similar improvements were also found by Haetami [37], who showed that STEM-based differentiated instruction supports problem-solving and conceptual understanding. Overall, the differentiated features in the AR comic contributed to balanced progress across multiple dimensions of critical thinking.

Hake's Scatterplot really brings to life how much of an impact the AR Comic had on students across various learning profiles. Seeing most of the data points clustered in the Medium to High Gain zones tells us that the vast majority of students significantly deepened their understanding between the pretest and the posttest. It's also important to note that these improvements were spread evenly across visual, auditory, and kinesthetic learning styles, which really speaks to how inclusive the media is. Perhaps most impressively, we can see students who initially struggled (the lower-tier color coding) accelerating into much higher gain paths, providing strong evidence that our differentiated approach helps create a more level playing field for everyone.

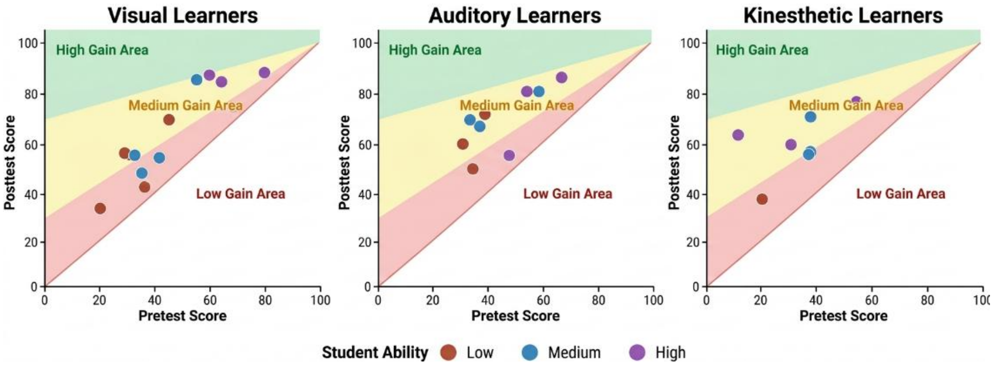

**FIGURE 6.** Effectiveness Analysis Hake's Zones by Learning Style & Ability Level

**Disseminate**

The final stage of this research was the dissemination phase, which involved the distribution and publication of the developed augmented reality comic product. In this study, dissemination was conducted on a limited scale by providing printed copies of the media to chemistry teachers and by registering the product for HaKI copyright protection under registration number EC002025027423, issued on March 4, 2025.

**Discussion**

These findings underscore how effective AR-powered comics, paired with differentiated instruction, can be for teaching molecular geometry, a topic notoriously difficult due to its abstract and spatially demanding nature. The lower levels of critical thinking we initially observed align with earlier research, suggesting that traditional, teacher-centered methods often fail to adequately develop high-level cognitive skills [38, 39]. By weaving personalized learning into an interactive AR comic, this study met diverse needs and encouraged active, inquiry-driven learning. The gains seen in the posttest show that this approach effectively sharpens critical thinking, echoing constructivist theories that prioritize student interaction and engagement [40].

High scores from media and content experts further confirm the instructional quality and scientific accuracy of the comic. Validators consistently pointed to linguistic clarity and learning impact as its strongest points, suggesting that the story-driven format really helped students grasp complex geometry. Previous studies have shown that AR-based visual narratives can ease the "mental load" by handling the tough visualization work, allowing students to focus on reasoning instead of just memorizing symbols [41, 42].That said, expert feedback also highlighted some hurdles with layout and story flow, showing the constant tug-of-war between aesthetic design and instructional function. These findings support the principles of design-based research, which views media development as an ongoing, iterative process that needs constant refining to get both the teaching and the user experience right [38].

From a results perspective, the moderate gain scores suggest the AR comic made a real difference in students' cognitive growth. The highest improvements were in supposition and integration, likely because the interactive 3D models allowed students to manipulate and visualize spatial relationships in real-time [39, 40]. In contrast, lower gains in inference and decision-making show that these evaluative skills remain a challenge, as they require more practice and specific guidance. This pattern fits with Ennis's framework, which suggests that high-level evaluation skills develop more slowly than basic analysis and are heavily influenced by long-term exposure to problem-based learning [36]. To address this, the study suggests an instructional implication: future media should incorporate "targeted scaffolding", such as explicit guided inquiry prompts or interactive tasks that require students to evaluate their 3D observations and make evidence-based decisions, rather than just observing the models.

The differentiated instruction framework embedded in the AR comic played a pivotal role in accommodating diverse learning styles and promoting equitable learning outcomes. The comparable n-gain scores among visual, auditory, and kinesthetic learners indicate that the multimodal design successfully mitigated potential disparities in learning achievement. Notably, auditory learners demonstrated the highest average n-gain, underscoring the pedagogical value of integrating audio elements, such as narrative dialogue and thematic songs, into science instruction. Cognitive multimedia learning theory suggests that presenting information through multiple sensory channels can enhance retention and conceptual understanding by promoting dual coding and cognitive flexibility [43]. By enabling students to engage with content through visual, auditory, and kinesthetic modalities simultaneously, the AR comic not only supported differentiated instruction but also fostered metacognitive awareness. In this sense, the instructional design aligns with inclusive education principles that emphasise responsiveness to learner diversity rather than uniform instructional delivery.

Administratively, this study points to a need for better teacher training in digital tools. Tech innovation, like AR comics, only works if it's backed by solid teaching. Plus, smartphone-based AR is a cost-effective solution since it uses devices students already have, making innovative tools much more accessible [44]. Politically, this fits right in with national curriculum reforms that emphasize student-centered learning and tech integration, providing the data needed to guide future school policies.

There are limits, like the small sample size and short timeline, which means we can't apply these findings everywhere just yet. Future research should involve larger, more diverse groups such as control-trial classes, and use longer timelines, to help students master tougher skills like inference and decision-maker across various educational contexts.

## CONCLUSION

This study concludes that the development of an augmented reality comic integrated with differentiated instruction is both valid and moderately effective in improving senior high school students' critical thinking skills in learning molecular geometry. The media underwent expert validation involving five reviewers, four university lecturers and one high school chemistry teacher, which resulted in a media validity score of 89.5 percent and a content validity score of 91 percent, both falling into the "very valid" category. Effectiveness was evaluated through a pretest and posttest design involving 30 students, yielding a normalised gain score of 0.4, which is categorised as moderate. The highest improvement was observed in supposition and integration indicators, suggesting enhanced reasoning and synthesis abilities, while moderate gains were noted in clarification and advanced clarification. Lower gains in inference suggest that further instructional reinforcement may still be necessary in those areas. The innovation of this study lies in the integration of visual, auditory, and kinesthetic elements within a narrative comic structure, enhanced by augmented reality features such as three-dimensional molecular models and an educational song about molecular shapes. This multimodal approach not only aligned with the principles of differentiated instruction but also demonstrated the potential to engage diverse learner profiles more effectively than traditional media. These findings highlight the pedagogical value of combining narrative-based learning with immersive technology to address abstract chemistry content, thereby supporting critical thinking and advancing the quality of science education in line with 21st-century learning.

### Authors'contribution

- ***Conceptualization***: *Nabila Hayu Prasetiyani*
- ***Data curation***: *Nabila Hayu Prasetiyani*
- ***Formal Analysis***: *Nabila Hayu Prasetiyani and Sigit Priatmoko*
- ***Methodology***: *Nabila Hayu Prasetiyani and Sudarmin*
- ***Project administration***: *Sigit Priatmoko*
- ***Supervision***: *Sudarmin and Edy Cahyono*
- ***Visualization***: *Nabila Hayu Prasetiyani*
- ***Writing – original draft***: *Nabila Hayu Prasetiyani*
- ***Writing – review & editing***: *Nabila Hayu Prasetiyani and Sigit Priatmoko*

*All authors have read and agreed to the published version of the manuscript.*

### Ethics Statement

*This research involved human subjects who had given informed consent to participate. All participants received treatment in accordance with their rights, dignity, and applicable research ethics principles.*

### Data availability statement

*The data will be available upon request.*

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*for the purposes of translating the manuscript into English and assisting in the visualization of research graphics. The authors have reviewed and revised the generated content and assume full responsibility for the final version of this publication.*

**Conflicts of Interest**

*The authors declare no conflicts of interest.*

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