

## THE EFFECTIVENESS OF AUGMENTED REALITY-BASED PHYSICS LEARNING USING ASSEMBLR EDU ON STUDENTS' CRITICAL THINKING SKILLS

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### Abstract :

In order to achieve conceptual understanding rather than rote memorization, students must analyze information, connect multiple representations, and evaluate solutions logically. This is why critical thinking is a fundamental requirement in 21st-century physics education, especially for abstract topics like fluids. The purpose of this study was to determine how well students' critical thinking abilities on fluid issues may be improved by Augmented Reality (AR)-based physics instruction utilizing the Assemblr Edu platform. At a public senior high school in Bengkulu City (N = 78), two Grade XI classes took part in a quasi-experimental study using a nonequivalent control group design. There was an experimental group and a control group. An essay-style critical thinking test that was created using Ennis's indicators and verified to satisfy acceptable criteria for validity, reliability, discrimination index, and difficulty level served as the research tool. Gain scores, normality and homogeneity tests, independent samples t-tests, Cohen's d effect size, and normalized gain (N-gain) were used to examine the data in order to determine how much the students' critical thinking abilities had improved. The experimental group received a higher posttest mean score (M = 70.76) than the control group (M = 50.51), indicating a statistically significant difference ( $p < 0.001$ ) in critical thinking abilities between the two groups. The effect size ( $d = 1.31$ ) shows that AR-based instruction with Assemblr Edu significantly enhances students' critical thinking abilities. These results imply that incorporating augmented reality (AR) into physics education strengthens attempts to improve students' critical thinking abilities in static fluid issues by enabling more tangible and interactive representations of abstract fluid notions.

Keywords: Augmented Reality, Assemblr Edu, Critical Thinking

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## INTRODUCTION

Students' capacity to comprehend ideas, evaluate natural occurrences, and approach issues logically and methodically is much enhanced by physics education (Nisa et al., 2024). Critical thinking is one of the most important skills in 21st-century physics education since it allows students to reason

with data, present arguments, and reach conclusions based on scientific ideas and principles. (Marwan et al., 2025; Thornhill-miller et al., 2023).

For the aim of educational assessment, numerous critical thinking frameworks have been created. Elementary clarification, basic support, inference, advanced clarification, and strategies and tactics are the five fundamental indications of critical thinking that Ennis (2011) presented. Conversely, Facione (1998) identified six components of critical thinking: interpretation, analysis, evaluation, inference, explanation, and self-regulation. Both frameworks stress analytical, evaluative, and reflective reasoning in scientific thought, albeit using distinct terminology. Because Ennis's indicators are thought to be more applicable and simpler to operationalize in the creation of physics assessment tools, the study uses them. (Sa'idah et al., 2025; Maknun, 2020).

Physics instruction in schools is still primarily teacher-centered and emphasizes memorizing of formulas and textbook-based problem solving. These methods restrict students' use of higher-order cognitive processes and lower their critical thinking abilities, especially when it comes to contextual problem analysis (Putri et al., 2020; Ariyatun & Octavianelis, 2020; Ariani, 2020). According to preliminary interviews and classroom observations of Grade XI physics instruction at a public senior high school in Bengkulu, students struggled to relate physics concepts to everyday phenomena, relied largely on rote memorization without deep understanding, and were unable to explain concepts in their own words. These findings indicate that several Ennis's critical thinking markers, including basic support and elementary explanation, and inference—have not yet developed optimally. Therefore, an initial assessment using an Ennis-based test is needed to map students' critical thinking profiles.

Static and dynamic fluid topics require strong conceptual understanding, reasoning, and visualization skills. Students continue to experience difficulties in learning fluid concepts, and numerous misconceptions have been identified in hydrostatic pressure, Pascal's law, and Archimedes' principle (Wicaksono et al., 2019; Busyairi & Zuhdi, 2024). Limited access to technology-enhanced learning media and inadequate laboratory facilities further constrain students' understanding of dynamic fluid concepts (Fitriyawany et al., 2023). These conditions underscore the need for instructional media that not only assist students with visualizing fluid phenomena, but also motivate them to actively engage critical thinking skills when solving physics problems.

Problem-Based Learning (PBL) is a relevant pedagogical approach to addressing these challenges. In PBL, instruction begins with an authentic problem that guides students to think, investigate, and solve problems scientifically, thereby providing opportunities for the development of higher-order thinking skills (Yu & Zin, 2023; Ismail et al., 2024). PBL helps students enhance their critical thinking abilities when studying science, according to a growing body of research (Fitria et al., 2025; Rahmawati & Setiaji, 2025). Technology-based learning resources that allow meaningful conceptual inquiry and student interaction are necessary for PBL deployment to have the greatest possible impact (Siswanti & Indrajit, 2023).

A possible technological advancement for enhancing students' comprehension of complex physics ideas is augmented reality (AR) learning materials. Concrete and interactive representation of fluid dynamics is made possible by augmented reality (AR), which incorporates virtual elements into the physical world (Socrates & Mufit, 2022; Christianingrum et al., 2024). Research indicates that augmented reality (AR) enhances students' conceptual comprehension, motivation, learning outcomes, and cognitive engagement in science and physics classes (Purnama & Nurhania, 2025; Sidik et al., 2024). Through AR-assisted physics worksheets and science learning designs that focus on analysis, evaluation, and inference markers, AR has also been explicitly used to promote critical thinking abilities. (Saputri et al., 2024).

Because it offers three-dimensional visualizations that enable students to observe concepts more concretely, investigate them on their own, and build understanding through observation and analysis, Assemblr Edu is an augmented reality platform that is especially pertinent for educational purposes (Berlian et al., 2024). According to a number of studies, incorporating Assemblr Edu into instruction improves content comprehension, makes abstract concepts easier to understand, and helps students at all educational levels develop their critical thinking and problem-solving abilities (Lestari et al., 2023; Retnaningtyas et al., 2021). Additional studies have demonstrated the development and use of STEM-based learning with augmented reality (AR) utilizing Assemblr Edu in primary scientific education, with beneficial benefits on students' critical thinking abilities (Ayuningtyas et al., 2025).

The development of critical thinking abilities as described by Ennis is conceptually closely related to AR-based educational materials. While interaction with virtual objects encourages situational analysis, justification construction, and logical inference (basic support and inference), as well as the development of methodical problem-solving techniques, three-dimensional visualizations help students identify pertinent information and clarify problems (elementary clarification) (strategies and tactics). When AR is integrated within a PBL framework, students do not merely view visual representations but actively use them to explore, discuss, and evaluate solutions to authentic problems. As a result, learning becomes more active, contextual, and oriented toward the development of critical thinking skills (Aunurofiq & Setyasto, 2025).

A growing body of research demonstrates that AR is successful in enhancing students' critical thinking and conceptual comprehension of physics, and that PBL continuously improves students' critical thinking skills across educational levels (Sembiring et al., 2024). Several studies have begun to integrate PBL with AR to enhance students' critical thinking skills. However, these studies generally utilize generic AR platforms or researcher-developed media rather than Assemblr Edu. Moreover, most of them focus on non-physics subjects or target elementary-level learners (Suharti et al., 2021; Novita et al., 2025).

Bibliometric analysis of Scopus-indexed publications from 2020 to 2025 shows that the keywords augmented reality, critical thinking, and physics education appear prominently in co-occurrence networks, indicating increasing scholarly attention to critical thinking and AR integration in physics teaching (Anesti & Irwanto, 2025). Nevertheless, the keyword Assemblr Edu appears infrequently, and only a limited number of studies explicitly examine this platform for fostering critical thinking in the teaching of science, particularly at the secondary level (Handayani & Handayani, 2025; Khairunisa et al., 2024). Reviews of these studies further suggest that research integrating Assemblr Edu-based AR within a PBL model, with a specific focus on Ennis's critical thinking indicators in Grade XI fluid topics, remains rarely reported in the literature.

Despite the growing use of AR in physics education, most existing AR platforms primarily focus on visualizing phenomena rather than fostering critical thinking skills. This constraint is especially noticeable in fluid themes, where it is challenging to understand abstract processes using traditional AR simulations or static diagrams. Students may change variables, explore different situations, and solve real-world issues using Assemblr Edu's interactive three-dimensional and scenario-based simulations, which go beyond simple visualization and are not usually offered by other AR platforms. However, limited empirical evidence specifically examines how these unique capabilities of Assemblr Edu affect students' critical thinking skills in fluid mechanics at the senior high school level. Therefore, this study employs Assemblr Edu integrated with the PBL methodology to examine its effectiveness in enhancing Grade XI students' critical thinking skills on fluid topics, using Ennis's indicators as a framework.

## RESEARCH METHOD

### *Research Design*

This study employed a nonequivalent control group design and a quasi-experimental methodology. The research design used in this study is depicted in Figure 1. Pretests (O1 and O3) were administered to the experimental and control groups prior to the treatment (X), and posttests (O2 and O4) were administered following the treatment. While the control group received conventional problem-solving training and assignments, the experimental group used Assemblr Edu to study physics using augmented reality (Creswell & Creswell, 2018). Figure 1 depicts the research design.

Experimental Group	$O_1$	×	$O_2$
Control Group	$O_3$		$O_4$

Figure 1. Nonequivalent control group design

### *Research Target/Subject*

This study was carried out in a public senior high school in Bengkulu City during the first semester of the 2025–2026 school year. The school was selected because it has sufficient technology-based learning facilities and had never used the Assemblr Edu platform to teach AR-based physics, *The Effectiveness of...* (Sinta Marsila) pp:56-70

which is in line with the goals of this project. 118 Grade XI students from three classes—XI D (39 students), XI E (40 students), and XI F (39 students)—made up the population.

The research sample was purposively selected, a common approach in quasi-experimental educational research where intact classes are maintained (Creswell & Creswell, 2018). Individual random assignment was not feasible, but classes could be treated as clusters, minimizing selection bias (Siska et al., 2025). In order to minimize baseline disparities and ensure that post-treatment differences represented the impact of AR-based learning, classes with comparatively comparable academic features were purposefully selected. The selection criteria were as follows: (1) comparable academic ability based on physics scores from prior semesters; (2) similar physics lesson plans; (3) a reasonably balanced gender makeup; and (4) teaching from the same teacher. Based on these criteria, classes XI D and XI F were selected as the research samples, as shown in Table 1, which presents the average physics scores from the previous semester and served as the basis for ensuring comparable academic abilities between the selected classes.

Table 1. Previous physics report card scores

Class	N	Mean	SD
XI D	39	83.92	2.94
XI E	40	84.95	3.13
XI F	39	83.02	2.79

### Research Procedures

The research procedure consisted of three stages: preparation and planning, implementation, and analysis of research results (Figure 2). In the preparation and planning stage, the research location, population, and sample were determined. PBL-based learning supported by AR media using Assemblr Edu was prepared for the experimental group, while a problem-solving learning approach was prepared for the control group. In the implementation stage, physics learning with fluid material was carried out during five meetings with a total allocation of 13 lesson hours (1 lesson hour = 45 minutes). Before learning began, students in both groups were administered a pretest to ascertain their starting proficiency. After learning, students in both groups were given a post-test. The results analysis stage included the processing and interpretation of pretest and posttest data to determine the effectiveness of the learning applied to the research subjects as a basis for drawing conclusions.

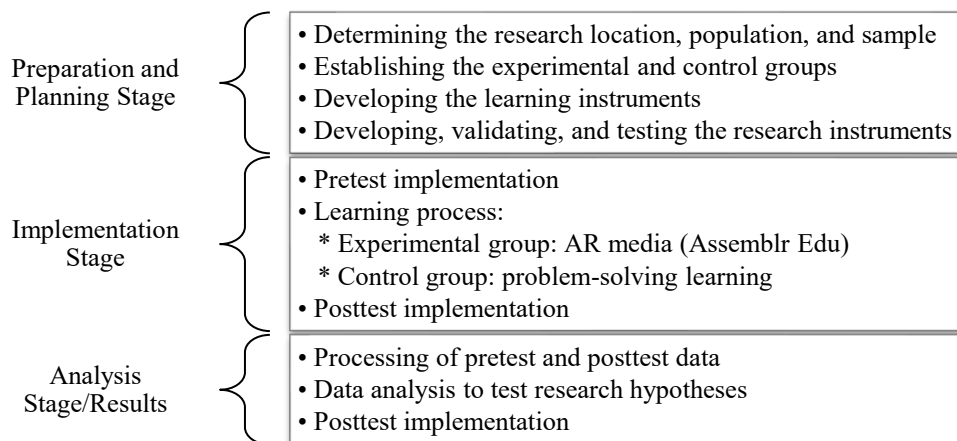


Figure 2. Research procedures

### Instruments and Data Collection Techniques

The research instrument was a test of critical thinking intended to gauge the capacity for critical thought of Grade XI students on fluid mechanics topics. The questions are compiled based on five main indicators of critical thinking skills according to Ennis (2011): Elementary clarification, basic support, inference, advanced clarification and strategies and tactics.

The critical thinking test comprised 25 essay items developed in the form of contextual stimuli aligned with Ennis' primary critical thinking indicators, allowing the questions to fully explore students' critical thinking skills through their responses. An illustration of a critical thinking stimulus is shown in

Figure 3: one question represents the main indicator of elementary clarification, and three additional questions are based on the sub-indicators a, b, and c, as listed in Table 4.

**Problem Stimulus** (Indicator: Elementary clarification)

A diver is at the bottom of a swimming pool with a depth of 3 m from the bottom of the column (Figure 3). The diver states that “The water pressure felt by his body is influenced by the surface area of the body submerged in water.”

**Questions**

- Analysis of the diver's statements based on the concept of hydrostatic pressure (Sub-indicator: focusing questions)
- Explain the factors that affect hydrostatic pressure at a certain depth (Sub-indicator: analyze arguments)
- Calculate the hydrostatic pressure experienced by a diver if the density of water weighs  $1000 \text{ kg/m}^3$ , and gravity accelerates it by  $9.8 \text{ m/s}^2$  (Sub-indicator: asking and answering questions)



Figure 3. Diver at a depth of 3 m

Prior to administering the test, items representing five main indicators of critical thinking were evaluated for construct validity by experts, including two lecturers and a physics teacher. The purpose of this evaluation was to determine the extent to which the developed items aligned with Ennis' primary indicators of critical thinking, such as elementary clarification, as well as the learning objectives of the fluid topic material based on the Merdeka Curriculum.

The assessment rubric is used as a guide to determine scores (0 to 5) for each answer to critical thinking questions, and the rubric was developed following the FRISCO principles (Ennis, 2011). The purpose of the assessment rubric is to ensure that the assessment process is conducted objectively, consistently, and in accordance with the established critical thinking skill indicators (Harjilah et al., 2019). FRISCO includes Focus (focus on the problem), Reason (reasoning), Inference (drawing conclusions), Situation (understanding the context), Clarity (clarity of explanation), and Overview (comprehensive review of the answer). Each aspect is scored on a scale of 0–5; A score of five indicates that the response is excellent, comprehensive, logical, and conceptually appropriate; a score of four indicates that the response is good but shallow; a score of three indicates that the response is adequate but still has flaws; a score of two indicates that the response is incorrect and irrelevant; a score of one indicates that the response is extremely weak; and a score of zero is assigned if the student does not provide a relevant answer. Before use, the FRISCO-based rubric was validated by two physics lecturers and a physics teacher to ensure that each indicator in the rubric represented aspects of FRISCO and was consistent with a specific critical thinking framework (Facione & Facione, 1994). Suggestions and corrections from the three validators were used to refine the content and construct validity of the rubric.

Before being used in research, test instruments and their assessment rubrics first undergo a validation stage. Test instruments are validated by one physics instructor and two physics specialists serving as validators to assess the suitability of the content, the aspects measured, and the clarity of the language used in the questions. In addition to expert validation, the test instruments are also empirically tested before being used in research. Item validity was tested using the Pearson product moment correlation coefficient. Item quality was evaluated based on discrimination power (DP) and difficulty level (DL) analyses, while instrument reliability was determined using Cronbach's Alpha. A test item is considered good if it demonstrates significant validity at  $\alpha = 0.05$ , high internal consistency (reliability coefficient approaching 1.00), a moderate difficulty index ( $0.25 \leq P \leq 0.75$ ), and satisfactory discriminating power within the acceptable range (Saputri et al., 2024).

**Data Analysis Techniques**

Data on students' critical thinking abilities in Grade XI, collected from pretest and posttest scores for the experimental and control groups, were analyzed using SPSS version 29.0.2.0. To ensure the assumptions of parametric analysis were met, gain scores (calculated as posttest minus pretest) were first examined for normality using the Shapiro–Wilk test and for homogeneity of variance using Levene's Test. Data were considered normally distributed and homogeneous if the significance value  $p > 0.05$  (Cohen et al., 2018).

After confirming that the gain scores met both normality and homogeneity assumptions, hypothesis testing was conducted using an independent samples t-test at a significance level of 5% ( $\alpha = 0.05$ ) to compare the gain scores of the experimental and control groups. Since the gain data were normally distributed and had homogeneous variances, the use of this parametric test was appropriate for quasi-experimental research (Nurwiani & Trisanti, 2025). The decision criterion was based on the significance value ( $p < 0.05$ ), indicating that the alternative hypothesis ( $H_1$ ) was accepted and the null hypothesis ( $H_0$ ) was rejected, which suggests that the learning treatment had a statistically significant effect (Nuryadi et al., 2017). To complement statistical significance, the magnitude of the treatment effect was calculated using Cohen's  $d$  based on the gain scores. The interpretation of effect size followed the criteria proposed by Cohen et al. (2018) as presented in Table 2.

Table 2. Effect size interpretation

Effect size	Interpretation
0.20	Small
0.50	Medium
0.80	Large

Considering the differences in pretest scores between groups, normalized gain (N-gain) analysis was conducted to evaluate students' relative improvement in critical thinking skills, providing a more accurate assessment of the effectiveness of AR-based physics instruction using Assemblr Edu. N-gain scores were interpreted based on Hake (1998) criteria, as shown in Table 3.

Table 3. N-gain interpretation criteria

N-gain Value (g)	Interpretation
$g < 30$	Low
$0.30 \leq g < 0.70$	Medium
$g \geq 70$	High

## RESULTS AND DISCUSSION

Empirical test analysis shows that 12 items meet the validity criteria based on Pearson product moment correlation. The results of the discrimination power (DP) analysis show that all twelve items are in the fair to good category, thus able to distinguish between high and low ability students. The difficulty level (DL) of all items retained is in the moderate category, so they are neither too easy nor too difficult (Rahman & Nasryah, 2019). In addition, the instrument is deemed trustworthy, as the Cronbach's Alpha coefficient obtained from the reliability test was 0.837, which falls into the very high category and indicates good internal consistency (Hildawati et al., 2024). Based on the overall analysis results, the items that meet the criteria are determined as research instruments listed in Table 4.

Table 4. Empirical test results

Critical thinking indicators	Sub-indicators	No question	Item validity		DP (Category)	DL (Category)
			$r$ coefficient (Criteria)	$p$ -value (Criteria)		
Elementary clarification	a. Focusing questions	1a	0.407* (Fair)	0.014 (Valid)	0.37 (Fair)	0.51 (Medium)
	b. Analyzing arguments	1b	0.345* (Low)	0.040 (Valid)	0.31 (Fair)	0.65 (Medium)
	c. Asking and answering questions	1c	0.369* (Low)	0.027 (Valid)	0.28 (Fair)	0.66 (Medium)
Basic support	a. Considering whether sources are reliable or not	3a	0.339* (Low)	0.043 (Valid)	0.24 (Fair)	0.61 (Medium)

	b. Observing and considering observation reports	3b	0.368* (Low)	0.027 (Valid)	0.31 (Fair)	0.52 (Medium)
Inference	a. Considering the results of deduction	5a	0.507** (Fair)	0.002 (Valid)	0.43 (Good)	0.49 (Medium)
	b. Considering the results of induction	5b	0.420* (Fair)	0.011 (Valid)	0.33 (Fair)	0.46 (Medium)
	c. Making decisions and considering the results	5c	0.413* (Fair)	0.012 (Valid)	0.36 (Fair)	0.51 (Medium)
Advanced clarification	a. Defining terms	8a	0.659** (High)	<0.001 (Valid)	0.60 (Good)	0.44 (Medium)
	b. Identifying assumptions	8b	0.490** (Fair)	0.002 (Valid)	0.39 (Fair)	0.32 (Medium)
Strategies and tactics	a. Thinking hypothetically	9a	0.360* (Low)	0.031 (Valid)	0.28 (Fair)	0.44 (Medium)
	b. Integrating dispositions and decision-making skills	9b	0.357* (Low)	0.033 (Valid)	0.24 (Fair)	0.47 (Medium)

Note: \*\*  $p < 0.01$ ; \*  $p < 0.05$

Based on Table 4, all retained items have a coefficient value of  $r > 0.30$  and are significant at a level of  $p < 0.05$  (Sugiyono, 2013). Although there were several items with low validity, these items still showed significance and were therefore considered in the initial analysis. The low validity coefficients for several items may be related to the sub-optimal discrimination index, meaning that the ability of the questions to distinguish between high-and low-ability students was not optimal. In addition, the moderate level of difficulty indicates a relatively even distribution of answers, which has the potential to affect score variation and item correlation with the total score. These findings are in line with the results of item characteristic analysis, which show that item validity quality is related to the discrimination index and item difficulty level (Handayani & Iba, 2020). Some questions did not meet the instrument feasibility standards and were therefore excluded from the test, but were used as practice items in the student worksheets.

Descriptive statistics were used to examine the development of students' critical thinking skills in both the experimental and control groups. As shown in Table 5, the pretest results indicate that both groups had relatively comparable initial skills, although the experimental group displayed a slightly higher mean score. The experimental group's critical thinking abilities significantly improved after the intervention as compared to the control group, according to the posttest findings, indicating the success of the adopted learning strategy.

Table 5. Descriptive statistical analysis

Test	Group	Mean	SD	Median	Mode
Pre	Experimental	29.61	7.60	30.00	31.67
	Control	22.90	8.96	21.67	16.67
Post	Experimental	70.76	9.51	68.33	63.33
	Control	50.51	11.34	51.67	53.33

Table 6 presents comprehensive descriptive data to investigate the distribution of pretest results among the various components of critical thinking.

Table 6. Pretest descriptive statistics by ennis’s critical thinking indicators

Indicators	Group	Mean	SD
Elementary clarification	Experimental	34.36	16.29
	Control	23.25	13.92
Basic support	Experimental	32.82	13.36
	Control	24.86	16.83
Inference	Experimental	29.74	10.57
	Control	20.85	11.46
Advanced clarification	Experimental	24.10	16.81
	Control	21.28	10.80
Strategies and tactics	Experimental	24.62	13.54
	Control	25.38	12.32

The pretest scores across indicators were usually low and reasonably matched between the groups, as Table 6 illustrates. The groups were not equal at baseline, though, as an independent samples t-test showed a statistically significant difference in total pretest scores ( $t(76) = 3.564, p < 0.001$ ). These variations are typical in nonequivalent control group designs, where internal validity may be limited and selection bias may be introduced by group selection without random assignment (Creswell & Creswell, 2018). Posttest results across Ennis's critical thinking markers were analyzed to better understand students' learning trends while taking baseline variances into consideration, as shown in Table 7.

Table 7. Posttest descriptive statistics by ennis’s critical thinking indicators

Indicators	Group	Mean	SD
Elementary clarification	Experimental	78.12	11.02
	Control	57.58	18.62
Basic support	Experimental	82.56	10.93
	Control	51.79	16.03
Inference	Experimental	76.75	14.42
	Control	50.60	14.80
Advanced clarification	Experimental	68.72	13.79
	Control	45.38	19.04
Strategies and tactics	Experimental	54.10	16.66
	Control	43.33	12.78

When combined, the descriptive data show that, while there were minor disparities between the groups in the pretest (Table 6), the experimental group had higher mean scores in all indicators in the posttest (Table 7). While conceding that causal inferences cannot be clearly reached due to the nonequivalent group design, this pattern indicates a good tendency in the experimental group's critical thinking abilities and highlights the potential advantages of AR-based physics training utilizing Assemblr Edu.

Prior to hypothesis testing using parametric inferential statistics, the assumption of normality was examined. The Shapiro–Wilk test revealed  $p$  values  $> 0.05$  for gain scores in both groups, indicating that the data were normally distributed (Wara et al., 2025), as shown in Table 8.

Table 8. Normality test results for gain scores

Group	N	Shapiro-Wilk	
		Statistics	Sig.
Experimental	39	0.980	0.710
Control	39	0.980	0.693

Since the gain scores met the normality assumption (Table 8), Levene’s Test was applied to assess variance homogeneity, a prerequisite for parametric comparison of means (Chapitak et al., 2025).

This test uses absolute deviations from the group mean, while median- or trimmed-mean approaches (e.g., Brown–Forsythe) improve robustness for non-normal data (Demirel et al., 2025). Table 9 shows that the gain scores were homogeneous ( $p > 0.05$ ), confirming suitability for parametric tests (Malay, 2022).

Table 9. Results of the Variance Homogeneity Test for Gain Scores

	Levene statistic	df 1	df 2	Sig
Based on mean	0.350	1	76	0.556
Based on median	0.246	1	76	0.621
Based on median and with adjusted df	0.246	1	68.639	0.621
Based on trimmed mean	0.337	1	76	0.563

After confirming the assumptions, an independent samples t-test was conducted to determine whether the improvements in students' critical thinking were statistically significant. The results (Table 10) show a significant difference ( $p < 0.001$ ) between the experimental and control groups, leading to rejection of the null hypothesis ( $H_0$ ).

Table 10. Independent Sample t-Test Results for Gain Scores

	f	t	df	Sig.(2-tailed)	Mean difference	95% Confidence interval	
						Lower	Upper
Equal variances assumed	0.350	5.803	76	<0.001	13.546	8.897	18.196
Equal variances not assumed		5.803	74.325	<0.001	13.546	8.895	18.197

The gain scores of Grade XI students in the experimental group, who received AR-based physics instruction using Assemblr Edu, were significantly higher than those of the control group, which received conventional problem-solving instruction and textbook-based exercises. Cohen's  $d$ , which represents the improvement in each group, was used to evaluate practical importance in addition to statistical significance. The findings showed a significant practical impact in Table 11.

Table 11. Effect Size Results

Group	Mean gain	SD	Effect size (Cohen's $d$ )	Interpretation
Experimental	41.15	11.05	1.31	Large
Control	27.61	9.50		

The effect size ( $d = 1.31$ ) shows a significant impact based on Cohen's criterion, indicating that students in Grade XI who received AR-based physics education utilizing Assemblr Edu in fluid mechanics had greater critical thinking advances as determined by Ennis' framework. As a complementary analysis, normalized gain (N-gain) scores were calculated to describe the relative improvement in students' critical thinking skills, as presented in Table 12.

Table 12. Descriptive results of normalized gain (N-gain)

Group	Mean	Interpretation
Experimental	0.58	Medium
Control	0.35	Medium

The results indicate that the experimental group achieved a higher mean N-gain (0.58) compared to the control group (0.35), both categorized as medium improvement. This finding is consistent with the results of the independent samples t-test. Overall, these results corroborate the independent samples

t-test results (Table 10) and indicate that AR-based physics training has a beneficial impact; nevertheless, care must be taken since pretest differences and the absence of random assignment may induce selection bias.

The experimental and control groups' disparities in critical thinking skills indicate that the alignment of learning media, instructional models, and the cognitive demands of the subject matter is crucial to the success of physics training. In this study, Assemblr Edu AR media concretely visualized hydrostatic pressure, facilitating students' engagement and reasoning, as reflected in the observed gains in critical thinking (Tugirin et al., 2025). The immersive visualization afforded by AR may support students in constructing conceptual representations of hydrostatic phenomena, thereby facilitating explanation, inference, and evaluation processes as described in Ennis's framework. However, the observed improvement should be interpreted as an outcome of the specific instructional affordances of Assemblr Edu within a PBL framework, rather than as evidence of the general effectiveness of AR.

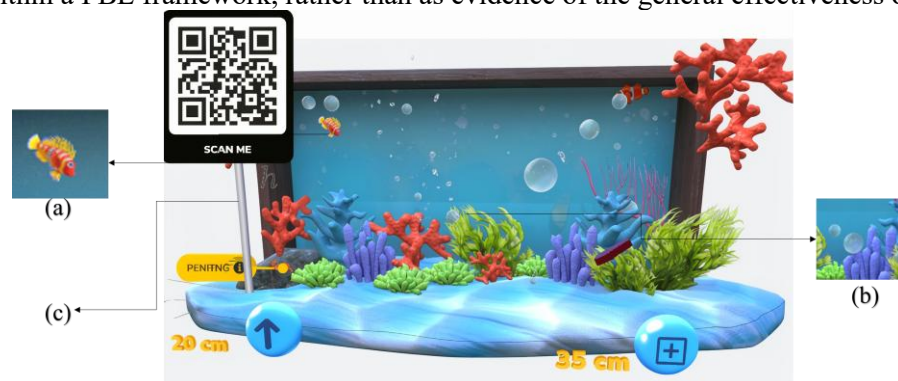


Figure 3. Assemblr Edu AR media on hydrostatic pressure material: (a) fish as a representation of object depth, (b) air bubbles as a representation of volume changes due to pressure changes, and (c) fluid depth scale.

The AR media created with Assemblr Edu, as shown in Figure 4, uses a three-dimensional aquatic scene with fish to represent object depth (Figure 4a), air bubbles to represent changes in gas volume under pressure (Figure 4b), and a measurable depth scale (Figure 4c) to visualize hydrostatic pressure. Rather than being only ornamental pieces, these components serve as manipulable representations of important physical characteristics. Students may see how decreasing bubble size correlates with increasing depth by rotating, enlarging, and repositioning the display using mobile devices. Students can link visual changes to the idea of hydrostatic pressure and the pressure–volume relationship of gases by comparing bubble volume at various depth levels shown on the scale. Students' capacity to construct fundamental support and make logical deductions is strengthened by this dynamic interplay, which turns abstract variables into visible evidence.

Students' critical thinking in fluid mechanics was greatly enhanced by the incorporation of Assemblr Edu AR into a PBL framework. Both groups had increases in all metrics, although the experimental group's improvements were consistently greater. Inference (47.01 points in the experimental group and 29.75 points in the control group) followed basic support (49.74 points in the experimental group compared with 26.93 points in the control group), which demonstrated improved evidential reasoning. While strategies and tactics showed the least improvement (29.48 and 17.95 points), advanced clarification (44.62 and 24.10 points) and elementary clarification (43.76 and 34.33 points) exhibited moderate gains, indicating that extended exposure to training is necessary for higher-order strategic and metacognitive skills. Overall, the trend shows that while strategic regulation grows more slowly, AR via Assemblr Edu most successfully boosts evidentiary and inferential aspects.

The effect size ( $d = 1.31$ ) falls within the large range, indicating strong practical significance. This value exceeds the medium effect sizes typically reported in AR-based physics learning ( $d \approx 0.5–0.8$ ) (Li et al., 2025; Chang et al., 2022). Some meta-analyses, however report similarly large effects ( $d = 1.06–1.23$ ) (Ramadhan et al., 2025; Hunaepi et al., 2023). The organized integration of AR inside the PBL framework, the novelty of the medium, and baseline pretest differences might all be contextual variables contributing to the exceptionally substantial effect seen in this study. There were only five sessions in the intervention, and conclusions about causality are limited by the nonequivalent control

group design. As a result, these findings should be seen as context-specific, showing how AR through Assemblr Edu might improve critical thinking while noting the need for more study on long-term impacts and generalizability.

These findings are consistent with prior studies reporting that AR visualization enhances engagement and promotes deeper reasoning through experimentation and immediate feedback (Radu et al., 2023). Hasan et al. (2025) similarly report increased analytical activity in AR-based physics learning. Unlike studies treating AR merely as a supplementary visualization tool, the study integrated Assemblr Edu as the primary investigative medium within PBL stages (Nabila et al., 2025; Sitompul et al., 2025). This structured inquiry combined with interactive visualization appears to have amplified reasoning processes, particularly in evidential justification and inference construction. By providing an indicator-level analysis within Ennis's framework, the study demonstrates that AR integration does not uniformly enhance all dimensions of critical thinking. This nuanced pattern refines theoretical assumptions regarding the broader effectiveness of AR in developing higher-order thinking skills. Additional evidence further supports that Assemblr Edu can enhance students' critical thinking (Ashari, 2023; Fitriana et al., 2025; Allo et al., 2025).

On the other hand, the control group's learning was mostly dependent on procedural problem-solving and instructor explanation. Interaction with phenomena remained metaphorical and two-dimensional during the conversation. Reasoning processes tended to depend more on symbolic and formula-based manipulation in the absence of dynamic depiction of variable interactions. The differences between the groups imply that Assemblr Edu serves as both a visualization tool and a cognitive scaffold that externalizes relationships between abstract variables, enabling conceptual restructuring and evidence-based reasoning.

Despite the favorable results, there are a few things to be aware of. The study's moderate sample size and single-school setting limited its applicability. The degree of progress may have been impacted by the groups' incomplete baseline equality, as shown by significant variations in pretest scores. Gain-based analysis was used to more precisely quantify relative learning progress in order to overcome this problem. Additionally, it's possible that the five-meeting intervention was insufficient to maximize the development of higher-order strategic thinking dimensions. It is advised that future studies with larger sample sizes and longer implementation times investigate the stability and applicability of these results in more detail.

Overall, students' critical thinking in fluid mechanics improved more when Assemblr Edu was included into a PBL framework, especially in the areas of evidentiary justification and inference formulation. While recognizing that the results are context-bound and should be taken cautiously, these findings demonstrate the potential of AR-supported training to increase particular aspects of critical thinking.

## **CONCLUSION**

While strategic regulation develops more slowly, this study shows that integrating Assemblr Edu within a PBL framework significantly improves Grade XI students' critical thinking skills in fluid mechanics, particularly in basic support and inference. This suggests that some aspects of critical thinking require longer or more intensive interventions. Assemblr Edu's interactive and manipulable elements serve as a cognitive scaffold, allowing students to observe, evaluate, and draw conclusions from data. The brief five-session intervention, the use of a non-equivalent control group, and differences in students' device capacity and AR technology experience are some of its limitations. Future studies should look at long-term impacts, various educational settings, and how to use interactive augmented reality platforms to further improve strategic control and metacognitive abilities.

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