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Author for correspondence:
Zetriuslita
zetriuslita@edu.uir.ac.id
Universitas Islam Riau, Pekanbaru, Riau, Indonesia

Using Problem-Based Learning-Autograph to Improve the Critical Thinking-Numeracy Ability: A Mixed Method Study in an Integral Calculus Course

Zetriuslita, Rezi Ariawan, Suripah, Ana Yulianti, Riyan Hidayat

Abstract

Background/purpose. This study aims to improve students' mathematical critical-numeracy thinking skills by applying the Problem-Based Learning-Autograph model.

Materials/methods. This study used a mixed method with a sequential explanatory strategy, and the research design is a one-group pretest-posttest design. The population included students who take the Integral Calculus course, and the sampling is a total sampling. The research instruments were mathematical critical thinking-numeracy test instruments and non-test instruments in the form of interview instruments. Data analysis was conducted using descriptive statistics and inferential statistics. Because the pre-test data were not normally distributed, a non-parametric analysis was conducted, namely the Wilcoxon Signed-Rank Test. The results of in-depth interviews were used to triangulate the data.

Results. From the Wilcoxon test, it is obtained that Asymp Sig (2-tailed) = 0.000 < α, Ho is rejected or H1 is accepted. It is concluded that there is a significant difference in students' mathematical critical thinking-numeracy skills before and after learning with the Problem-Based Learning-Autograph model. It means that the results of data analysis showed that there was an increase in students' mathematical critical thinking-numeracy skills after learning using the Problem-Based Learning-Autograph model. The students felt more engaged and motivated in the learning process, which contributed to the improvement of their skills.

Conclusion. There is an increase in students' mathematical critical thinking-numeracy skills after learning by using PBL-Autograph learning in the course of Calculus Integral, and students are motivated in the learning process.

1. Introduction

In this digital era in the 21st century, incorporating critical thinking and numerical skills into education is vital for preparing students for future challenges. Tools like Autograph not only facilitate understanding but also make learning more engaging and effective. (Hasibuan, 2016). However, critical thinking skills, this ability is often ignored by teachers in the learning process in the classroom, teachers emphasize learning to the level of knowledge and understanding, rarely to the level of analysis and evaluation (Santos Meneses, 2020). Critical thinking is a person's effort to gather, interpret, analyze, and evaluate information for the purpose of reaching reliable and valid conclusions (Cáceres et al., 2020).

According to Cockroft in Goos Merrlyn (2011), Sri Hartatik (2020) state that numeracy skills is the ability of a person in using numbers to solve practically various daily problems Meanwhile, according to (Ekowati et al., 2019) numeracy ability is the ability a person has to formulate, apply or apply, control, and evaluate mathematical problems in various contexts, including mathematical reasoning, procedural to solve a problem. This ability is important because it directly affects a person's ability to make decisions, solve problems, and live life more effectively. This numeracy skill is very necessary in mathematics, because mathematics is not only always related to formulas, but also requires reasoning power or critical thinking patterns of students in answering every problem presented (Murtiningsih et al., 2024). Numeracy can also help learners understand the role of mathematics in solving problems related to everyday life (Pulungan, 2022).

Based on data from PISA (Programme for International Student Assessment), the mathematical numeracy skills of students in Indonesia are still below the international average (OECD, 2023; Stacey, 2011). Therefore, serious efforts are needed to improve this numeracy skill. There are already numeracy guidebooks at the primary and secondary school levels produced (Elementary & Education, 2020; Algebra, 2019; Dewayani et al., 2021), but it still needs to be done at the university level, especially in integral calculus courses.

These critical thinking and mathematical numeracy skills must be developed in learning, especially for students. To develop these abilities, learning needs to be facilitated. One of them is technology-assisted learning, because with the help of technology, students can independently master learning materials, choose the accuracy of work, repeat learning materials, know their progress, and also increase effectiveness in the implementation of the learning process (Howard & Tondeur, 2023). With the rapid advancement of technology, many things have changed in various fields, especially in education. One of the technologies that is growing rapidly today is Autograph. Autograph is an interactive software designed to assist in the visualization of mathematics (Hasibuan, 2016; Telaumbanua & Zendrato, 2019). Autograph allows students and teachers to dynamically create, manipulate, and analyze various geometric shapes and mathematical functions. In the context of spatial figures, this application can provide a deeper understanding of the properties and relationships between various spatial figures. The benefits of using this Autograph application are: 1) improve students' understanding of the concept of spatial shapes through interactive visualization, 2) facilitate more interesting and interactive learning, 3) improve students' ability to solve problems related to spatial shapes, 4) equip teachers with effective tools for teaching integral calculus (Bina & Triandi, 2021; Ghozi & Hilmansyah, 2018).

Based on the above research, teachers/educators must apply Autograph in learning, which aims to improve students' critical thinking and mathematical numeracy skills. Problem-Based Learning assisted by Autograph is given the name of the learning, namely Problem-Based Learning-Autograph (PBL-Auto).

PBL-Auto begins with giving problems. After that, students in groups solve the problems given with the help of Autograph on the material of the area and volume of rotating objects in the integral

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calculus course, and ask the teacher if there are things that are not clear. After completing the discussion in groups, they were told to present the results of their discussion. Then, independently, work on problems that are integrated with mathematical critical thinking and numeracy.

Based on the above, the researcher wants to conduct a study with the title "Application of Problem-Based Learning-Autograph on Spatial Buildings Material in Facilitating the Improvement of Students' Mathematical Critical Thinking-Numeracy Ability".

The formulation of this research problem is:

1. Is there a significant difference in students' mathematical critical thinking-numeracy skills before and after learning with the Problem-Based Learning-Autograph model?

2. What is the critical thinking process, mathematical numeracy, among students who are taught with Problem-Based Learning-Autograph?

3. How do students respond to Problem-Based Learning- Autograph learning?

While the purpose of this research is:

1. To determine the improvement of students' mathematical critical thinking-numeracy skills through Problem-Based Learning-Autograph.

2. To deeply examine students' mathematical critical-numeracy thinking process through Problem-Based Learning-Autograph learning.

3. To find out student responses to Problem-Based Learning- Autograph learning.

The Autograph-supported Problem-Based Learning (PBL) model innovatively integrates technology into the PBL framework, enhancing both student engagement and learning outcomes. This model addresses a significant gap in existing literature, which often overlooks the role of digital tools in facilitating collaborative problem-solving in educational contexts. By providing a structured approach that leverages Autograph's capabilities, this research not only contributes a novel pedagogical strategy but also offers empirical evidence on its effectiveness in fostering critical thinking and analytical skills among students.

Despite the recognized benefits of PBL, there remains a lack of comprehensive strategies that effectively incorporate technological tools like Autograph, leading to missed opportunities for enhancing student learning experiences (Nurapriani et al., 2024; Bina & Triandi, 2021; Putri, 2020). This study seeks to fill this gap by demonstrating how the Autograph-supported PBL model can transform traditional learning environments into dynamic, interactive spaces that promote deeper understanding and application of knowledge.

2. Literature Review

2.1. Autograph

Autograph is a software specifically designed to support the learning of mathematics. Autograph is one of the media that can be used in learning about two dimensions, three dimensions, statistics, transformations, geometry, equations, coordinates, differentials, graphs, algebra, and others. Autograph is one of the latest products from London, England, which can display a fairly complete menu including geometry and algebra (Nurapriani et al., 2024). The software can create graphical representations in 1D, 2D, and 3D for a variety of topics, such as geometric transformations, conic wedges, vectors, slope, plane area, and volume of rotating bodies. Autograph allows users to observe the relationship between functions, graphs, equations, and calculation results. With simulation and graph or shape modification features, Autograph helps to enhance the understanding of mathematical concepts interactively. Autograph provides three types of graphical representation

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models that can be used as needed. The 1D model is designed for statistical and chance analysis, while the 2D model is used to create graphs, manage coordinates, perform geometric transformations, and visualize bivariate data. In addition, there is a 3D model that allows the creation of three-dimensional graphs, space coordinates, and geometry transformations. In operation, Autograph has two levels of modes, namely the "Standard" mode, which is suitable for basic use, and the "Advanced" mode, which provides more complex features for more in-depth analyses (Hasibuan, 2016).

2.2. Problem-Based Learning

Arends (Trianto, 2015) states that the Problem-Based Learning (PBL) model is a learning model where students work on authentic problems to compile their own knowledge, developing inquiry and higher-level thinking skills, and developing independence and self-confidence. Furthermore, Rusman (2012) states that problem-based learning is the use of various kinds of intelligence needed to confront the challenges of the real world, the ability to deal with everything that is new, and the complexity that exists.

According to Harahap et al. (2021, the steps of PBL are:

1. Orient learners to the problem
2. Organizing learners to learn
3. Guiding individual and group enquiry
4. Develop and present
5. Analyze and evaluate the results of critical thinking

Furthermore, the Problem-Based Learning model assisted by Autograph is called Problem-Based Learning-Autograph (PBL-Auto), which is learning by using PBL steps assisted by the Autograph application in solving the problems given.

2.3. Critical Thinking-Mathematical Numeracy

Critical thinking is one of the high-level skills that is very important to be taught to students in addition to logical, analytical, and creative thinking skills (Zetriuslita & Ariawan, 2021). Numeracy is an important tool for making wise decisions in everyday life, both in personal, professional, and social contexts. Numeracy includes the skills to use, interpret, and communicate various mathematical concepts in everyday life (Dilla Nurfadillah et al., 2024).

Mathematical critical thinking-numeracy skills are a combination of critical thinking and mathematical numeracy indicators. The indicators of mathematical critical thinking-numeracy skills are:

1. Identify and justify data
2. Analyze a problem
3. Conduct
4. Solving a problem

While the numeracy context used is personal, socio-cultural, and scientific context.

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3. Methodology

3.1. Research Design and Participants

The research used is quasi-experimental research (Cohen et al., 2007) and the research method uses mixed methods with a sequential explanatory strategy (Creswell, 2014), that the interview data complements the data obtained from the test data. The research design used in this study was a one-group pre-test and post-test design (Setyosari, 2010). This means that there is only one class, which is analyzed for differences in students' mathematical thinking-numeracy skills before and after being given learning treatment with the problem-based learning-autograph model.

The type of research is quasi-experimental research. The one group with the Pre-test and Post-test Design is described below:

	Pre-test	Treatment	Posttest
Experiment	O1	X	O2

The population in this study was students of the mathematics education study programme at Riau Islamic University. The sampling method is a total sampling technique. There is one class that is given treatment, namely, the 3A semester students, who are 17 people.

3.2. Research instruments

Quantitative data instruments in the form of tests to measure mathematical critical thinking-numeracy skills were developed by making test grids with steps: a) designing test grids, b) compiling test items, c) validating experts, d) testing the tests, e) testing validity and reliability, f) making revisions, if needed. After that, the development of questionnaires to capture student responses to problem-based learning and autograph learning.

To answer research question number 1, a test was developed that contained indicators of critical thinking-numeracy skills. The critical thinking-numeracy skills indicators used are

1. Identify and justify data
2. Analyzing a problem
3. Conducting an evaluation
4. Solving a problem

The numeracy context used is personal, socio-cultural, and scientific.

To answer research question number 2, there were 10 statements that students were asked to fill in so as to answer the research questions given. The research questions were:

1. Explain what you have learned and what you know about the basic introductory integral material.
2. Explain the difficulties you face in understanding the basic introductory integral material.
3. Explain what efforts you have made in overcoming the difficulties you found in the basic integral introduction material.
4. Explain what you have learned and know about indefinite integrals.
5. Describe any difficulties you encountered in understanding the indefinite integral material.
6. Explain what efforts you have made to overcome the difficulties you face in understanding indefinite integral material!

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7. Explain what you have learned and what you know about the integral material of the course.

8. Describe any difficulties you encountered in understanding the integral material.

9. Explain what efforts you have made to overcome the difficulties you face in understanding the integral material!

10. Explain what you have learned and what you know about the application of the definite integral: determining the area of a flat plane.

For the development of questionnaires to answer research question number 3, there were 20 statements that students were asked to choose an answer from among the statements given. There are four answer choices from the statements given, namely Strongly (SS), Agree(S), Disagree (TS), and Strongly Disagree (STS).

The instruments for qualitative data were structured interviews and students' work (posttest results). The interview guideline was used to explore information about students' mathematical critical-numeracy thinking process. The interview answers answered the research questions about the pre-test and post-test, which contained the ability to think critically and numerically.

3.3. Data Collection and Analysis

The data in this study will be collected through mathematical critical thinking-numeracy ability tests and through structured interviews. The test data is obtained from the pre-test and post-test results. Data obtained from the results of communication skills tests through pre-tests and post-tests of students were analyzed statistically, both descriptive statistics and inferential statistics. While the results of interviews with students were analyzed qualitatively to complement the results of quantitative data

Data were analyzed by comparing student scores obtained from student test results before (pre-test) and after being treated (post-test) with problem-based learning and autograph learning. The amount of improvement before and after learning is calculated using the normalized gain formula (N-Gain) developed by Hake (1998) in (Siti et al., 2021) as follows

The N-Gain score formula used is as follows:

$$\frac{score\ posttest - score\ pretest}{score\ ideal - score\ pre - test}$$

Description:

Ideal score = 100

The N-Gain score criteria used are as follows:

Table 1. *N-Gain Score* Criteria

N-Gain	Criteria
$0{,}70 \leq \boldsymbol{N - Gain} \leq 1{,}00$	High
$0{,}30 \leq \boldsymbol{N - Gain} \leq 0{,}70$	Medium
$0{,}00 \leq \boldsymbol{N - Gain} \leq 0{,}30$	Low
$\boldsymbol{N - Gain} = 0{,}00$	No Improvement
$-1{,}00 \leq \boldsymbol{N - Gain} \leq 0{,}00$	There was a decrease

Furthermore, to test the significance of the increase, the Wilcoxon paired test, a non-parametric statistical test, was conducted (V. Wiratna Sujarweni, 2014).

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4. Results

4.1. Research Results

In accordance with the research procedures presented in Chapter 3, the results of this study will be described in accordance with the procedures carried out. The activities or procedures that have been carried out in accordance with what has been planned are:

4.2. Descriptive Statistical Analysis

The pre-test and post-test data were analyzed descriptively, looking at the minimum value, maximum value, mean (average), standard deviation, and variance.

The pre-test data are described in Table 2 below.

Table 2. Pre-test Descriptive Statistics

	N	Range	Minimum	Maximum	Mean	Std Deviation	Variance
Student's score	17	30.00	20.00	50.00	32.5329	8.12359	65.993
Valid N (listwise)	17						

Furthermore, the posttest data can be described in Table 3 below:

Table 3. Posttest Descriptive Statistics

	N	Range	Minimum	Maximum	Mean	Std Deviation	Variance
Student's score	17	20.00	70.00	90.00	76.1765	5.73624	32.904
Valid N (listwise)	17						

From the data above, there is a significant difference between the pre-test and post-test results:

1. Mean: The average posttest score (76.1765) was higher than the average pre-test score (32.3259), indicating an increase in student understanding after learning.

2. Range: The range of posttest scores (20.00) is smaller than that of the pre-test (30.00), which indicates that the posttest scores are more focused and less spread out.

3. Standard Deviation and Variance: The standard deviation and variance of the posttest were lower than the pre-test, indicating greater consistency in the posttest results.

Descriptively, from between the pre-test and post-test, the results of mean, range, standard deviation, and variance show that the PBL-Auto model improves students' mathematical critical thinking-numeracy skills.

4.3. Descriptive Analysis of N-Gain Data

N-Gain data is obtained from posttest data and pre-test data; the results can be seen in Table 4 below:

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Table 4. N-Gain Data of Critical Thinking Skills-Numeracy Students in the Integral Calculus Course

No.	Student Name	*Pre-test* Score	*Posttest* Score	N-Gain	Criteria
1	AH	40	70	0,60	Medium
2	AL	30	75	0,75	High
3	ESK	30	75	0,75	High
4	FER	30	80	0,83	High
5	GSJS	20	75	0,78	High
6	INA	30	75	0,75	High
7	IF	30	75	0,75	High
8	KAPG	30	75	0,75	High
9	KN	30	70	0,67	Medium
10	KEPH	30	75	0,75	High
11	NIK	30	75	0,75	High
12	PIPP	30	75	0,75	High
13	RSO	20	70	0,71	High
14	SR	50	90	1	High
15	HIGH SCHOOL	45	75	0,67	Medium
16	LAW	45	90	1	High
17	YAY	30	75	0,75	High

Table 4 shows that 14 students (82.4%) were categorized as high (High N-Gain (≥ 0.7)), SR and UU students had the highest N-Gain (1.0), indicating excellent understanding and three students (17.6%) were categorized as medium N-Gain Medium (0.3 - 0.7), none were categorized as low let alone no improvement and decline, Most students showed significant improvement in their scores from pre-test to posttest, with 82.4% of students obtaining high N-Gain. Many students achieved a uniform posttest score (75), reflecting stable understanding after learning. Although the majority showed improvement, there was some variation in the results, with some students achieving higher posttest scores. Three students meet the medium criteria, and 14 students meet the high criteria. From the pre-test to the post-test, all students increase their scores. Thus, descriptively, there is an increase in students' critical thinking-numeracy skills in the Integral Calculus course after learning with Problem-Based Learning assisted by Autograph (PBL-Auto).

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4.4. Inferential Statistical Analysis

To answer the hypothesis proposed earlier with the research design of the one-group pretest-posttest design, the inferential test results can be seen below:

Hypothesis 1:

1. There is a significant difference in mathematical critical thinking-numeracy skills between students before and after learning with the *Problem-Based Learning-Autograph* model.

In this hypothesis testing, formally, the statistical hypothesis H0) and the research hypothesis (H1) are as follows:

H_0: $\mu_1 = \mu_2$: There is no significant difference in mathematical critical thinking-numeracy skills between students before and after learning with *Problem Based-Learning-Autograph* model.

H1: $\mu 1 \neq \mu 2$: There is a significant difference in mathematical critical thinking-numeracy skills between students before and after learning with the Problem-Based model.

Testing criteria: Ho is accepted if sig ≥ α = 0.05 and Ho is rejected if sig < α = 0.05. To test hypothesis 1, the following steps were taken:

1. Normality Test of Pre-test and Post-test Data

The results of the pre-test data normality test (before learning) can be seen in Table 5 below:

Table 5. Normality Test of Pre-test Data

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
Student's Score	Statistic	df	sig	Statistic	df	Sig
	0.379	17	.000	0.790	17	0.001

Because the number of samples is less than 30, we use the normality test using *the Shapiro-Wilk test*. Based on the results, the significance value is 0.01. Because of the p < 0.05, the data is not normally distributed.

The following are the results of the *posttest* data normality test *(after* learning*)*. The results can be seen in Table 6 below:

Table 6. Post-test Data Normality Test

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
Student's Score	Statistic	Df	sig	Statistic	df	Sig
	0.405	17	.000	0.687	17	.000

Because the number of samples is less than 30, we use the normality test using the Shapiro-Wilk test. Based on the results of the Shapiro-Wilk test, the significance value is 0.00. Because p < 0.05, the data are not normally distributed.

From Tables 5 and 6, it is obtained that the pre-test data and post-test data are not normally distributed. For this reason, non-parametric statistical analysis is used. The non-parametric statistical analysis used is paired samples statistics. The results can be seen in Table 7.

Table 7. Paired samples statistics test for pre-test and post-test data, Wilcoxon signed-rank test

Ranks

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		N	Mean Rank	Sum of Ranks
Posttest Pre-tests	Negative Ranks	0[a]	.00	.00
	Positive Ranks	17[b]	9.00	153.00
	Ties	0[c]		
	Total	17		

a. Posttest < Pretest
b. Posttest > Pretests
c. Posttest = Pretests

Test Statistics[a]

	Posttest - Pre-tests
Z	-3.710[b]
Asymp. Sig. (2-tailed)	.000

a. Wilcoxon Signed Ranks Test
b. Based on negative ranks.

From the Wilcoxon test above, it is obtained that Asymp Sig (2-tailed) = 0.000 < α, Ho is rejected or H1 is accepted. It is concluded that there is a significant difference in students' mathematical critical thinking-numeracy skills before and after learning with the Problem-Based Learning-Autograph model. It is concluded that there is an increase in students' mathematical critical thinking-numeracy skills after learning with the Problem-Based Learning- Autograph model.

2. Research Question:

What is the critical thinking process, mathematical numeracy, among students who are taught with Problem-Based Learning-Autograph?

To answer the research question above, the students' test answers provide insight.

The description of the test is as follows.

Question No.1

Mr Ahmad has a column of koi fish as shown below.

If the curved line on the surface plan of the koi fish column is a function curve $f(x) = 4x - x^2$ *with boundary (0,4).*

a. Sketch the curve of the function $f(x) = 4x - x^2$ *with boundary (0,4) on cartesian coordinates!*

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b. State the area to be determined by shading!

c. Identify the method that can be used to determine the surface area of the koi fish with a reason!

d. If it is stated that the surface area of the koi fish column is $\frac{6}{5}$ unit area, determine the truth value of the statement with reasons?

e. Calculate the surface area of the koi fish pond!

In the pre-test, all students were unable to answer this question correctly. Students have not been able to sketch the curve of the given function. Then students are also not correct in determining the method that can be used to determine the area formed from the curve equation and the given boundary. This indicates that students cannot identify and analyze concepts. Furthermore, students are also unable to determine the truth value of question point d. This indicates that students cannot identify and analyze concepts. This indicates that students are unable to evaluate. Then the students are also unable to determine the surface area of koi fish correctly. This also indicates that students are unable to solve problems appropriately. A snapshot of students' answers to question number 1 can be seen in the picture below.

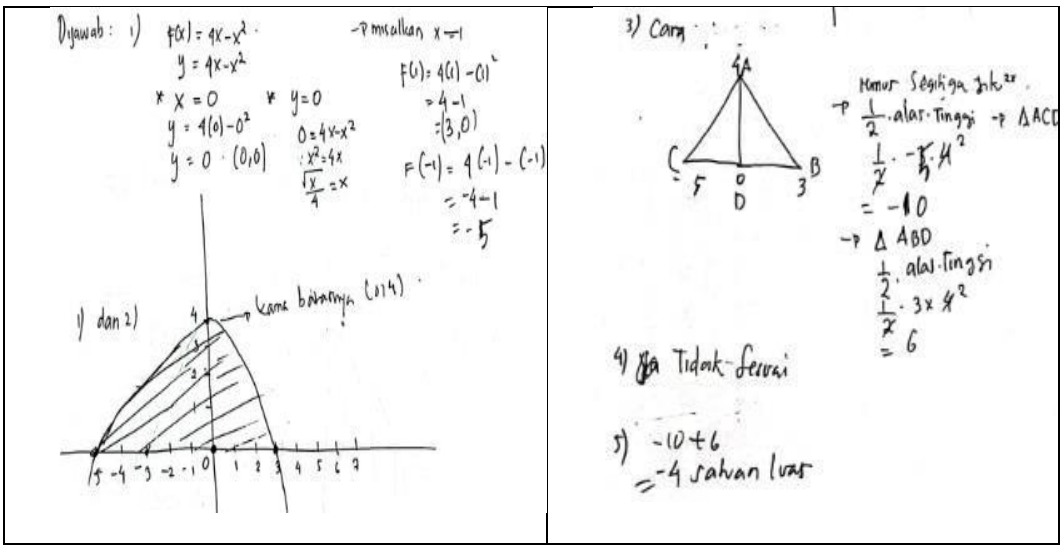

Figure 1. Student's Answer to Question No. 1 on the Pre-test

The snippet of Figure 1 above informs that students try to sketch the curve from the given equation and boundary. Students try to find auxiliary points to sketch the curve by substituting x = 0 and y = 0 into the equation$f(x)$ = 4x − x2, then students try to substitute x = 1 and y = -1 into the equation$f(x)$ = 4x − x2. Once the point is obtained, students use it to sketch the curve of the given equation. So far, the steps taken by students are correct, namely by trying to make auxiliary points to be able to sketch the curve, but what needs to be explored more deeply is why the points to be substituted are x = 0 and y = 0 and x = 1 and y = -1. Then the students stated that the limit given was (0,4). This also needs to be confirmed to the students, why the given limit of (0,4) is stated in the y-coordinate.

Next, students tried to calculate the area of the flat area formed by using the triangle area formula. If seen from the answer snippet, it is reasonable to assume that students assume that the curve formed is a triangle, so students use the triangle area formula. However, this needs to be explored more deeply through interviews. Furthermore, for question point d, students only stated that it was not appropriate without giving reasons. Students directly answered question point e by adding the area of the left triangle, namely -10, with the area of the right triangle, namely 6, so that

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the area of the flat area obtained was -4 units of area. This also needs confirmation, considering that there is no negative area.

The next step that the researchers took was to conduct in-depth interviews with students to clarify the points mentioned in the answer snippets above. The following will present excerpts of the researcher's interviews with students.

P : *Firstly, I would like to thank you for trying to respond to the pre-test questions. However, there are some things that you need to confirm to clarify the answers you have stated. Are you willing?*

SR : *Yes, sir, God willing.*

P : *In your answer, you see that you tried to sketch the curve by trying to substitute the points x = 0 and y = 0 and x = 1 into the equation* $f(x) = 4x - x^2$ *With what considerations did you determine the points x = 0 and y = 0 and x = 1 to the Equation?* $f(x) = 4x - x^2$

SR : *Yes, sir, to my knowledge, by substituting some points, it will be able to sketch the curve. Then, for the points x = 0 and y = 0, I used to determine the vertex, while the points x = 1 and y = -1 were used to get the left and right limits of the curve.*

P : *Which theory or concept did you base this on?*

SR : *I don't know which theory or concept, sir. I was just trying it out. I actually don't know how to sketch a curve correctly.*

P : *Yes. Next, you want to confirm why the limit (0.4) is stated at the cusp of the curve?*

SR : *The limit (0,4) is, in my opinion, the point x,y. so x = 0 and y = 4.*

P : *Why do you think that? Do you know what a quadratic curve looks like and what the function of the limit (0,4) is?*

SR : *I am confused, sir. I do not know the shape of the quadratic curve or the function of the limit given in the question. As I recall, if given the point (0,4), this can be translated as x = 0 and y = 4. That is why I stated it in the curve, sir.*

P : *Okay, then why did you use the triangle area formula to determine the area of the shaded area?*

SR : *The curve I got is triangular sir. So, to get the area, I used the formula for the area of a triangle.*

P : *Is there any other way to determine the area of the shaded area?*

SR : *No, sir. I don't think I've ever learnt about this*

P : *Okay, then why did you give this answer to question point d? Can you explain?*

35 SR : *Because from my calculation in question number c, I got the area of the left triangle = -10 and the area of the right triangle = 6. So if you add it up, the result is -4. So 5/6 does not correspond to -4. That's it, sir.*

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P : *Is there any other way to determine the area of the shaded area?*

SR : *No, sir. I don't think I've ever learnt about this.*

P : *Okay, you have got the information you need regarding question number 1. Thank you.*

SR : *You're welcome, sir. Sorry if I didn't get it right, sir.*

Based on the answer snippets and interview results, it can be concluded that students still do not understand how to draw curves, and cannot determine the limits of integration. Then, students also do not know how to determine the area of the shaded area and are not correct in analysing, evaluating, and solving problems. This indicates that they do not have good critical thinking skills on personal context numerical problems.

Furthermore, students' knowledge has improved after learning using the problem-based learning model assisted by Autograph. This can be seen from students' responses to question number 1. In question number 1, almost 80% of students can answer correctly. The following is a snapshot of student answers to question number 1.

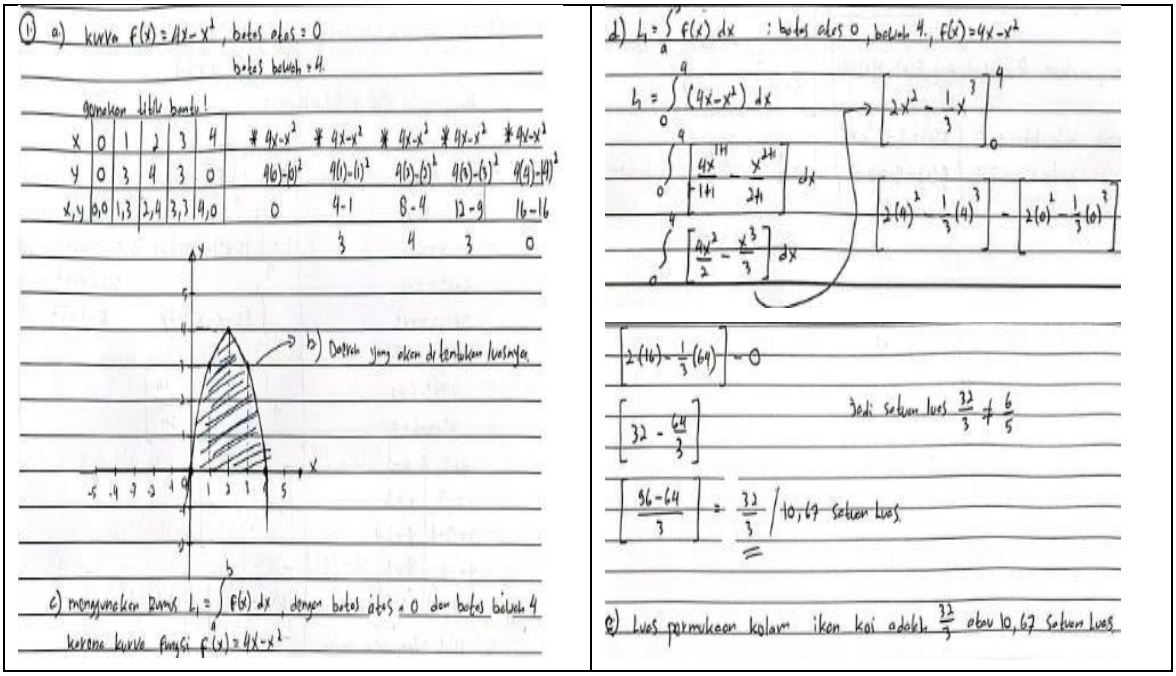

Figure 2. Snippet of Students' Answers during the Posttest for Question Number 1

Based on the excerpt of the student's answer, it can be seen that the student has been able to sketch the curve from the given curve equation. Students sketch the curve by first determining the auxiliary points. The auxiliary points are determined based on the given boundary point, namely (0,4), so the auxiliary points used are 0,1,2,3, and 4. Students substitute the points x = 0, x = 1, x = 2, x = 3, and x = 4 into the equation $f(x) = 4x - x2$. Next, students sketch the curve with the points they have obtained, namely: (0,0), (1,3), (2,4), (3,5) and (4,0). The resulting curve drawing is correct. Then the students have also correctly determined the area to be calculated by shading. This can be seen in the answer above.

Furthermore, students have also been able to determine the area of the shaded area by using the definite integral rule, namely \int_{a}^{b}f\left(x\right)dx, with an upper limit of 0 and a lower limit of 4. Although the method used is correct, namely using the definite integral rule to determine the area of the shaded area, the upper and lower limits stated by students are still not correct.

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However, after being confirmed, the student realized that it was wrong and was able to state the correct upper limit of 4 and the lower limit of 0. Then the student used the definite integral rule to determine the area of the shaded area. Students were then able to evaluate that the question in point d was wrong by presenting the correct answer.

Based on the explanations above, it is suspected that students have good critical thinking skills. Students have been able to identify and justify concepts, analyze, evaluate and solve problems correctly.

Furthermore, suppose the above problem is related to determining the area of a flat area. In that case, the following will present a problem related to determining the volume of a rotary object using the concept of a definite integral.

Question No.2

A laboratory requires an inverted parabolic test tube whose volume meets certain specifications. The test tube design is formed by a parabolic curve $y = 4 - x^2$ *about the x-axis with* $0 \leq x \leq 2$

a. Draw the parabolic curve $= 4 - x^2$ *on the Cartesian coordinate plane*

b. Identify the shape of the resulting volume if the curve is rotated degrees about the x-axis

c. Identify the boundaries of the integral formed!

d. State the integral formula to calculate the volume of the rotating object with reasoning!

e. If it is stated that the volume of the rotating body formed by the two curves is 45 unit volumes, determine the truth value of the statement with reasons.

f. Calculate the volume of the rotating body shape using the formula stated in point B!

If the laboratory requires a test tube volume of 50 cm^3, determine whether the given curve specification fulfils this requirement and give reasons!

This question was not answered by all students who took the pre-test. After being confirmed by conducting interviews with students, it was found that there was not enough time. Students were only focused on solving problems about the area of a flat plane. Then, after the researcher asked if additional time would help solve the problem. All students answered that they could not solve it because they did not understand.

This is contrary to what was learned using the problem-based learning model assisted by autograph. Almost all students were able to answer the question correctly. A snapshot of students' answers to the question about the volume of rotating objects is shown below.

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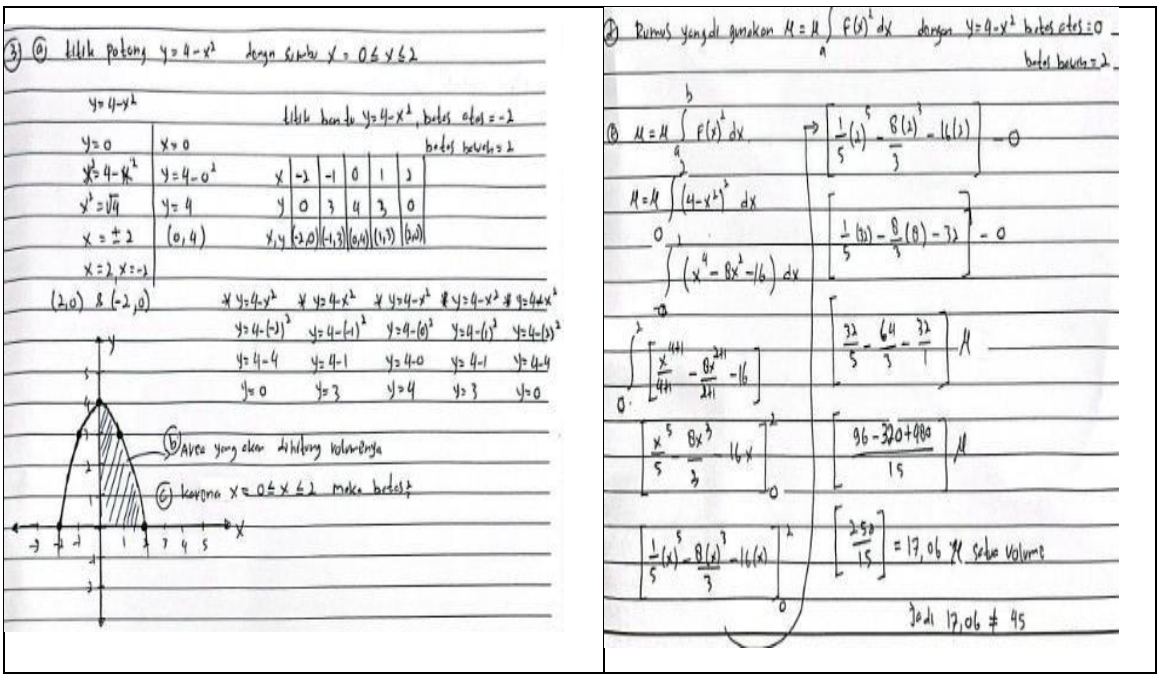

Figure 3. Excerpt of Students' Answers During the Posttest for Question Number 2

Based on the picture of the student's answer above, it can be seen that the student has been able to sketch the curve, able to determine the integration boundary, determine the way to calculate the volume of the rotary object formed, able to calculate the volume of the rotary object and able to evaluate and draw conclusions by providing reasons.

Research Question 3

How do Students Respond to Problem-Based Learning-Autograph Learning?

After the implementation of learning using the problem-based learning model assisted by autograph, researchers tried to get student responses through distributing questionnaires with Google Forms and interviews. The recapitulation of students' responses to the problem-based learning model assisted by the autograph on integral application material is presented in the table below.

Table 8. Recapitulation of Students' Responses to the Problem-Based Learning Model Assisted by Autograph on the Application of Definite Integral Material

No.	Statement	Strongly Agree (SS)	Agree (S)	Disagree (TS)	Strongly Disagree (STS)
1	The PBL model helps me understand mathematics concepts better.	60%	40%		
2	Learning with PBL makes me more active in discussions.	66,7%	33,3%		
3	I feel more motivated to learn math with the PBL model.	60%	40%		
4	The PBL model improved my ability to solve math problems.	46,7%	53,3%		

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No.	Statement	Strongly Agree (SS)	Agree (S)	Disagree (TS)	Strongly Disagree (STS)
5	I am more confident in doing math problems after learning with PBL.	53,3%	46,7%		
6	PBL helped me develop critical and analytical thinking skills.	60%	40%		
7	I feel comfortable with the PBL learning system in this course.	60%	40%		
8	PBL encourages me to work together in teams to solve problems.	60%	33,3%		
9	Learning with PBL improved my communication skills.	40%	60%		
10	PBL makes me more independent in learning and finding solutions.	40%	60%		
11	The use of Autograph helps me understand the math material.	53,3%	46,7%		
12	Visualization using Autograph makes concepts easier to understand.	60%	40%		
13	I feel more interested in learning math with the help of Autograph.	60%	33,3%	6,7%	
14	Using Autograph clarified my understanding of mathematical graphs and functions.	46,7%	53,3%		
15	I feel comfortable using Autograph in learning.	53,3%	46,7%		
16	Autograph helps me connect mathematical concepts with more concrete visualizations.	60%	40%		
17	I can operate Autograph easily with guidance in class.	46,7%	53,3%		
18	Autograph improves my understanding of the concepts of area and volume of a rotating object.	66,7%	33,3%		
19	I find it easier to understand the concept of integral applications (area of flat areas and volume of rotating objects) with the help of *Autograph*.	60%	40%		
20	I would like to use Autograph more in other math lessons.	60%	40%		

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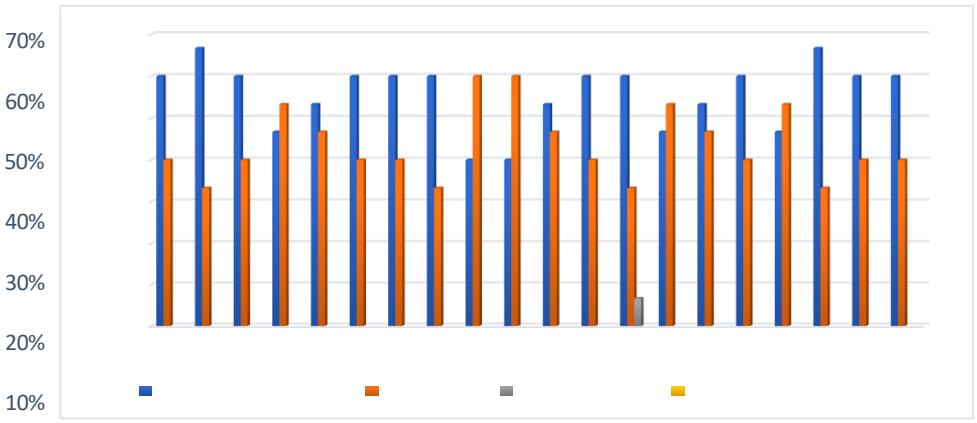

Figure 4. Recapitulation of Student Responses to 20 Statements About the Problem-Based Autograph Model

After getting the answers to student responses based on the questionnaire above, the researcher tried to confirm several statements that still received disagreeing scores and added several question items for the students. The following is a snippet of the results of the researcher's interview with

P : *Have you filled out the questionnaire according to the link you provided?*

F : *I have, sir.*

P : *On the statement "I feel more interested in learning math with the help of Autograph", you saw Ananda give a disagreeing response, is that correct?*

F : *Yes, sir.*

P : *Can you give reasons why you disagree with this statement?*

F : *Well, sir, during yesterday's lesson, I had problems installing Autograph on my laptop, because my laptop doesn't support it. So I thought, of course, this is an obstacle for me in learning. That's why I don't feel interested in learning by using an autograph.*

P : *Okay, during yesterday's lesson, you were in a group with another friend, right? Can your friend install and operate the autograph?*

F : *Yes, sir, it is group learning. Friends in the laptop group can use the autograph, sir.*

P : *If your laptop can support autographs, do you think the learning will be more interesting?*

F : *I think so, sir, it will be much more interesting. Because I don't just see it, but can use the autograph in classroom learning. The visualization is also good. It makes it easier for me to understand.*

P : *Ok, then, in the future, before learning using autographs is carried out, you must first ensure the readiness of all students regarding the availability of autographs.*

F : *Yes, sir.*

P : *Okay, thank you then.*

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In addition to conducting interviews with subject F, the researcher also asked open-ended questions to students in the class. The questions asked included:

1. What are the advantages of learning with the PBL model assisted by Autograph, in your opinion?

Student Response:

- makes learning easier
- Makes it easy for me to form curves by inserting x and y lines and their boundaries
- Make the learning process more interesting and effective, easier to understand the concept, compared to just reading the
- easy to understand
- With autographs, it helps students understand the learning more clearly.
- Through autographs, I can more easily understand and determine the volume of a space and the rotation of the space against a predetermined line.
- I think the advantages are that it can improve critical thinking and problem-solving skills.
- Very easy, especially in
- Makes me better able to solve problems by thinking critically
- It can tell the original shape when finding the volume, and is very interesting.
- Very easy for me to
- Easy to
- Can make it easier to understand the material
- The advantage is that we can better understand and can directly assemble the PBL model with the help of Autograph.
- Makes it easier to hide something integral

2. What obstacles did you experience during learning with this model?

Student Response:

- None
- None
- For obstacles, thank God, there are none
- Adaptation when using the Autograph software
- How the results work
- I don't think there are any problems, because the autograph is very interesting to learn and helpful.
- The obstacle is that when in class, I can follow well and do the work, but when studying alone at home, I sometimes have
- None
- Maybe in producing the final result sometimes it is not synchronized with the results that are done manually.

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- Maybe it's because I've still learnt to use the autograph several times, but I still have trouble using it.
- The obstacle is that sometimes the Autograph is not the same as using the manual
- In using Autograph, the obstacle is the network because Autograph is an application that uses the network.
- The obstacle I face is entering formulas and numbers in the Autograph application.
- The media and tools used are slow

3. Suggestions to improve the effectiveness of learning with the PBL model assisted by an autograph? Student response:

- None
- Often utilize autographs to visualize abstract concepts, such as function graphs, calculus, and geometry.
- Short training or longer tutorial on how to use autographs
- Also include the working stage of the formula
- None
- Maybe add a feature on how to solve the problem of determining the volume or area of the space.
- So that users can learn and know where their mistakes are when calculating manually and when using the autographs.
- The suggestion is to provide a step-by-step guide on how to use autographs outside of lecture hours.
- None
- Hopefully, it can be even more effective
- Maybe the feature is complemented by working on it step by step, not only directly to the results
- Utilize the "features" in Autograph to make it easier for students to learn Autograph.
- So far, learning to use Autograph is good; it's just that maybe you need to understand more about Autograph's features.
- The suggestion is that before entering the material, we must make sure that students understand how to use Autograph first.
- To use autographs, we should ensure that the facilities used are safe and slow so that there are no problems.

4. Are there any other aspects you would like to share regarding your experience in this learning? Student response:

- None
- Autograph helped me find the area boundary after I searched it manually, and the result was the same.
- No

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- None
- Learning using autograph becomes more exciting when in class, not monotonous, and not only focused on books. But also proven by the application and technology.
- There is no exciting split using autographs
- In learning to use the PBL model that uses Autograph, the time is longer so that students understand more about using Autograph-assisted applications.
- Very exciting and satisfying because it is easy to
- None because using an autograph is very helpful for students in learning to use the PBL model.
- Learning using the PBL model assisted by Autograph makes me aware of the technological developments.

From the results of the interview above, it can be said that students feel helped by PBL-Autograph and that it has an effect on improving students' critical thinking skills in numeracy.

5. Discussion

Problem-Based Learning (PBL) assisted by Autograph is a constructivist learning approach that emphasizes the active involvement of students (student-centered) and puts forward the problem as the starting point for understanding the learning material. (Ali et al., 2010) states that in PBL, learners who are passive listeners of information become active learners, learn independently, and become problem solvers. Research that is in line with the above research on the application of PBL is Hmelo-Silver, (2004) in Masek, A and Yamin, S (2011) that if the steps of PBL are correctly implemented, it will allow students to develop their critical thinking skills, especially in the second and third steps of PBL, students will focus on solving the problems given both individually and in groups, at that time the role of the educator is to provide direction so that students are not confused by the problems given.

In this study, the application of PBL assisted by autograph helps a lot in terms of calculating and visualising the concept of area under the curve and volume of rotating objects in integral calculus material, so that it can facilitate the improvement of students' critical thinking skills-numeracy, area and volume of rotating objects can be seen from the results obtained through autograph.

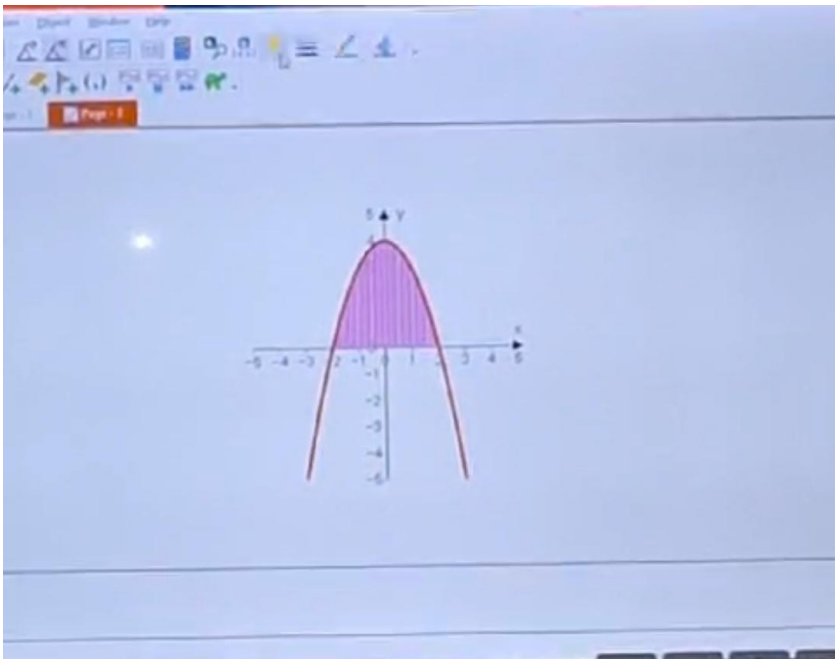

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Figure 5. Determining Area Under a Curve with Autograph Assisted by Autograph

Autograph helps students visualize the results of the Area under a curve graph that they obtained manually. In the topic of the volume of rotating objects, Autograph is very helpful in visualizing and calculating the obtained volume, allowing students to compare it with manually drawn diagrams. With Autograph, the results can be seen in the following picture:

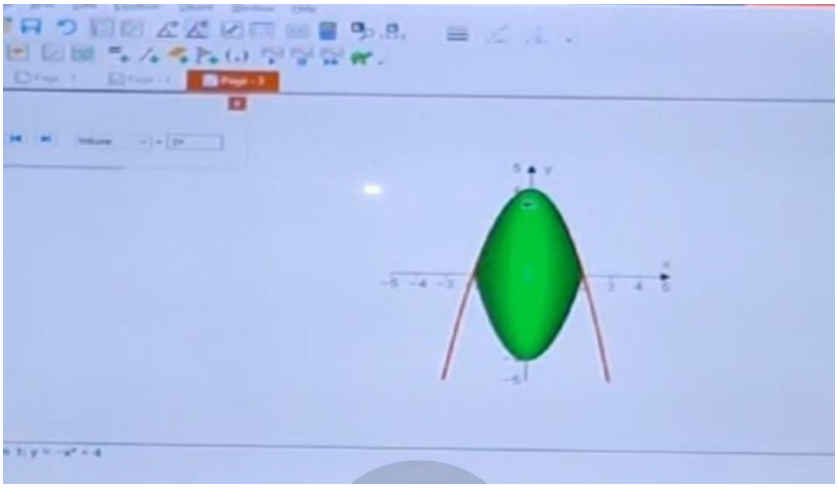

Figure 6. Determining Volume of Rotating Objects with Autographs

For the indicator of mathematical critical thinking skills for this volume of rotating objects, the question is solved by conducting a problem. At the same time, the numeracy context used is a socio-cultural context. Khusna et al., (2024); Cáceres et al., (2020); Nurlaelah, (2019); Zaqiah et al., (2022); Din, 2(020), state that critical thinking skills can be developed with learning such as, Collaborative Problem Solving, augmented reality-based interactive multimedia, problem-based learning and Brain-Based Learning, while for numeracy skills, research from (Ekowati et al., 2019; Alhamuddin et al., 2018) and autograph itself has been studied by previous researchers including (Bina & Triandi, 2021; Ghozi & Hilmansyah, 2018; Hasibuan, 2016; Nurapriani et al., 2024; Telaumbanua & Zendrato, 2019).

So that the results of this study are a development of previous research that has not combined critical thinking skills with numeracy with the PBL model assisted by Autograph, especially in integral calculus courses, the results of this study indicate that there is an increase in students' mathematical critical thinking-numeracy skills after using Problem-Based Learning assisted by Autograph.

From the analysis of quantitative data in the form of descriptive and inferential analysis and complemented by qualitative data analysis in the form of response questionnaires and interviews, it is obtained that the application of the Problem-Based Learning-Autograph model can improve students' mathematical critical thinking-numeracy skills in the material Area and Volume of rotating objects in the Integral Calculus course. This is supported by previous research from Bima et al., (2021) in his entitled research "Application of Integral in Daily Life with Autograph Assistance", The results of the research showed that 80% of students' knowledge about the application of Integral in daily life increased and 75% of students were able to use Autograph in solving Integral problems. The advantages of this autograph are also in terms of visualization of the area and volume of rotating objects, which are very helpful for students in understanding the application material of integral calculus. From the results of questionnaires and interviews, it is obtained that the use of autographs in learning greatly helps students and enables them to better understand the material provided.

However, the relatively small sample size, a single sample group, and short intervention duration are limitations of this study. Consequently, greater sample sizes and a control class and longitudinal research are required to test the effect's durability and the findings' generalizability.

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6. Conclusion

From the results of data analysis, it can be concluded that there is an increase in students' mathematical critical thinking-numeracy skills after learning by using PBL-Autograph learning in the course of Calculus and Integral Calculus. Supported by the results of interviews about student responses to learning using PBL-Autograph, students benefit significantly from the learning provided. From the results of the interview response to learning, in general, students answered through autographs. The students can more easily understand and determine how the volume of a space and the rotation of the space against a predetermined line, using autographs, is very helpful for students in learning using the PBL model. Learning using the PBL model assisted by Autograph makes me aware of the technological developments.

Declarations

Author Contributions. All authors contributed to the study's planning, design of the data collection instrument, and data collection and analysis. The first author led the writing process with assistance from other authors. All the authors read and approved the final manuscript.

Conflicts of Interest. The authors declare no conflict of interest.

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Ethical Statement. This research has been approved by the Directorate of Research and Community Service of Riau Islamic University (Number: 762/KONTRAK/P-UNGGULAN UIR/DPPM-UIR/10-2024).

Data Availability Statement. Data supporting the findings of this research are available upon request from the corresponding author. Data are not publicly available due to privacy or ethical restrictions.

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About the Contributor(s)

Zetriuslita, Department of Mathematics Education, Universitas Islam Riau, Indonesia
Email: zetriuslita@edu.uir.ac.id
ORCID: https://orcid.org/0000-0002-4037-0896

Rezi Ariawan, Department of Mathematics Education, Universitas Islam Riau, Indonesia
Email: reziariawan@edu.uir.ac.id
ORCID: https://orcid.org/0000-0003-1043-3400

Suripah, Department of Mathematics Education, Universitas Islam Riau, Indonesia
Email: rifah@edu.uir.ac.id
ORCID: https://orcid.org/0000-0002-2974-5669

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Ana Yulianti, Department of computer engineering, Universitas Islam Riau, Indonesia
Email: ana.yulianti@eng.uir.ac.id

Riyan Hidayat, Department of Science and Technical Education, Universiti Putra Malaysia, Malaysia
Email : Riyan@upm.edu.my
ORCID: https://orcid.org/0009-0008-9493-7166

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