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Critical Thinking Skills in Rotational Dynamics: Learning Physics With and Without Free-body Diagrams

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Abstract. This quasi-experimental study investigates the impact of using free-body diagrams on the critical thinking skills of students studying rotational dynamics at MAN 1 Sungai Penuh. The study involved 140 eleventh-grade students, divided into an experimental group and a control group, each consisting of 70 students. The experimental group received instruction using free-body diagrams, while the control group followed traditional teaching methods. Critical thinking skills were assessed using a test comprising five essay questions, each representing different aspects of critical thinking: likelihood and uncertainty analysis, problem solving and decision making, reasoning, hypothesis testing, and argument analysis. Descriptive statistics and independent samples t-tests were employed to analyze the data. The results revealed that the experimental group outperformed the control group in all aspects of critical thinking skills, with statistically significant differences ($\rho < 0.05$) and strong effect sizes ($d > 1$). Specifically, the experimental group showed notable improvements in argument analysis, reasoning, and hypothesis testing. The findings suggest that the use of free-body diagrams significantly enhances students' critical thinking skills in the context of rotational dynamics. This study underscores the importance of incorporating visual learning aids in physics education to foster deeper understanding and improve analytical skills. The results have important implications for teaching practices, advocating for the integration of free-body diagrams to develop students' higher-order thinking skills effectively.

***Keyword**: Critical thinking; Free-body diagrams; Physics learning; Quasi-experimental; Rotational dynamics*

INTRODUCTION

Thinking skills are crucial components that must be developed from an early age. Higher-order thinking skills, particularly critical thinking, have become priorities in all aspects of life, especially in education. Initially, efforts to develop critical thinking skills were separate from the subject matter that taught in schools (Ennis,s 1993), like science. Due to its importance, critical thinking has since been integrated into the science curriculum (Tiruneh et al., 2015), becoming a primary goal in science education.

Science educators, particularly in physics, agree that the main reason for students to study physics is not only to understand the concept, but also to learn how to think critically (Etkina & Planinšič, 2015). By focusing on critical thinking skills, education addresses a crucial aspect beyond rote learning. Critical thinking skills can be learned within the context of physics and then applied to everyday life (Judge et al., 2009). Critical thinking aligns with the top three levels of Bloom's taxonomy (Ennis, 1993): analyzing, evaluating, and creating. Students can reason, reflect, and make decisions based on their critical thinking abilities (Brookhart, 2010), process information, and make logical decisions (Stobaugh, 2013).

Successful learning involving critical thinking that requires processes such as predicting, analyzing, synthesizing, evaluating, and reasoning (Tiruneh et al., 2016). Integrating critical thinking into subject matter taught in classrooms enhances students' overall critical thinking skills (Dwyer et al., 2012). Therefore, it is vital to incorporate critical thinking into science, especially in physics education. However, further exploration is needed to determine the types of learning processes that support critical thinking.

In physics, basic concepts are often used technical terms and symbolically represented and abstract (Winter & Hardman, 2020) such as force, work, energy, momentum, torque, and others. In physics, one of the most difficult subject is rotational dynamics. Previous studies reported that rotational dynamics is a challenging topic for many students (Pranata et al., 2017, 2016). The terms and symbols uniqeu for each topics in physics and have specific meanings and must be used correctly. Students' familiarity with the terms is important part in their understanding concept (Aprilia et al., 2023; Reiss & Winterbottom, 2021). Then to engage critical thinking, visual aids are necessary to make these abstract concepts easier for students to analyze. One such aid is using visual representations like arrows to represent vector quantities(Heafner, 2015; Pranata & Lorita, 2023). For the concept of force, a suitable visual representation is the free-body diagram.

A free-body diagram is a visual representation that shows the forces acting on an object or system. Free-body diagrams offer numerous benefits in learning concepts related to vector quantities, especially forces (Pranata, 2017, 2024). It helps students analyze forces (Aviani et al., 2015; Berge & Weilenmann, 2014) and can be applied to many mechanics situations (Fredlund et al., 2014). Free-body diagrams aid in determining the equations of motion for an object (Rosengrant et al., 2009; Savinainen et al., 2013) using principles of superposition or decomposition of forces (Aviani et al., 2015). They also serve as a transitional tool from physical situations to mathematical equations (Fredlund et al., 2014; Rosengrant et al., 2009). Constructing and analyzing free-body diagrams requires systematic thinking, essential for problem-solving (Lo & Beichner, 2019). This systematic thinking can be directed towards Halpern's system of thinking, which relates to critical thinking skills.

Improving comprehension through effective teaching tools is crucial. This research targets a specific educational tool (free-body diagrams) within a specific topic (rotational dynamics) to determine how and to what extent their use in the learning process affects students' critical thinking skills. The research aims to answer whether using free-body diagrams in rotational dynamics material influences students' critical thinking abilities and to what extent this influence occurs. It hypothesizes that there is a significant influence of using free-body diagrams on students' critical thinking abilities.

METHOD

A quasi-experimental research design was employed, specifically using the post-test control and experimental group design (L. Cohen et al., 2018). The design is illustrated in Table 1.

Table 1. Quasi-Experimental Research Design

Group	Random Selection	Treatment	Observation
Experimental Group	R_1	X	O_1
Control Group	R_2		O_2

The population for this study consisted of 11th-grade students from MAN 1 Sungai Penuh. The sample included four classes drawn from this population, with two classes assigned to the experimental group and two to the control group. A Cluster Random Sampling technique was employed, where intact classes were randomly selected. This approach was chosen because it was impractical to randomly assign individual students to new classes.

In this study, two groups of students were compared. The experimental group received a special treatment, specifically instruction using free-body diagrams, while the control group followed the standard curriculum without this instructional method. The experimental group focused on learning rotational concepts, with particular emphasis on applying free-body diagrams during conceptual discussions and problem-solving activities related to rotational dynamics.

Symbols R_1 and R_2 represent the randomly selected groups for the study. Cluster random sampling was used, which is common in educational research where individual random assignment is often impractical. Symbol X denotes the treatment provided to the experimental group (teaching using free-body diagrams), while O_1 and O_2 represent the activities of observation, measurement, or data collection. Data were collected using test items designed to measure critical thinking skills.

Instruments were prepared by the researcher to collect data on the measured variable (critical thinking skills). Five test items were designed based on five aspects of critical thinking skills, with each aspect represented by one essay question as shown in Table 2.

Table 2. Relationship Between Questions and Critical Thinking Skill Aspects

Aspect	Question Number and Indicator
Reasoning	3. Provide reasoning on how mass and its distribution affect the moment of inertia and rotational motion
Hypothesis Testing	4. Test the hypothesis on the concept of speed and angular momentum of bicycle gears
Argument Analysis	5. Analyze arguments related to force and torque in the equilibrium of rigid bodies
Likelihood and Uncertainty Analysis	1. Analyze various alternatives of force and arm length, and their effects on the rotational motion of an object
Probem soving and decision making	2. Provide solutions for problems involving rotational motion based on the concepts of force and arm length

The aspects of critical thinking skills were adopted from previous theories and studies (Halpern, 2014; Tiruneh et al., 2016).

Data on critical thinking skills were collected through students' responses to the test questions. The test instrument was aligned with the learning material and the aspects of critical thinking skills. The test questions, consisting of five items, were validated by experts and underwent empirical testing in a previous study (Pranata, 2017). The instrument underwent two stages of testing: expert review and empirical testing. The empirical testing was conducted at the school where the research was carried out, with 12th-grade students serving as subjects to ensure the instrument's high validity and reliability (0.81).

The instrument was administered to students during the final meeting for each class (experimental and control). The collected data on critical thinking skills were analyzed using SPSS. Quantitative data analysis determined the students' thinking skills, employing both descriptive statistics and the Independent Samples t-Test. This test was used to determine the differences between the two groups. Additionally, the researcher measured the effect of using free-body diagrams on critical thinking skills by calculating the effect size. The categories for the d-value scale are shown in Table 3.

Table 3. d-effect Size Categories*

Range	Criteria
0 – 0.20	Weak effect
0.21 – 0.50	Moderate effect
0.51 – 1.00	Sufficient effect
>1.00	Strong effect

*(R. J. Cohen & Swerdlik, 2009)

FINDINGS

Based on the data collected and analyzed using SPSS, the descriptive statistics results are summarized in Table 4, and score distributions are shown in Figure 1.

Table 4. Descriptive Statistics

Groups	N	Min	Max	Mean		Std. Deviation	Skewness	
				Statistic	Std. Error		Statistic	Std. Error
All Students	140	24.00	100.00	60.49	1.66	19.62	-0.02	0.21
Experimental Group	70	52.00	100.00	74.74	1.48	12.38	0.16	0.29
Control Group	70	24.00	88.00	46.23	1.73	14.47	0.61	0.29

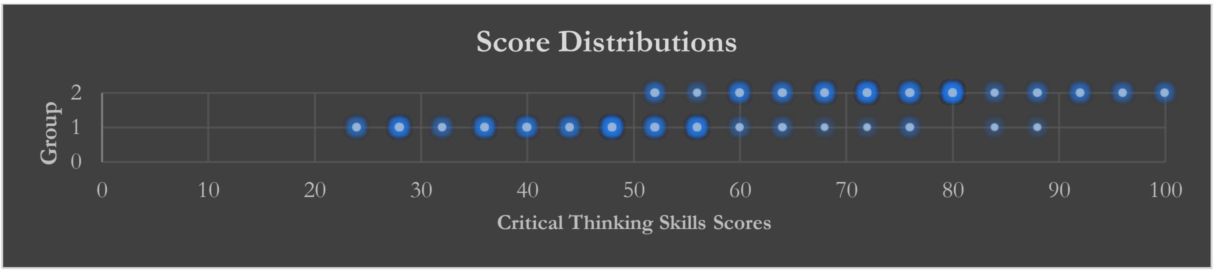

Figure 1. Score Distributions ($y = 1$ for Control group and $y = 2$ for experimental group)

Each of the experimental and control classes consisted of 70 students (N). Based on the average data (Mean) in Table 4, it can be concluded that the average critical thinking skills of the experimental group (74.74) are much higher than the average critical thinking skills of the control group (46.23). The score distributions for each group represented in scatter diagram, as shown in Figure 1, confirmed that findings. The standard deviations are not much different for both groups, being 12.38 and 14.47 for the experimental and control groups, respectively. The average difference between the two classes is 28.51 on a scale of 100, which is more than a quarter of the maximum score. However, this difference cannot be determined as significant or not without further testing. Comparative tests using the independent sample t-test or Mann-Whitney U-Test are needed to determine significance, based on data conditions (parametric or non-parametric).

Based on the statistical skewness, it can be seen that the critical thinking skills data for both groups are in the range of -1 to +1. Therefore, it can be concluded that both distributions are approximately normal (Leech et al., 2005; Morgan et al., 2004). Thus, the independent sample t-test can be applied. The test results are shown in Table 5.

Table 5. Independent Samples t-Test for Critical Thinking Skills

Varaiances	Levene's Test		t-test for Equality of Means						
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
								Lower	Upper
Ev assumed*	1.17	0.28	12.53	138	0.000	28.51	2.278	24.01	33.02
Ev not assumed*			12.53	134.77	0.000	28.51	2.28	24.01	33.02

*Ev=equal variances

The analysis of the data collected and summarized in Table 4 and Figure 1 provides clear evidence of the impact of using free-body diagrams on students' critical thinking skills. The descriptive statistics show that the experimental group, which received instruction using free-body diagrams, had a significantly higher mean score (74.74) compared to the control group (46.23). This difference of 28.51 points on a scale of 100 is substantial and suggests a notable enhancement in critical thinking skills due to the intervention. Further statistical analysis using the independent samples t-test confirms the significance of this difference. The t-test results ($t = 15.32, df = 138, \rho = 0.000$) indicate that the difference in mean scores between the experimental and control groups is statistically significant, reinforcing the conclusion that the use of free-body diagrams positively impacts students' critical thinking skills. Additionally, the effect size ($d = 2.12$) falls into the strong category, indicating a large impact of the treatment. The value of 2.12 can be interpreted as the difference between the experimental and control classes being 2.12 times the combined standard deviation (SD_{pooled}).

Further analysis was conducted by examining the differences in critical thinking skills for each question (indicator) between the experimental and control groups. The descriptive statistics for each indicator are summarized in Table 6, and a visual comparison of the mean scores for each group is shown in Figure 2.

Table 6. Descriptive Statistics for Each Aspects or Question

No and Aspects	Groups	N	Min	Max	Mean		Std. Deviation	Skewness	
					Statistic	Std.Error		Statistic	Std.Error
1. Likelihood and Uncertainty Analysis	Experiment	70	20.00	100.00	82.29	2.39	20.01	-0.95	0.29
	Control	70	20.00	100.00	49.71	3.15	26.32	0.64	0.29
2. Probem Solving and Decision Making	Experiment	70	0.00	100.00	70.86	2.63	21.98	-0.96	0.29
	Control	70	20.00	100.00	47.14	2.82	23.60	0.79	0.29
3. Reasoning	Experiment	70	60.00	100.00	86.57	2.06	17.27	-0.70	0.29
	Control	70	20.00	100.00	59.71	3.19	26.70	0.10	0.29
4. Hypothesis Testing	Experiment	70	0.00	100.00	60.57	2.41	20.14	-0.23	0.29
	Control	70	20.00	100.00	36.29	2.28	19.05	0.91	0.29
5. Argument Analysis	Experiment	70	20.00	100.00	73.43	2.90	24.25	-0.19	0.29
	Control	70	20.00	80.00	38.29	2.50	20.92	0.41	0.29

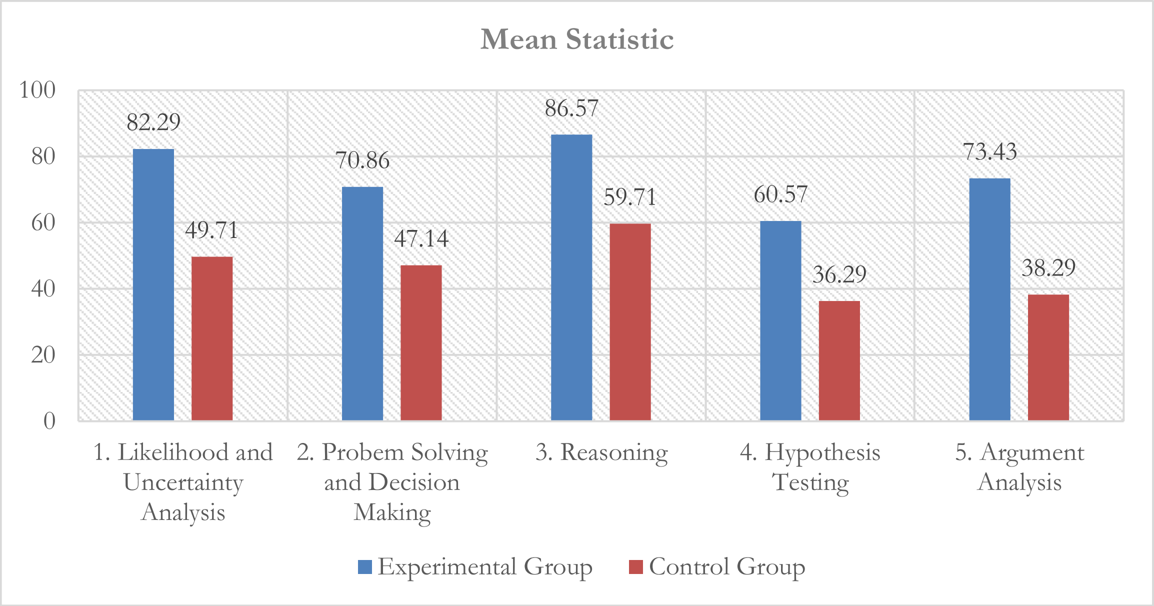

Figure 2. Mean Statistic for Each Aspect of Critical Thinking Skills

Based on the mean scores in Table 6 and Figure 2, it is evident that the experimental group consistently outperformed the control group across all aspects of critical thinking skills. The standard deviations varied, ranging from 17.27 to 26.70. The highest average difference was observed in aspect number 5 (argument analysis), with a mean difference of 35.14 on a scale of 100, which is more than one-third of the maximum score.

While these differences are substantial, further statistical tests are necessary to determine their significance. Given that the skewness values for each aspect of critical thinking are within the range of -1 to +1, it can be concluded that the distributions are approximately normal (Leech et al., 2005; Morgan et al., 2004). Therefore, the independent samples t-test is appropriate for comparing groups across each aspect of critical thinking skills. The results of these tests are presented in Table 7.

Table 7. Independent Samples t-Test for Each Aspect of Critical Thinking Skills

		Levene's Test		t-test for Equality of Means						
No and Aspects	Variances	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
1. Likelihood and Uncertainty Analysis	Ev assumed*	6.88	0.01	8.24	138.00	0.00	32.57	3.95	24.76	40.39
	Ev not assumed*			8.24	128.80	0.00	32.57	3.95	24.75	40.39
2. Probem Solving and Decision Making	**Ev assumed***	0.49	0.49	6.15	138.00	0.00	23.71	3.85	16.09	31.34
	Ev not assumed*			6.15	137.31	0.00	23.71	3.85	16.09	31.34
3. Reasoning	Ev assumed*	4.46	0.04	7.07	138.00	0.00	26.86	3.80	19.34	34.37
	Ev not assumed*			7.07	118.13	0.00	26.86	3.80	19.33	34.38
4. Hypothesis Testing	**Ev assumed***	0.02	0.88	7.33	138.00	0.00	24.29	3.31	17.74	30.84
	Ev not assumed*			7.33	137.58	0.00	24.29	3.31	17.73	30.84
5. Argument Analysis	**Ev assumed***	2.39	0.12	9.18	138.00	0.00	35.14	3.83	27.57	42.71
	Ev not assumed*			9.18	135.09	0.00	35.14	3.83	27.57	42.71

*Ev=equal variances

Table 7 shows that the critical thinking skills of the experimental group differ significantly from the control group for each question (aspect of critical thinking skills), with all p-values less than 0.01. The mean differences range from 23.71 to 35.14 on a scale of 100, further confirming the substantial impact of the intervention.

The effect size (d-value) for each aspect is also in the strong category, with all d-values greater than 1. Figure 3 illustrates these effect sizes, highlighting the robust impact of using free-body diagrams on each aspect of critical thinking skills.

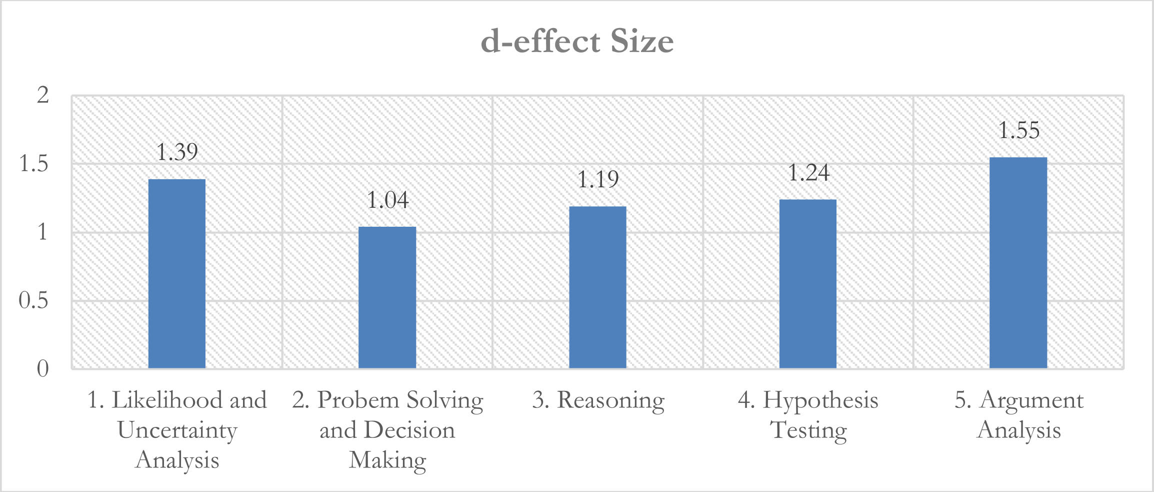

Figure 3. d-effect Size for Each Aspect of Critical Thinking Skills

The strongest effect is observed in question number 5 (argument analysis) with a d-value of 1.55, indicating that the difference in critical thinking skills between the experimental and control groups is approximately 1.55 times the pooled standard deviation for this question. Similar strong effects are observed for the other questions, confirming the overall effectiveness of the intervention.

DISCUSSION

The findings of this study align with existing literature emphasizing the importance of visual aids in enhancing cognitive skills, particularly in physics education. Free-body diagrams, as visual representations, help students break down complex problems into manageable parts, facilitating better understanding and analysis. This aligns with previous studies (Aviani et al., 2015; Fredlund et al., 2014; Pranata, 2024; Rosengrant et al., 2009; Stadlbauer et al., 2018) that highlight the effectiveness of free-body diagrams in physics education.

The significant improvement in the critical thinking skills of the experimental group can be attributed to several factors. First, free-body diagrams require students to engage in systematic thinking (Stobaugh, 2013), as they need to identify and represent forces acting on an object accurately (Pranata, 2017). This process inherently involves critical thinking components such as analysis, synthesis, and evaluation, which are crucial for problem-solving in physics. Second, the use of free-body diagrams may also enhance students' spatial reasoning skills, allowing them to visualize and manipulate physical concepts more effectively. This visual-spatial engagement could lead to deeper understanding and retention of the concepts being taught (Pranata & Lorita, 2023), thereby improving critical thinking skills. Third, using free-body diagrams not only supports critical thinking skills but also helps to interpret physical situations and address misconceptions (Lo & Beichner, 2019; Pranata et al., 2017).

The strong effect size ($d = 2.12$) further underscores the effectiveness of this teaching method. An effect size above 0.80 is generally considered large (J. Cohen, 1988), and a value of 2.12 indicates that the intervention had a substantial impact on students' performance. This finding suggests that incorporating free-body diagrams into physics instruction could be a highly effective strategy for fostering critical thinking skills.

The most significant difference was observed in argument analysis, where the experimental group outperformed the control group (Mean = 73.43 vs. 38.29) with a mean difference of 35.14 points. This question involved a balance system and required students to identify the important parts of an argument, interpret data, and reach a conclusion about the validity of the argument. The strong effect size in this aspect indicates that free-body diagrams not only aid in comprehension but also enhance students' abilities to critically analyze and construct scientific arguments. The data show that learning using free-body diagrams can help students analyze arguments as an aspect of critical thinking skills. Identical findings related to arguments and critical thinking skills are found in argument-based learning (Yilmaz, 2017), argument mapping (Dwyer et al., 2012), and using Toulmin's Argument Pattern (TAP) (Giri & Paily, 2020). Implementing argument-based learning, argument mapping, and TAP in the learning process can improve students' critical thinking skills.

Second most significant difference was observed in likelihood and uncertainty analysis, where the experimental group scored significantly higher (Mean = 82.29) than the control group (Mean = 49.71) in likelihood and uncertainty analysis. The mean difference of 32.57 points is substantial, and the effect size indicates a strong impact of the intervention. This question directed students to predict the likelihood of events and make decisions based on possibilities. Free-body diagrams likely helped students visualize and understand the forces involved, enabling them to better predict outcomes and assess uncertainties. This visualization fostered a deeper comprehension, allowing students to develop stronger analytical skills in evaluating different scenarios and their likelihoods. For the quality of free-body diagram construction, previous research suggest to use interaction diagram. Interaction diagram has the potential of safeguarding missing force(s) are identified and the likelihood of including extra forces in an FBD is diminished (Savinainen et al., 2013).

Then the experimental group again outperformed the control group hypothesis testing, reasoning, and problem-solving and decision-making with varied mean difference and effect size. Hypothesis testing aspect required students to formulate, test, and validate hypotheses based on data. Free-body diagrams provided a visual aid that made it easier for students to identify variables, predict outcomes, and evaluate their hypotheses. As previous study explore that students usually make prediction based on their dialy experineces, free-body diagram could make the prediction better (Lin & Singh, 2015; Rosengrant et al., 2009). The significant improvement suggests that free-body diagrams are an effective tool in teaching the scientific method and critical evaluation of hypotheses (Etkina et al., 2006).

Reasoning in physics involves logical thinking and justifying actions based on evidence. Free-body diagrams aided students in understanding the relationships between forces and motions, allowing them to construct logical arguments and reason through problems more effectively. The substantial improvement in reasoning skills indicates that free-body diagrams help students develop a clearer and more structured approach to thinking and making sense physical phenomena, in line with previous research on different physics topics, firctional forces (Lin & Singh, 2015) and magnetic forces (Lo & Beichner, 2019).

Problem-solving and decision making aspect often requires a structured approach to identify, analyze, and solve problems. Free-body diagrams provided a visual tool that helped students break down complex problems into manageable parts. This method enhanced their ability to systematically approach tasks, make informed decisions, and apply theoretical knowledge to practical situations. This findings align with previous study that found large group difference when solving problems with and without free-body diagram (Mešić et al., 2017) and errors in problem solving were a direct result of errors from the free-body diagrams (Davis & Lorimer, 2018; Thabit et al., 2016). Then free-body diagrams also important to evaluate the final result and making decision (Etkina et al., 2006).

The consistent improvement across all aspects of critical thinking skills indicates that free-body diagrams are a powerful pedagogical tool in physics education. They provide a visual representation of physical concepts, which helps students better understand and analyze the material. The significant differences in mean scores and the strong effect sizes across all aspects suggest that incorporating free-body diagrams into teaching methods can substantially enhance students' critical thinking abilities. These findings have important implications for educational practice. Educators should consider integrating visual aids like free-body diagrams into their teaching strategies to foster deeper understanding and enhance critical thinking skills. This approach not only improves students' performance in specific tasks but also equips them with valuable analytical skills essential for scientific inquiry and problem-solving in real-world contexts. In conclusion, the use of free-body diagrams in teaching physics significantly enhances students' critical thinking skills, making it a highly effective educational tool. The strong performance of the experimental group across various critical thinking aspects highlights the value of visual learning aids in developing students' cognitive abilities and preparing them for advanced studies and careers in science and engineering.

CONCLUSION

The study provides compelling evidence that using free-body diagrams in teaching rotational dynamics significantly enhances students' critical thinking skills. The significant improvement observed in the experimental group, coupled with the strong effect size, highligshts the potential of this visual aid as an effective instructional tool in physics education. By integrating free-body diagrams into the curriculum, educators can support the development of higher-order thinking skills, preparing students for complex problem-solving tasks both within and beyond the classroom. The results of the further analysis reinforce the initial findings, showing that the use of free-body diagrams significantly enhances students' critical thinking skills across multiple dimensions. Each aspect of critical thinking skills shows significant improvement in the experimental group compared to the control group, with strong effect sizes indicating substantial educational benefits. These findings underscore the importance of incorporating visual aids such as free-body diagrams in physics education to foster critical thinking skills.

However, while the results are promising, it is essential to consider potential limitations. The study was conducted within a specific educational context (11th grade students at MAN 1 Sungai Penuh), and the results may not be generalizable to other contexts or age groups without further research. Additionally, it would be beneficial to replicate the study in different educational settings and with diverse student populations to validate the findings further. The study used a quasi-experimental design, which, while robust, does not entirely eliminate the possibility of confounding variables. Future research could explore the long-term effects of using free-body diagrams and investigate how these tools impact other cognitive skills and across various physics topics. Investigating how different types of visual aids or instructional approaches influence critical thinking skills in physics education could also provide insights into optimizing teaching strategies.

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Data availability and sharing policy: The data and test instrument that support the process and findings of this study are available from the corresponding author, Ogi Danika Pranata (ogidanika@gmail.com), upon reasonable request.

REFERENCES

Aprilia, S. L., Pranata, O. D., & Haryanto, T. (2023). Analisis Tingkat Familiaritas Siswa Terhadap Istilah Sains dan Biologi. *Bioedusains:Jurnal Pendidikan Biologi Dan Sains*, *6*(2), 580–591.

Aviani, I., Erceg, N., & Mešić, V. (2015). Drawing and using free body diagrams: Why it may be better not to decompose forces. *Physical Review Special Topics - Physics Education Research*, *11*(2), 1–14. https://doi.org/10.1103/PhysRevSTPER.11.020137

Berge, M., & Weilenmann, A. (2014). Learning about friction: group dynamics in engineering students' work with free body diagrams. *European Journal of Engineering Education*, *39*(6), 601–616. https://doi.org/10.1080/03043797.2014.895708

Brookhart, S. M. (2010). *How to Assess Higher-Order Thinking Skills in Your Classroom*. ASCD.

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Science. Second Edition*. Lawrence Erlbaum Associates.

Cohen, L., Manion, L., & Morrison, K. (2018). *Research Methods in Education* (Eighth edi). Routledge.

Cohen, R. J., & Swerdlik, M. E. (2009). *Psychological Testing and Assessment: An Introduction to Tests and Measurement* (7th Editio). The McGraw−Hil.

Davis, J. A., & Lorimer, S. (2018). Student performance on drawing free body diagrams and the effect on problem solving. *ASEE Annual Conference and Exposition, Conference Proceedings*, *2018-June*. https://doi.org/10.18260/1-2--31013

Dwyer, C. P., Hogan, M. J., & Stewart, I. (2012). An evaluation of argument mapping as a method of enhancing critical thinking performance in e-learning environments. *Metacognition and Learning*, *7*(3), 219–244. https://doi.org/10.1007/s11409-012-9092-1

Ennis, R. H. (1993). Critical Thinking Assessment. In *Theory Into Practice* (Vol. 32, Issue 3, pp. 179–186). https://doi.org/10.1080/00405849309543594

Etkina, E., & Planinšič, G. (2015). Defining and Developing " Critical Thinking " Through Devising and Testing Multiple Explanations of the Same Phenomenon. *The Phy*, *53*(October), 432–437. https://doi.org/10.1119/1.4931014

Etkina, E., Van Heuvelen, A., White-Brahmia, S., Brookes, D. T., Gentile, M., Murthy, S., Rosengrant, D., & Warren, A. (2006). Scientific abilities and their assessment. *Physical Review Special Topics - Physics Education Research*, *2*(2), 1–15. https://doi.org/10.1103/PhysRevSTPER.2.020103

Fredlund, T., Linder, C., Airey, J., & Linder, A. (2014). Unpacking physics representations: Towards an appreciation of disciplinary affordance. *Physical Review Special Topics - Physics Education Research*, *10*(2), 1–13. https://doi.org/10.1103/PhysRevSTPER.10.020129

Giri, V., & Paily, M. U. (2020). Effect of Scientific Argumentation on the Development of Critical Thinking. *Science and Education*, *29*(3), 673–690. https://doi.org/10.1007/s11191-020-00120-y

Halpern, D. F. (2014). *Thought and Knowledge. An Introduction to Critical Thinking*. Psychology Press.

Heafner, J. (2015). The language of the arrows. *The Physics Teacher*, *53*(7), 445–446. https://doi.org/10.1119/1.4931020

Judge, B., Jones, P. J., & McCreery, E. (2009). *Critical Thinking Skills for Education Students*. Learning Matters Ltd.

Leech, N. L., Barret, K. C., & Morgan, G. A. (2005). *SPSS for Intermediate Statistics. Use and Interpretation*. Lawrence Erlbaum Associates, Inc. All.

Lin, S. Y., & Singh, C. (2015). Effect of scaffolding on helping introductory physics students solve quantitative problems involving strong alternative conceptions. *Physical Review Special Topics - Physics Education Research*, *11*(2), 1–19. https://doi.org/10.1103/PhysRevSTPER.11.020105

Lo, W., & Beichner, R. J. (2019). Stick With It! Helping Students Understand Free-Body Diagrams – A Magnet Activity as a Tool for Understanding. *The Physics Teacher*, *57*(7), 459–461. https://doi.org/10.1119/1.5126823

Mešić, V., Mahmutović, S., Hasović, E., & Erceg, N. (2017). Free-Body Diagrams and Problem Solving in Mechanics: An Example of The Effectiveness of Self-Constructed Representations. *European J of Physics Education*, *7*(3), 1309–7202.

Morgan, G. A., Leech, N. L., Gloeckner, G. W., & Barret, K. C. (2004). *SPSS for Introductory Statistics. Use and Interpretation*. Lawrence Erlbaum Associates, Inc. All.

Pranata, O. D. (2017). Analisis penguasaan konsep dan kemampuan berpikir kritis siswa dalam pembelajaran interactive demonstration dengan bantuan free-body diagram pada materi dinamika rotasi di SMA Negeri 2 Sungai Penuh-Jambi. In *Universitas Negeri Malang*. Universitas Negeri Malang.

Pranata, O. D. (2024). Analisis Kualitas Free-Body Diagram, Penguasaan Konsep Siswa, dan Korelasinya Pada Materi Dinamika. *Jurnal Ilmu Fisika Dan Pembelajarannya (JIFP)*, *8*(1), 26–37. https://doi.org/10.19109/rf6wgk84

Pranata, O. D., & Lorita, E. (2023). Analisis Korelasi Kemampuan Berbahasa Panah Dengan Kualitas Free-Body Diagram Siswa Pada Materi Dinamika. *Jurnal Pendidikan Fisika Dan Sains*, *6*(1), 22–31. https://doi.org/10.52188/jpfs.v6i1.394

Pranata, O. D., Wartono, W., & Yuliati, L. (2016). Kesulitan siswa SMA pada Penggunaan Free-body Diagram dalam Materi Dinamika. *Proseiding Seminar Nasional Pendidikan IPA Pascasarjana UM*, 394–404. http://pasca.um.ac.id/wp-content/uploads/2017/02/Ogi-Danika-394-404.pdf

Pranata, O. D., Yuliati, L., & Wartono. (2017). Concept Acquisition of Rotational Dynamics by Interactive Demonstration and Free-Body Diagram. *Journal of Education and Learning (EduLearn)*, *11*(3), 291–298. https://doi.org/10.11591/edulearn.v11i3.6410

Reiss, M. J., & Winterbottom, M. (2021). Teaching Secondary Biology. In M. J. Reiss & M. Winterbottom (Eds.), *Teaching Secondary Science* (3rd ed.). Hodder Education.

Rosengrant, D., Van Heuvelen, A., & Etkina, E. (2009). Do students use and understand free-body diagrams? *Physical Review Special Topics - Physics Education Research*, *5*(1), 1–13. https://doi.org/10.1103/PhysRevSTPER.5.010108

Savinainen, A., Mäkynen, A., Nieminen, P., & Viiri, J. (2013). Does using a visual-representation tool foster students' ability to identify forces and construct free-body diagrams? *Physical Review Special Topics - Physics Education Research*, *9*(1), 1–11. https://doi.org/10.1103/PhysRevSTPER.9.010104

Stadlbauer, J. M., Kehrer, L., & Bauer, S. (2018). Using history to foster critical scientific thinking: Aristotle and Galileo's debate resolved through high-speed motion tracking in the classroom. *American Journal of Physics*, *86*(12), 903–908. https://doi.org/10.1119/1.5062167

Stobaugh, R. (2013). *Assessing Critical Thinking in Middle and High Schools. Meeting the Common Core*. Routledge.

Thabit, A. K., Mater, A. N., & Al-Nami, A. (2016). A study of the effect of student utilization of the free-body diagram on their performance. *International Journal of Educational Research and Reviews*, *4*(1), 577–582. www.internationalscholarsjournals.org

Tiruneh, D. T., De Cock, M., Weldeslassie, A. G., Elen, J., & Janssen, R. (2016). Measuring Critical Thinking in Physics: Development and Validation of a Critical Thinking Test in Electricity and Magnetism. *International Journal of Science and Mathematics Education*, *15*(4), 663–682. https://doi.org/10.1007/s10763-016-9723-0

Tiruneh, D. T., Weldeslassie, A. G., Kassa, A., Tefera, Z., De Cock, M., & Elen, J. (2015). Systematic design of a learning environment for domain-specific and domain-general critical thinking skills. *Educational Technology Research and Development*, *64*(3), 481–505. https://doi.org/10.1007/s11423-015-9417-2

Winter, J. de, & Hardman, M. (2020). Teaching Secondary Physics. In J. de Winter & M. Hardman

(Eds.), *Teaching Secondary Science* (3rd ed.). https://books.google.com.my/books?id=ZSoryQEACAAJ

Yilmaz, R. (2017). Exploring the role of e-learning readiness on student satisfaction and motivation in flipped classroom. *Computers in Human Behavior*, *70*, 251–260. https://doi.org/10.1016/j.chb.2016.12.085