PAEDAGOGIA
Jurnal Penelitian Pendidikan
http://jurnal.uns.ac.id/paedagogia

DOI : 10.20961/Paedagogia.v28i2.99583
Vol. 28, No. 2, 2025, pp. 234-245
p-ISSN 0126-4109
e-ISSN 2549-6670

Writing to Learn Strategies: Improving Students' Critical Thinking and Science Communication Skills in Wave Concepts

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Keywords: *Critical Thinking Abilities, Science Communication Skills, Wave Concept, Writing to Learn Strategies*

Article history
Received: 17 February 2025
Revised: 15 May 2025
Accepted: 31 May 2025
Published: 21 June 2025

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Doi: 10.20961/paedagogia.v28i2.99583

Abstract: This research analyses the impact of writing to learn strategies on students' critical thinking and science communication skills, particularly on light and sound waves. The research employed a quasi-experimental approach, utilising a nonequivalent control group design. The study involved students from a high school in Palembang, with 32 participants in the experimental group and 32 in the control group. Before being tested on students, the critical thinking skills test items and science communication item sheets were evaluated by three experts. The research used pretest and posttest scores to assess the enhancement of students' cognitive abilities and critical thinking skills. The results showed that the experimental class showed significantly higher essential thinking abilities than the control class. The calculation of Cohen's d effect size is 1.5, which is included in the large category. The results of the analysis show that the test items can be used to test students. The results showed that students in the experimental class wrote conclusions well, but some wrote them less clearly due to repetition. The study concluded that the writing to learn approach effectively improved students' critical thinking skills, indicating that the writing to learn strategy can be an effective learning method. These findings suggest that integrating writing-based approaches in physics instruction can support the development of 21st-century skills. For future education practice, the test items can be combined with education technology, like flipbooks, to assess the development of students' critical thinking and communication skills.

How to cite: Patriot, E. A. & Anggraini, P. (2025). Writing to Learn Strategies: Improving Students' Critical Thinking and Science Communication Skills in Wave Concepts. *PAEDAGOGIA*, *28*(2), 234-245. doi: 10.20961/paedagogia.v28i2.99583

INTRODUCTION

The learning process in physics education is increasingly shaped by the dynamics of the Fourth Industrial Revolution (Industry 4.0) and the emerging Society 5.0 paradigm. These movements demand a shift in educational practices to emphasize critical thinking, creativity, collaboration, and the integration of advanced technologies such as artificial intelligence and big data. As industries evolve, education must follow, preparing students not only with technical competencies but also with essential soft skills, including science communication and analytical reasoning (Yudiono, 2021; Hafni et al., 2020; Yudiono et al., 2019; Hafni et al., 2020; Mudzar & Chew, 2022).

Based on the results of observations made by researchers, the learning process of students has not been optimal, the level of communication is still low, and critical thinking skills have not been trained during the physics learning process. Some factors cause this because the teacher only provides material in one direction, without providing feedback or practicing students' communication skills and critical thinking. Other factors that support this are that the learning approach used is still conventional (Suprapto et al., 2024); a lack of practicing problem-solving skills and critical thinking (Cahyani et al., 2023); not actively involved in the learning process (Tegeh et al., 2022); difficulty reflecting on learning experiences (Musyarrof et al., 2018); and low motivation to communicate and engage in group discussions (Azmi et al., 2018).

Students' communication skills have been observed during the learning process. Writing and presentation activities reviewed through the observation sheet showed that only 32% of students were able to show medium and high levels of communication. Several studies underscore the importance of mastering basic as a precursor to effective science communication (Asih & Ellianawati, 2019). Science communication skills encompass essential abilities such as observation, measurement, data interpretation, and communication that are integral to scientific inquiry (Harrington et al., 2024; Patriot et al., 2018; Patriot & Jannah, 2022). However, many physics education students struggle with these foundational skills, which are crucial for articulating scientific concepts effectively. Another study has shown that physics students often experience difficulties in demonstrating practical skills during laboratory work, hindering their ability to communicate scientific findings (Admawati et al., 2018; Valls-Bautista et al., 2021). Observations have revealed that many students lack the necessary understanding of tools and materials, contributing to their inability to communicate their results effectively during practical sessions.

Through the research gap above, the learning process that should be applied is a model, approach or strategy that can train students' critical thinking process in the context of physics learning. In addition, a strategy is needed to train writing and presentation skills. According to Reynolds et al. (2012) writing and presentation have been widely used to communicate ideas, so that writing will involve students' thinking activities (Suteja & Setiawan, 2022) reasons for the importance of communication: (1) The results of writing and presentation can assess students' knowledge, (2) writing is an essential skill that students need, (3) helps students learn to express their thoughts comfortably and contributes to increasing self-confidence, (4) Students who write and present clearly have a better chance of directing their way to face obstacles, and (5) writing and presenting verbally is the power to understand yourself.

Writing-to-Learn (WTL) strategies in educational settings, particularly in physics learning, have garnered attention for their potential to enhance students' critical thinking abilities. Critical thinking is the complex ability that encompasses the ability to analyze, evaluate, and synthesize information, which is essential in the study of physics, where complex problem-solving is often required (Musyarrof et al., 2018; Panjaitan & Sabani, 2021). WTL strategies facilitate this process by encouraging students to articulate their understanding and reasoning through writing, thereby promoting deeper cognitive engagement with the concept (Reynolds et al., 2012; Finkenstaedt-Quinn et al., 2021).

Previous research indicates that writing serves as a powerful cognitive tool that fosters critical thinking. Kayaalp et al. highlight that writing activities enable students to compare and contrast concepts, establish cause-and-effect relationships, and ultimately enhance their critical thinking skills (Kayaalp et al., 2020). Similarly, Cintamulya et al. emphasize that the act of writing scientific articles necessitates high-level cognitive processes, thereby reinforcing critical thinking abilities (Cintamulya et al., 2023). This is further supported by Yuliyani et al., who found that WTL strategies, particularly those focused on social-oriented scientific issues, significantly improve students' critical thinking and argumentation skills (Munawaroh et al., 2020).

Moreover, the effectiveness of WTL strategies in physics education is underscored by studies that demonstrate the positive impact of writing on students' conceptual understanding and critical thinking. For instance, Musyarrof et al. discuss the critical thinking weaknesses observed in high school physics students, suggesting that integrating writing tasks could address these deficiencies by promoting reflective thinking (Musyarrof et al., 2018). Additionally, Sinaga and Feranie's research on non-traditional writing tasks in modern physics courses indicates that such approaches can significantly enhance both critical thinking and writing skills among students (Gupta et al., 2015; Sinaga, et al., 2017; Teng & Yue, 2023).

Based on the urgency of the researchers presented through the background above, this study aims to determine whether there is an effect of increasing students' critical thinking skills and science communication skills through the application of write to learning strategies on wave material. Sinaga et al.'s (2013) research also showed that the writing to learn strategy can improve students' cognitive abilities and writing skills. Critical thinking skills are one of the 21st-century skills that will be trained, and the communication skills measured in this study are written and oral communication skills. Writing to learn strategies can be implemented with these stages: 1) Pre-Writing Phase; 2) Engagement through Writing Prompts; 3) Peer Discussion and Reflection; 4) Synthesis Writing / Summative Task; 5) Evaluation and reflection. The thing that needs to be considered in learning the writing to learn strategy is to optimize the stages in Fulwiler (2007). This research aims to analyze the impact of writing to learn strategies on students’ critical thinking skills and science communication skills, particularly on the topic of light and sound wave.

Although WTL strategies have been explored in general science and chemistry education, few studies have applied them specifically to wave material in physics. This study addresses that gap by investigating the dual impact of WTL on students' critical thinking and science communication within a focused physics content area. The integration of WTL in this context represents a novel contribution to physics education research. This study aims to analyze the effectiveness of Writing to Learn (WTL) strategies in improving students' critical thinking and science communication skills in the context of wave material in physics. The following research questions are posed: 1) How does the implementation of WTL strategies affect students' critical thinking skills in wave material?; 2) How does the use of WTL influence students' science communication abilities, both written and oral?

METHOD

The research employed a quasi-experimental approach, utilizing a nonequivalent control group design as described by Creswell (2015). The study involved students from a high school in Palembang, with 32 participants in the experimental group and 32 in the control group. The learning process was analyzed over three meetings, focusing on wave topics, specifically sound and light waves. During each session, the experimental group was exposed to a writing-to-learn strategy, while the control group received instruction using the scientific approach in physics class that the teacher usually used. The writing to learn strategy in this study is a learning strategy whose learning process is related to writing activities by students. At the end of each lesson, students are assigned to write back what they have learned in the form of a learning journal. The implementation of writing to learn strategy in learning is measured by using observation sheet. The non-equivalent control group design can be seen in Table 1 below.

Table 1. Non-equivalent Control Group Design

Group	Pretest	Treatment	Posttest
Experiment	O_1	X_1	O_3
Control	O_2		O_4

The instrument used to assess critical thinking skills, as described by Ennis (Handayani, 2020), focuses on indicators such as giving a simple explanation, building basic skills, and drawing a conclusion. The instrument was tested for feasibility before use using the validity and reliability test analysis approach. Asra et al., (2016) revealed that the research instrument items are said to be valid if the instrument can measure the variables under study permanently. The Cronbach’s alpha coefficient of internal consistency reliability of the scale was calculated as 0.88 for this study. The critical thinking indicator and sub indicator are presented in Table 2 below.

Table 2. Critical Thinking Indicators

Critical Thinking Indicator	Sub Indicator
Give a simple explanation (elementary clarification)	• Focusing questions • Analyze arguments • Ask and answer questions that require explanation challenge
Build Basic Skills (Basic support)	• Consider the credibility of the source • Make observational considerations
Conclusion (inference)	• Compile and consider deductions • Construct and consider induction • Formulate decisions and consider the results

(Source : Susanti, 2017)

This instrument consists of 5 essay questions, each representing a specific indicator. Meanwhile, to evaluate science communication skills, a separate instrument is employed by Spektor-Levy et al., (2008) yaitu 1) searching for information through references to references; 2) group discussion; 3) Arrange the resume according to the guidelines (writing); and 4) Communicate the report orally (presentation). The instrument used is an observation sheet to see the improvement of students' science communication skills. The format of the science process skills indicators is presented in Table 3 below.

Table 3. The indicator of the Scientific Communication Skills Assessment Format

Components of Scientific Communication skills	Indicator
Searching information	• Use of library resources (printed books, teaching modules, articles, and the internet) • Selection of Library source quality
Scientific writing (Compiling the report)	• Quality of exposure (citation) of the literature review • Discussion of content in the report
Communicate the report orally (presentation)	• Fluency of speech in expressing opinions • Delivery of the content of the opinion • Active in expressing ideas, respecting other students' opinions • Ability to present material (focused, systematic) and display quality • Using of language

The criteria for science communication skills were used as a guideline in this study, and science communication skills data were analyzed statistically. The indicators of the science communication skills assessment range are listed by Spektor-Levy et al., (2008) that shown in Table 4.

Table 4. The rubric of science communication skills

The range (%)	Category
81 ≤ score ≤ 100	Very skilled
61 ≤ score ≤ 80	Skilled
40 ≤ score ≤ 60	Enough Skilled
<40	Less Skilled

After the learning activities, data were obtained in the form of pretest and posttest results. The n-gain value was calculated from both data to determine the improvement of critical thinking skills and science communication. The n-gain formula (Hake, 1998) used is as follows in Table 5.

$$\langle g \rangle = \frac{\% \langle G \rangle}{\% \langle G \rangle_{max}} = \frac{\% \langle S_f \rangle - \% \langle S_i \rangle}{100 - \% \langle S_i \rangle} \qquad (1)$$

Table 5. Interpretation of n-gain score

n-gain score $\langle g \rangle$	Interpretation
$\langle g \rangle \geq 0.7$	High
$0.7 > \langle g \rangle \geq 0.3$	Medium
$\langle g \rangle < 0.3$	Low

Then, the posttest results of the control class and the experimental class were calculated using Cohen's d effect size to determine the difference in the results of improving critical thinking skills and large science communication skills between the control class and the experimental class. The Cohen's d formula is as follows.

$$\langle \boldsymbol{d} \rangle = \frac{M_{group1} - M_{group2}}{SD_{pooled}} \qquad (2)$$

While the interpretation of the results of the Cohen's d value (Becker, 2000; Kayaalp et al., 2020) is in Table 6.

Table 6. Interpretation of Score Cohen's d

Cohen's Standard	Effect Size	Percentile Standing	Percent of Nonoverlap
Large	2.0	97.7	81.1%
	1.9	97.1	79.4%
	1.8	96.4	77.4%
	1.7	95.5	75.4%
	1.6	94.5	73.1%
	1.5	93.3	70.7%
	1.4	91.9	68.1%
	1.3	90	65.3%
	1.2	88	62.2%
	1.1	86	58.9%
	1.0	84	55.4%
	0.9	82	51.6%
Large	0.8	79	47.4%
	0.7	76	43.0%
	0.6	73	38.2%
Medium	0.5	69	33.0%
	0.4	66	27.4%
	0.3	62	21.3%
Small	0.2	58	14.7%
	0.1	54	7.7%
	0.0	50	0%

RESULT AND DISCUSSION

Improving Learners' Critical Thinking Skills Through the Implementation of Writing to Learn Strategy

The research yielded data in the form of pretest and posttest scores, which were utilized to assess improvements in students' cognitive abilities and critical thinking skills. To evaluate the enhancement of critical thinking skills, 5 questions were employed for both the pretest and posttest. These questions were in the form of essays and categorized as Higher Order Thinking Skills (HOTS). The analysis of the pretest and posttest results revealed the following outcomes through Figure 1.

Figure 1 shows that the n-gain in the control class is in the low category, while the n-gain in the experimental class is in the high category. It can be seen that there are significant results for n-gain in the experimental class. Therefore, it can be said that the use of writing to learn strategies in the learning process can effectively improve students' science critical thinking skills. From the n-gain value obtained, the following is a description of the results of the calculation of critical thinking indicators through Table 7.

Based on Table 7 above in the experiment, the average score is 90, so that it can be categorized as the critical thinking ability of students in answering questions is very high. This proves that in the experimental class, at the beginning of student learning, good critical thinking skills. From the two results of the average value obtained by the experimental class and the control class, it can be proven that the students' critical thinking skills in the experimental class are higher than in the control class.

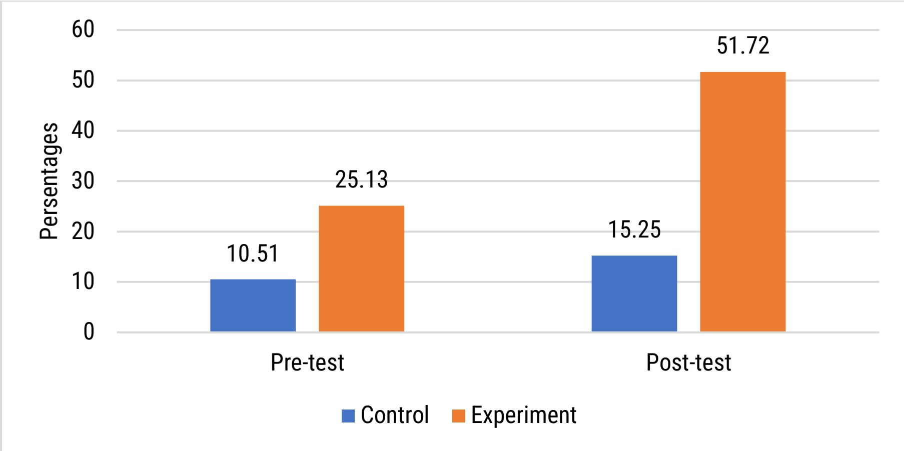


Figure 1. Graph of Increasing The Critical Thinking Abilities

Table 7. Results of Critical Thinking Indicators

Indicator	Experiment Class			Control Class	
	No. item	CTS	Category	CTS	Category
Give a simple explanation	1	90	Very high	72	High
	5	58	Medium	40	Low
Build Basic Skills (Basic support)	4	72	High	68	High
	3	64	High	55	Medium
Conclusion	2	80	High	75	High

In the indicator of providing simple explanations, students' critical thinking skills get a score of 64, which can be categorized as students' critical thinking skills in answering high-level questions. In the control class, the average is 56, so that it can be categorized as the critical thinking skills of students in answering questions in the low category. Like previous research conducted by Stephenson et al., (2019) that in the control class, the low writing culture was caused by the weak writing learning system in schools. The reality that occurs shows that learning to write is still not getting the attention it deserves. Writing learning as one of the aspects in learning that is not handled seriously.

Observations on the aspects of critical thinking skills using the writing to learn strategy are assessed from the results of the reports made. The aspects of the report assessment are assessed based on Ennis' critical thinking skills aspects. The report is made from light wave material based on the video shown by the teacher during learning. It can be seen that the indicator of skills to account for the results of observation obtained an average value of 80. From the results of the observations and data analysis described above, it is concluded that the indicator of accountability skills is categorized as high. In the sub-indicator of reporting observation results, the value obtained is 100. From the results of the observations and data analysis described above, it is concluded that the sub-indicator category of reporting the results of observations is very high. While in the sub-indicator analyzing the results of observations by describing in the form of a simple explanation, the result obtained is 60, classified as medium.

Based on the results of analyzing student answers, it shows that most students write conclusions well. Basically, almost all groups write the core conclusions almost the same and are in accordance with or related to the formulation of the problem, but judging from the arrangement of words or sentences, there are still incomplete. This is because students in a group are less able to express something through clear and directed language.

At the end of the experimental activity, after each group had made a conclusion from an experiment, the conclusions of each group were then put forward and discussed until a single conclusion was obtained from all groups. After that, each group wrote the conclusion of the class discussion (between groups). Observation and assessment were carried out by looking at the overall coverage of the material contained in the conclusions they made. Some students/groups write conclusions less clearly because, in the preparation of words according to their own opinions, there are words that are repeated. The following results of the calculation of Cohen'd effect size are presented in Table 8.

Table 8. *Effect Size Cohen'd*

Class	M	SD	SD_{pooled}	D	Category
Experiment	40.55	13.00	11.56	1.5	Large
Control	20.11	10.25			

Based on Table 8, the result of the calculation of Cohen's d effect size is 1.5, which is included in the large category. These results indicate that there is a large difference in the results of improving critical thinking skills between the control class and the experimental class. Then, compared again with Table 4, the price of 1.5 also shows that the average posttest score of the experimental class (40.55) is at the 91.5th percentile of the control class. This means that 91.5% of the control class scores were below the value of 40.55. So, students taught with the writing to learn approach have higher critical thinking skills than students taught without the writing to learn approach.

The integration of the Writing to Learn (WTL) strategy in teaching wave phenomena in physics aimed to enhance students' critical thinking abilities. This approach included reflective and analytical writing exercises that encouraged students to deeply engage with intricate topics like wave propagation, interference, diffraction, and resonance. At the start of each subtopic, students kept organized learning journals where they noted their interpretations, inquiries, and conceptual difficulties related to wave behavior. For example, following a lesson on wave interference, students were asked to describe in their own words the conditions for constructive and destructive interference and to connect these to real-world instances, such as noise-cancelling headphones or diffraction patterns in optics.

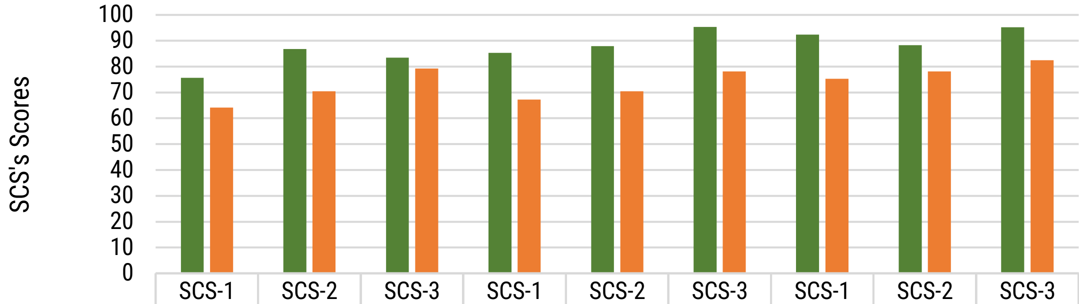
To foster higher-order thinking, "quick write" activities were regularly conducted in class. Prompts like "How does the principle of superposition apply to both mechanical and electromagnetic waves?" or "In what ways might resonance be both beneficial and hazardous in real-life engineering applications?" required students to apply their conceptual understanding, make cross-domain connections, and assess implications beyond textbook definitions. These initial writings were succeeded by collaborative group discussions, where students shared their interpretations and challenged each other's reasoning using evidence from simulations, lab experiments, and theoretical models. This dialogic process aided students in refining their thoughts and developing more sophisticated scientific arguments. As a final task, students wrote a structured essay analyzing a wave phenomenon of their choice, such as seismic waves in geophysics or ultrasound in medical imaging, by integrating theoretical concepts, experimental data, and practical applications. These essays showed significant improvements in logical reasoning, conceptual integration, and the use of scientific evidence, indicating progress in their critical thinking skills. The implementation of the Writing-to-Learn (WTL) approach in the instruction of wave topics has demonstrated efficacy in enhancing students' conceptual comprehension and analytical reasoning. The iterative process of writing, reflecting, and discussing facilitated learners' transition from rote memorization to critical engagement with fundamental physical principles.

Kayaalp et al. highlight that writing-to-learn activities facilitate the establishment of cause-and-effect relationships and enable students to compare similarities and differences in their learning processes, thereby accelerating the development of critical thinking skills (Kayaalp et al., 2020). This aligns with findings from Qoura and Zahran, who assert that the 6+1 Trait Writing Model significantly enhances both critical thinking and writing achievement among students, demonstrating that writing serves as a manifestation of critical thinking practices (Suteja & Setiawan, 2022; Negretti et al., 2023). Furthermore, the Think-Talk-Write (TTW) learning strategy has been shown to be more effective than conventional methods in promoting critical thinking skills, suggesting that structured writing activities can lead to improved cognitive outcomes (Nasrulloh & Umardiyah, 2021; Patriot et al., 2018; Patriot & Jannah, 2022).

The effectiveness of the writing to learn approach lies in its ability to enhance students' capabilities, particularly in knowledge acquisition. According to Waters, P. M (2014), this strategy is highly effective in improving students' skills across various disciplines and educational stages, ranging from elementary school to university level. Physics learning activities on wave material through the report writing process can help students build and modify their understanding. At each stage of report writing, students are trained to build their critical thinking process. According to Fellows (1994), writing-to-learn exercises can enhance students' understanding and cognitive capabilities by fostering critical thinking, analytical skills, and practical application. The act of writing not only improves scientific observation and reasoning abilities but also helps students organize their thoughts more effectively. Furthermore, engaging in writing tasks encourages students to become more actively involved in their learning process.

Improving Learners' Science Communication Skills (SCS) through the Implementation of Writing to Learn Strategy

Besides that, students can enhance their ability to effectively communicate in academic and real-world settings by using writing as a means to express their comprehension of intricate scientific ideas. This analysis examines how different writing techniques contribute to the growth of these crucial skills (Pisano et al., 2021). In this study, observations were made to see how the improvement of students' science communication skills occurred at each meeting in both the experimental and control classes. The results of observations at each meeting are represented in Figure 1 below.



	SCS-1	SCS-2	SCS-3	SCS-1	SCS-2	SCS-3	SCS-1	SCS-2	SCS-3
	1st Meeting			2nd Meeting			3rd Meeting		
Experiment	75.7	86.8	83.5	85.3	87.9	95.4	92.4	88.3	95.2
Control	64.2	70.5	79.2	67.3	70.5	78.2	75.3	78.2	82.5

Figure 1. Histogram the percentage of SCS's observation result

The figure above represents different improvements at each meeting in both the control and experimental classes on wave material. The communication skills that were given more attention were written communication skills. Students' written communication skills were obtained from journal writing assignments given to students at each meeting and assessed based on an assessment rubric developed by Sinaga (2014). The assessment of students' written communication skills is seen from the clarity and correctness of concepts, the mode of representation used, the breadth and depth of the material, the conceptual hierarchy and organization of writing, the main idea of writing, as well as writing rules and punctuation and influence. Another result of science communication skills for each meeting can be represented from Table 9 below.

Table 9. Increase of Students' Science Communication Skills

Component	1st Meeting	2nd Meeting	Averages (%)	Category
SCS-1	9.6%	7.1%	84.5%	High
SCS-2	1.1%	2.3%	87.7%	High
SCS-3	11.9%	12.0%	91.4%	High

The SCS-1 component experienced a significant increase in the first two meetings. The average achievement of 84.5% indicates that the majority of students have mastered this skill in the high category. The consistent improvement in both meetings indicates that the learning approach used effectively developed this aspect from the beginning. SCS-2 showed a smaller increase than the other components, but the average achievement remained high. This can be interpreted as students already having a fairly good initial ability in this component, so the room for improvement is relatively smaller. The "High" category indicates that although the improvement is not drastic, students' competence in this aspect is stable and strong.

SCS-3 experienced the greatest and most consistent improvement between the first and second meetings. The average achievement reached 91.4%, the highest among the three components. This shows that students not only progressed quickly in this aspect, but also reached a very high level of mastery. This may reflect the success of the learning method in stimulating critical, collaborative thinking or scientific presentation skills. Overall, all three SCS components were in the "High" category, both in terms of improvement and average achievement. This indicates that the learning approach used in the experimental class improved students' science communication skills. The skills achieved improved over time and showed strong and evenly distributed outcomes across all components.

One effective approach is the use of self-regulated writing strategies (SRWS), which empower students to take control of their writing processes. Research indicates that explicit instruction in SRWS can improve writing performance and promote greater self-regulation among students. By linking their writing strategies to other relevant learning strategies, students become more resourceful and strategic in their approach to writing tasks, which is crucial in the context of physics, where complex ideas must be communicated clearly (Umamah et al., 2022). Furthermore, the development of metacognitive knowledge through writing instruction enhances students' understanding of their own learning processes, enabling them to plan, organize, and evaluate their writing more effectively (Lam, 2015).

Graphic organizers are another valuable tool that can enhance students' academic achievement in physics. By providing a structured framework for organizing information, graphic organizers facilitate the writing process and help students clarify their thoughts before communicating them (Uzomah et al., 2024). This strategy not only aids in the retention of scientific concepts but also fosters a deeper understanding of the material, which is essential for effective science communication (Glogger et al., 2012; Harrington et al., 2024). The combination of graphic organizers with writing tasks encourages students to engage with the content actively, leading to improved writing skills and better communication of scientific ideas.

This study has shown new findings that the application of the Writing to Learn strategy can improve students' critical thinking skills and transfer students' communication skills both verbally and non-verbally. This study showed that the *Writing to Learn (WTL)* strategy significantly improved students' critical thinking and scientific communication skills on the topic of waves. The experimental group that received WTL treatment showed significant improvement compared to the control group. The *Cohen's d* value of 1.5 indicates a large effect. All indicators of students' scientific communication fell into the high category, and there was a significant increase in critical thinking scores in the high category based on *n-gain*.

These results are in line with the research of Kayaalp et al. (2020), Cintamulya et al. (2023), and Sinaga et al. (2017), which showed that writing activities can encourage higher-order thinking skills and strengthen concept understanding. This study has shown novelty by explicitly integrating WTL strategies in the context of physics (wave material), which has not been specifically reviewed in other studies. Most other studies emphasize general or chemistry lessons, while this study focuses on the real context of wave matter. The results reflect the urgency of learning that emphasizes 21st-century competencies, especially in facing the challenges of the Industrial Revolution 4.0 and society 5.0. The WTL strategy shows that the development of *science literacy* and *critical thinking skills* can be achieved not only through lectures or experiments, but through reflective and collaborative writing processes. This brings students closer to authentic scientific processes and strengthens their readiness to face real-world challenges.

Limitation and Recommendation

Significant results were obtained because reflective writing encourages students to process information more deeply (*deep learning*); discussions between students after writing activities allow clarification of concepts; structured assignments encourage students to develop argumentation and synthesis of information, which is the essence of critical thinking. Based on the findings in the field, it is necessary to organize teacher training on WTL strategies and develop appropriate assessment instruments. Writing to Learn strategies can be integrated with digital and collaborative media, such as online *learning journals* or online discussion forums. In the development of further research, it is recommended to examine the effect of Writing to Learn on other aspects such as learning motivation, concept retention, and scientific argumentation skills.

CONCLUSION

In wave material, students' critical thinking skills have increased to high criteria after the implementation of writing to learn strategies. This can be seen from the results obtained through the pre-test and post-test, before and after implementation, and after going through the learning process, which is then analyzed using N-gain. The implementation of *Writing to Learn* (WTL) strategies in physics instruction on wave concepts has proven effective in enhancing students' critical thinking and science communication skills. The experimental group, which engaged in reflective writing, structured journaling, and peer discussions, demonstrated significantly higher gains in critical thinking compared to the control group, as evidenced by a large effect size (Cohen's d = 1.5). Furthermore, students showed marked improvement in communicating scientific ideas both in written and oral forms, with all components of science communication skills reaching the "high" category. These findings highlight the potential of writing-based instructional strategies to foster deeper conceptual understanding, analytical thinking, and effective communication key competencies required in 21st-century science education. For future education practice, the test items can be combined with education technology, like flipbooks, to assess the development of students' critical thinking and communication skills. Future studies are encouraged to integrate WTL with digital tools to further enhance learning outcomes.

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