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Enhancing High School Students' Critical Thinking in Physics through a Virtual Classroom Critical Thinking Model: Supporting SDG 4 (Quality Education)

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Abstract: Developing students' critical thinking skills (CTS) has become an essential focus in 21st-century education, particularly in digital learning environments. This study aims to examine the effectiveness of the Virtual Classroom Critical Thinking (VC2T) model in enhancing senior high school students' CTS in physics learning. A pre-experimental one-group pre-test–post-test design was employed involving 56 eleventh-grade students from two science classes at a private senior high school in Surabaya, Indonesia. Data were collected using a CTS test based on Facione's indicators: interpretation, analysis, evaluation, inference, and explanation, and a student response questionnaire. Data analysis involved normalized gain (n-gain), paired-sample t-test, and effect size calculations. The results indicate a statistically significant improvement in students' CTS after the implementation of the VC2T model, with a medium n-gain and strong effect size. In addition, students expressed positive response toward the VC2T-based learning experience. These findings suggest that the VC2T model has strong potential as an effective online instructional approach for fostering critical thinking skills in physics learning.

Keywords: Critical thinking skills; Higher-order thinking skills; Physics learning; VC2T model; Virtual classroom

Introduction

Critical thinking refers to an individual's ability to connect ideas, evaluate information, and develop logical understanding in order to solve complex problems. It is not a single skill, but a combination of knowledge, dispositions, and cognitive abilities that enable individuals to reason reflectively and make well-grounded judgments (Hitchock, 2017; Lestari et al., 2021b). Through critical thinking, learners are able to relate new information to prior knowledge, assess alternative perspectives, and arrive at reasoned decisions. As emphasized by Halpern (2014), critical thinking skills (CTS) are essential for preparing individuals who can respond effectively to the challenges of the 21st century, particularly in contexts that require complex decision-making and problem solving.

In physics education, CTS are widely recognized as a core component of higher-order thinking skills (HOTs). Students with well-developed CTS tend to approach scientific problems more thoughtfully, evaluate evidence, and articulate conclusions logically (Cheng et al., 2020). Empirical studies consistently show that students with well-developed CTS achieve higher learning outcomes than those with lower levels of critical thinking, as CTS involve not only cognitive processes but also attitudes, evaluative judgment, and reflective reasoning (Almubarokah et al., 2025; Lestari et al., 2021a, 2021b).

Despite its importance, evidence from international assessments indicates that Indonesian CTS remain limited. Results from the 2022 Programme for International Student Assessment (PISA) reveal that most Indonesian students aged 15 perform at Level 2, which reflects basic recall and recognition, whereas

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higher levels require complex reasoning and evaluation (Lestari et al., 2024; OECD, 2023). This gap indicates that current physics instruction has not yet effectively facilitated the development of higher-order thinking, particularly CTS. Therefore, there is a strong need for instructional approaches that explicitly integrate CTS into learning processes.

At the same time, digital technology has become an integral part of contemporary education. Learning is no longer confined to traditional classrooms but increasingly occurs through digital platforms that enable flexible interaction and access to information (Lestari et al., 2021b; Li et al., 2023; Wang et al., 2023). Within network-based learning environments, teachers and students can interact, exchange ideas, and construct understanding beyond the constraints of time and place (Cheung et al., 2020; Kementerian Pendidikan, 2023; Lie et al., 2023; Opdenakker & Minnaert, 2014; Ping et al., 2026; Schneider & Council, 2021; Thaiposri & Wannapiroon, 2015). However, the integration of technology in many classrooms still tends to focus on content delivery rather than fostering students' higher-order thinking. This creates a critical gap between technological adoption and pedagogical effectiveness, particularly in supporting CTS development in physics learning.

In response to this need, the VC2T Model was developed as a technology-enhanced instructional approach that embeds opportunities for interpretation, analysis, evaluation, inference, and explanation within virtual learning environments, enabling students to engage in evidence-based reasoning and reflective thinking. Previous findings from a small-scale study involving 33 students indicated a moderate improvement in CTS (n-gain = 0.38) (Lestari et al., 2021a, 2021b). However, these findings are limited to a small sample and a single-class context, leaving a gap in understanding the broader applicability and consistency of the model's effectiveness.

Therefore, the novelty of this study lies in extending the implementation of the VC2T Model to a broader and more representative sample in senior high school settings, while systematically examining its effectiveness in enhancing students' CTS within a structured virtual classroom environment. This study not only replicates previous findings but also strengthens empirical evidence by applying the model across multiple classes, thereby improving the reliability and generalizability of the results.

Teaching in physics education involves facilitating students' development of scientific understanding and higher-order thinking skills through active learning processes such as inquiry and problem solving. In the digital age, this requires teachers to design interactive and technology-supported learning environments that effectively engage students and promote meaningful learning (Rajagopalan, 2019). Within this framework, teaching models play a critical role in structuring instructional practices (Joyce et al., 2015).

According to Joyce et al. (2015), an effective teaching model comprises five essential elements: social system, support system, syntax, instructional as well as nurturant effects, and principles of reaction. The syntax defines the sequence of learning phases, while the social system regulates patterns of interaction between teachers and students. These interactions are particularly important in physics learning, as knowledge is constructed through dialogue, collaboration, and shared inquiry. Drawing on the ideas of John Dewey, learning becomes more meaningful when classrooms function as social environments that promote active participation and reflective thinking (Bryce & Blown, 2024). Consequently, the success of a teaching model depends not only on its structure but also on the extent to which it fosters productive social and cognitive engagement.

Building on these theoretical foundations, the VC2T Model was developed as a technology-enhanced instructional model designed to explicitly foster students' CTS in physics learning contexts (Lestari et al., 2021b). The model systematically integrates the core components of critical thinking as proposed by Facione: interpretation, analysis, evaluation, inference, and explanation—into each phase of the learning process. The VC2T Model combines principles of blended learning and inquiry-based learning, integrating asynchronous and synchronous activities to support students in interpreting information, analyzing problems, evaluating evidence, drawing logical inferences, and articulating reasoned explanations (Lestari et al., 2021b, 2021a). Rather than positioning technology as a mere delivery tool, VC2T emphasizes structured pedagogical design that actively engages students in these higher-order cognitive processes within virtual learning environments.

Based on Table 1, the VC2T Model consists of six sequential phases: problem orientation, formulation, group discussion, analysis, results discussion, and reflection (Lestari et al., 2021b). These phases are implemented using digital platforms such as Google Classroom for asynchronous activities and zoom for synchronous interactions. Learning begins with problem orientation, where contextual scientific phenomena are presented to activate prior knowledge and stimulate curiosity (Slavin, 2017). Students then formulate hypotheses based on the given problems and relevant literature, which are subsequently examined through collaborative group discussions and data analysis activities (Fine & Desmond, 2015).

Table 1. The VC2T Model Syntax, Teaching System, and Description of Each Phase

Phase	Teaching System	Description
Phase 1: Problem Orientation	Asynchronous	Delivering learning objectives presenting videos/pictures/animations to motivate students to participate in learning process
Phase 2: Formulation	Asynchronous	Formulating hypotheses according to literature review
Phase 3: Group Discussion	Synchronous	Facilitating and instructing students to observe video-based experiments (YouTube) and systematically record the observed data
Phase 4: Analysis	Synchronous	Analyzing observational data obtained from video-based experiments (YouTube) to determine whether the proposed hypothesis can be accepted or rejected
Phase 5: Results Discussion	Synchronous	Presenting observational data
Phase 6: Reflection	Asynchronous	Evaluating learning activities and conducting further investigations by presenting problems in the form of anomaly data that is still related to observations that have been carried out

In the later phases, students present and discuss their findings, engage in argumentation based on evidence, and reflect on their learning processes. The reflection phase encourages students to evaluate their conceptual understanding and extend inquiry through follow-up problems. Through this structured and iterative process, the VC2T Model is designed to support sustained engagement in critical thinking and scientific reasoning across multiple learning sessions. However, many existing digital learning practices still lack structured mechanisms that explicitly guide students through higher-order thinking processes, resulting in limited development of CTS. This highlights the need for instructional models that systematically integrate cognitive processes within each phase of learning.

Thinking is a central component of the learning process because it allows learners to relate newly acquired information to their existing knowledge and use it meaningfully when addressing problems (Heard et al., 2020; Kadel, 2014). Memory and thinking operate as interdependent cognitive processes, where long-term memory and working memory interact to support understanding, reasoning, and decision making (Duran & Dökme, 2016; Heard et al., 2020; Lestari et al., 2021b). This dynamic interaction becomes increasingly important in higher-order cognitive processes, including critical thinking, which requires learners to retrieve, evaluate, and integrate information across contexts (Kadel, 2014).

From a theoretical perspective, experiential learning theory introduced by David Kolb views learning as an iterative process involving concrete experience, active experimentation, abstract conceptualization, and reflective observation. This cyclical process provides a strong foundation for the development of problem-solving abilities and CT, as learners are encouraged to reflect on experiences, construct conceptual understanding, and test ideas through active inquiry (Ghazivakili et al., 2014; Zulmaulida et al., 2018).

Critical thinking (CT) is commonly understood as a core cognitive skill that supports effective problem solving and informed decision making. It involves purposeful, reflective, and rational thinking processes that enable individuals to analyze information, evaluate evidence, and draw logical conclusions (Kadel, 2014; Karakoç, 2016). Within educational settings, CT plays a vital role not only in supporting academic achievement but also in preparing students to engage meaningfully with complex scientific concepts and real-world problems. Learners with strong CT abilities are generally more capable of proposing hypotheses, interpreting data, integrating multiple sources of information, and constructing explanations grounded in evidence (Ghazivakili et al., 2014; Lestari et al., 2021b).

In the context of 21st-century education, the development of CTS has become a central objective of physics education worldwide (Heard et al., 2020). However, fostering these skills remains challenging, particularly when learning environments emphasize passive reception of information rather than active inquiry and reflection. This gap indicates that the integration of digital technology alone is not sufficient; it must be accompanied by well-structured pedagogical strategies that actively engage students in critical thinking processes.

Responding to this challenge, the VC2T Model was designed as a structured instructional approach that embeds critical thinking processes within virtual learning environments. The model aligns with established theories of learning and cognition by providing systematic opportunities for students to engage in problem analysis, evidence-based reasoning, collaborative discussion, and reflective evaluation across learning phases (Lestari et al., 2021b). In this study, students' CTS are operationalized using five core indicators: inference, interpretation, explanation, analysis, and evaluation, as proposed by Peter Facione (2015). The novelty of this study lies in the explicit integration of these five critical thinking components into a structured virtual classroom model and its application in a broader classroom context to examine its effectiveness. This study is important as it provides empirical evidence on how a technology-enhanced instructional model can bridge the gap between digital learning practices and the systematic development of students' critical thinking skills in physics education.

Method

This study used pre-experimental one-group pre-test–post-test design without a control group, utilizing a repeated pre-experimental methodology. In this design, students' CTS were measured prior to the intervention (pre-test) and after the implementation of the VC2T model (post-test) (Lestari et al., 2021a). The design shows in Figure 1.

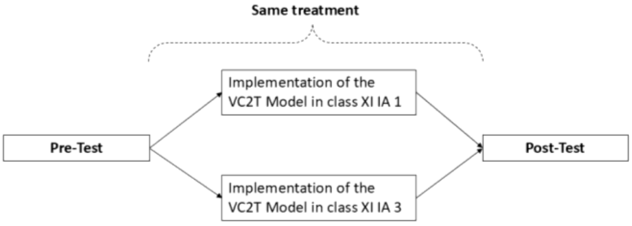

Figure 1. Research design

The participants were 56 eleventh-grade students from two science classes at a private senior high school in Surabaya, Indonesia. All participants received the same instructional treatment using the VC2T Model throughout the study period.

Data were collected through a CTS test and a student response questionnaire. The CTS test and learning instruments associated with the VC2T model had previously demonstrated high levels of validity and acceptable reliability. Following the completion of the post-test, students were asked to complete a questionnaire to capture their responses to the learning process.

Equation (1) was used to calculate the normalized gain (n-gain) based on the data from the students' CTS test results in order to determine the degree of increase in the CTS score with the criteria displayed in Table 2 (Lestari et al., 2021a).

$$n - gain = \frac{X_m - X_n}{100 - X_n} \tag{1}$$

Remarks: X_n = score before learning process; n-gain = normalized gain; X_m = score after learning process.

The paired t-test, which is used to ascertain whether or not there was an increase in students' CTS at a significance level of 5% following learning with the VC2T model, is calculated using SPSS 26 after the n-gain has been calculated. Calculating the effect size comes next after running the paired t-test. One technique for calculating effects in a study is effect size (Cohen et al., 2007). Equation (2) can be used to calculate effect size, and Table 3 displays the effect size categories (Cohen et al., 2007).

Table 2. Criteria N-Gain (Hake & Reece, 1999; Lestari et al., 2021b)

Interval	Criteria
N-gain > .7	High
.3 ≤ N-gain ≤ .7	Medium
N-gain < .3	Low

$$Effect\ size = \frac{mean\ of\ post\ test - mean\ of\ pre\ test}{standard\ deviation} \tag{2}$$

Table 3. Effect Size Category (Cohen et al., 2007; Lestari et al., 2021b)

Interval	Category
> 1.00	Strong Effect
.51 – 1.00	Moderate Effect
.21 – .50	Modest Effect
0 – .20	Weak Effect

Students completed the questionnaire following the teacher's application of the VC2T paradigm. A Likert scale is used in the questionnaires. Equation (3) was used to calculate the student response questionnaires, which were then subjected to both quantitative and qualitative analysis.

$$P = \frac{\Sigma K}{\Sigma N}\ x\ 100\ \% \tag{3}$$

Remarks: ΣN = Number of the highest students' scores ; ΣK = Number of scores students get; P = Percentage of student responses. Following that, the student replies are categorized, as Table 4 illustrates (Lestari et al., 2021b).

Table 4. Category Percentage of Student Responses

Interval	Category
0 - 20	Bad
21 - 40	Not Good
41 - 60	Adequate
61 - 80	Good
81 - 100	Very Good

The VC2T model was considered effective in fostering students' CTS when the following criteria were met: (1) a statistically significant improvement in students' CTS at the 5% significance level; (2) an average CTS n-gain in each experimental class that reached at least the moderate category; (3) a minimum effect size classified as moderate; and (4) student responses toward learning with the VC2T model that were rated at least as good.

Result and Discussion

Students' (CTS) were measured using a CTS instrument consisting of 20 open-ended essay items focused on static fluid concepts. The test was administered twice, namely before instruction (pre-test) and after the implementation of the VC2T model (post-test). Normalized gain (n-gain) values were calculated based on the pre-test and post-test scores to determine students' improvement in CTS. The pre-test, post-test, and n-gain results across the two experimental classes are presented in Table 5.

Table 5. Pre-test, Post-test, and N-gain CTS

Class	Pre-test	Post-test	n-gain	Category
XI IA 1	45.28	77.86	.59	Medium
XI IA 3	43.59	76.59	.58	Medium

As shown in Table 5, the mean pre-test scores in Classes XI IA 1 and XI IA 3 were all below 46, indicating a low initial level of CTS. Following the implementation of the VC2T model, the mean post-test scores in all classes exceeded 77, which falls within the high category. In addition, the average n-gain values across the two classes were greater than 0.50, indicating a moderate level of improvement.

Table 6. CTS Scores for Each Indicator

Indicator of CTS	Class	Pre- test	Post-test	n-gain	Category
Interpretation	XI IA 1	48.24	79.96	0.61	Medium
	XI IA 3	40.15	81.24	0.69	Medium
Analysis	XI IA 1	46.58	76.18	0.55	Medium
	XI IA 3	44.98	75.62	0.56	Medium
Evaluation	XI IA 1	46.55	78.65	0.60	Medium
	XI IA 3	46.46	77.94	0.59	Medium
Inference	XI IA 1	42.78	77.61	0.61	Medium
	XI IA 3	47.24	76.43	0.55	Medium
Explanation	XI IA 1	42.26	76.88	0.60	Medium
	XI IA 3	39.12	71.72	0.54	Medium

Table 6 presents students' CTS scores in Classes XI IA 1 and XI IA 3 based on the CTS indicators applied in this study. The results indicate that the mean pre-test scores across all indicators in the two classes were categorized as low, ranging from 39.12 to 48.24. After instruction using the VC2T model, the mean post-test scores for all CTS indicators in each class increased to the high category, with values ranging from 71.72 to 81.24. Furthermore, the normalized gain (n-gain) values for all indicators ranged from 0.54 to 0.69, indicating a moderate level of improvement.

The improvement in students' CTS was examined by comparing the mean pre-test and post-test scores of each class using a paired-sample t-test. This parametric test was applied after the assumption of normality was satisfied, as indicated by the Shapiro–Wilk normality test showing that the CTS n-gain data from all two classes were normally distributed. The results of the paired t-test comparing students' CTS pre-test and post-test scores are presented in Table 7.

Table 7. The Results of Paired T-Test Students' CTS Scores

Class	N	Mean	S	df	t	Sig. (p)
XI IA 1	29	-32.73	4.29	28	-41.71	.000
XI IA 3	27	-33.00	5.24	22	-30.20	.000

Table 7 indicates that the significance values ($p < .05$) were obtained for all two classes, leading to the rejection of the null hypothesis, which assumed no difference between the mean pre-test and post-test scores. This result demonstrates that a statistically significant difference existed between students' pre-test and post-test CTS scores. The negative t-values observed in each class further indicate that the post-test means were higher than the pre-test means. Accordingly, it can be concluded that students' CTS increased significantly after the implementation of the VC2T learning model in all two classes.

Following the paired-sample t-test analysis, the magnitude of the instructional impact was examined by calculating the effect size. The results, presented in Table 8, indicate that the effect size values for all classes fall within the strong effect category. These findings suggest that the implementation of the VC2T model produced a substantial improvement in students' CTS.

Table 8. Effect Size Calculation Results for Each Class

Class	Score	Category
XI IA 1	7.59	Strong Effect
XI IA 3	6.30	Strong Effect

Based on the findings summarized in Tables 5–8, students' CTS demonstrated a statistically significant increase at the 5% significance level after engaging in physics instruction through the VC2T Model. The mean normalized gain (N-gain) across all CTS indicators consistently fell within the medium category, and statistical analysis revealed no significant differences among the two experimental classes. In addition, the large effect size values obtained in each class reflect a strong instructional influence of the VC2T Model on the development of students' CTS, indicating that the model functions effectively and consistently across different learning groups.

This observed improvement appears to stem from the structured and explicit integration of CT activities within each phase of the VC2T learning process. Before the intervention, students had relatively few opportunities to practice CTS indicators—such as analysis, evaluation, and inference—when addressing physics problems. After the VC2T Model was implemented, students were repeatedly engaged in guided learning cycles that required them to formulate hypotheses, conduct observations, analyze findings, test alternative ideas, and communicate evidence-based conclusions. Such sustained active engagement supports prior arguments that students' CTS often remain underdeveloped when instruction is detached from real-life phenomena and authentic problem situations (Heard et al., 2020; Utami et al., 2017). Furthermore, limited mastery of fundamental concepts has been reported to restrict students' reasoning abilities, particularly when they encounter complex problem scenarios (Fitarahmawati & Suhartini, 2021; Siswanto et al., 2018). Through problem-based inquiry activities, the VC2T Model helps reduce this gap between conceptual understanding and higher-order reasoning.

The results of this study are theoretically in line with Jean Piaget's cognitive development perspective, which posits that knowledge is constructed through active experience and social interaction rather than passive information reception (Lourenço, 2012; Pakpahan & Saragih, 2022). Piaget emphasized that learners continuously reorganize their cognitive structures through interactions with their environment and peers (Huitt & Hummel, 2003; Pakpahan & Saragih, 2022). Learning activities embedded in the VC2T Model—such as experiential tasks, collaborative discussions, and reflective exercises—mirror this constructivist orientation by positioning learning as an active meaning-making process instead of mere knowledge transmission (Deechai et al., 2019).

These findings also resonate with Albert Bandura's social cognitive theory, which underlines the importance of observational learning through processes of attention, retention, and reproduction of behavior (Arends, 2012; Firmansyah & Saepuloh, 2022; Fryling et al., 2011). Within the VC2T framework, students observe peers' reasoning during group interactions, internalize conceptual and procedural insights through joint analysis, and subsequently reproduce these skills when solving new problems, thereby reinforcing their CTS. Empirical evidence from earlier studies likewise indicates that inquiry-oriented physics instruction—particularly when supported by digital technology—can substantially enhance students' critical thinking abilities (Duran & Dökme, 2016; Williams et al., 2017).

In the context of contemporary education, digital technology has become increasingly integral to fostering inquiry-based and student-centered learning environments (Mccormick & Scrimshaw, 2001; Riyanto et al., 2020). Previous investigations have shown that learners exposed to technology-supported inquiry approaches generally achieve better academic outcomes than those taught through conventional methods (Hwang et al., 2013; Mensah-Wonkyi & Adu, 2016). While earlier research often highlighted the benefits of online or distance learning during emergency situations, the present study broadens this perspective by demonstrating that thoughtfully designed virtual instructional models can promote CTS development beyond crisis-driven contexts. Importantly, the VC2T Model prioritizes pedagogical design over situational limitations, hybrid, and blended learning implementations.

Table 9. The Results of Student Responses

Group	N	Student Responses (%)	Category
XI IA 1	29	87.25	Very Good
XI IA 3	27	88.46	Very Good

In Table 9, it appears that student's classes XI IA1 and XI IA 3 gave a positive response to teaching using the VC2T model. Most students expressed high levels of enjoyment and learning motivation, which may be associated with the novelty of the instructional experience, the use of meaningful problem contexts, and the availability of opportunities for active participation. These outcomes are in line with previous studies indicating that well-designed online learning environments can enhance students' attention and interest when they correspond with learners' preferences (Nouri, 2016; Wang et al., 2023). In addition, embedding contextual and real-life problems within virtual learning settings has been reported to improve students' readiness and engagement in instructional activities (Adilla & Utami, 2022; Lestari et al., 2021b; Uzunboylu & Karagozlu, 2015). Therefore, educators are encouraged not only to strengthen their subject-matter expertise but also to continuously develop pedagogical and technological competencies in order to design learning experiences that align with instructional objectives (Haleem et al., 2022; Keller, 2016; Mau et al., 2021; Swart, 2017).

Overall, the findings suggest that the VC2T Model is effective in promoting senior high school students' CTS in physics learning. The consistent improvement across CTS indicators, the strong magnitude of instructional impact, and the positive student responses indicate that the VC2T Model represents a pedagogically sound strategy for integrating critical thinking training within virtual and blended physics learning environments. Future studies are recommended to explore the application of the VC2T Model in other physics topics and educational levels, as well as to involve larger and more diverse participant groups to enhance the generalizability of the results.

Conclusion

This study demonstrates that the implementation of the VC2T model effectively enhances students' CTS in physics learning, as evidenced by statistically significant improvements between pre-test and post-test results. The increase in CTS is consistently reflected across all five indicators proposed by Facione: interpretation, analysis, evaluation, inference, and explanation. These findings are supported by moderate n-gain scores in both classes and a moderate to strong effect size, confirming that the VC2T model provides a meaningful contribution to students' cognitive development. The effectiveness of this model is closely related to the implementation of its sequential phases, namely problem orientation, formulation, group discussion, analysis, results discussion, and reflection, which facilitate a structured learning process that supports the development of students' CTS in virtual physics classrooms.

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Conceptualization, methodology, formal analysis, investigation, preparation of original draft, writing—reviewing and editing; TL. The author have read and approved the published version of the manuscript.

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The authors declare no conflict of interest.

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