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ENHANCING PHYSICS LEARNING ACHIEVEMENT, MOTIVATION AND INQUIRY SKILLS IN A FLIPPED CLASSROOM: A STRUCTURED INQUIRY-BASED VIRTUAL LAB APPROACH

Chuang Chen,
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Abstract. *Integrating virtual laboratories (VLs) with science education promotes inquiry-based learning by providing an interactive, dynamic environment in which students actively engage with scientific concepts. While previous research highlights the effectiveness of VLs as tools in the IBL process, few studies have embedded the entire inquiry process within VLs or explored their application in flipped classrooms. This study addresses these gaps by proposing a Structured Inquiry-Based Virtual Lab (SIVL) approach to improve students' physics learning achievement, motivation, and inquiry skills in a flipped physics classroom. A quasi-experimental design was used with 120 ninth grade students from three intact classes in a lower-secondary school located in central China. The three classes were randomly assigned to one of these groups to implement flipped physics learning by using SIVL, General Virtual Lab (GVL), or a traditional flipped classroom (TFC) by using the physics laboratory method, respectively. The results revealed the SIVL approach improved students' physics learning achievement, inquiry skills, and intrinsic and extrinsic learning motivation, which indicates its effectiveness as an innovative model for physics education.*

Keywords: *Inquiry-based learning, structured virtual laboratory, physical learning, learning motivation, inquiry skills*

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Introduction

The study of physics has a positive effect on the development of the student's problem-solving and critical thinking skills, but students often find certain topics particularly confusing. For example, electrical circuits pose particular challenges due to their abstract nature and the difficulty of making connections between theoretical concepts and practical applications (Burde & Wilhelm, 2020). Circuitry involves abstract concepts such as current, voltage, and resistance that are difficult to understand intuitively through everyday experience (Jaakkola & Veermans, 2020). Circuit analysis also requires students to have strong logical thinking skills and spatial imagination to understand the path of current and the distribution of voltage (Preston, 2019). Numerous studies have shown that lower-secondary school students hold many alternative concepts when learning about electrical circuits, such as the concept that current decreases rather than remains constant after passing through each device (Moodley & Gaigher, 2019; Saba et al., 2023). In addition, students tend to confuse current and voltage, often believing that "more current" means "more voltage," and lack a proper modeling understanding of energy transfer and current paths in circuits. These misconceptions prevent them from properly analyzing circuit phenomena and solving circuit problems (Preston et al., 2022). Students' alternative conceptions are difficult to change in traditional physics classrooms, even though these environments allow some physics experiments to be performed in physics laboratories (Tseng et al., 2023). However, due to time constraints, limited equipment, and other resources, physics laboratories are neither widely used nor consistently used in many schools (Gericke et al., 2023). Previous studies have shown that laboratory operations in many science classrooms are hampered by inadequate design, lack of necessary support, unclear pedagogical objectives, and inconsistent implementation (Kaya & Kaya, 2024; Reyes et al., 2024). Given this situation, there is an urgent need for researchers to find more effective ways of overcoming these problems in the traditional classroom in order to improve students' scientific knowledge (Chen & Xiao, 2021).

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With advances in technology, the virtual laboratory (VL) has emerged as an innovative learning environment that allows students to perform experiments without the limitations of physical apparatus and time. A VL is a simulation-based learning platform that allows learners to do experiments online, observe phenomena, and analyze results using virtual tools and interactive designs (Aktaş & Karamustafaoğlu, 2024; Kolil & Achuthan, 2024). Compared to general physical laboratory (GVL), VLs offer high flexibility, reproducibility and real-time feedback, enabling learners to build and refine their comprehension of physical concepts more effectively in a safe and repeatable environment (Aljuhani et al., 2018; Reyes et al., 2024). VLs offer numerous benefits for students learning physics. For example, VLs provide interactive platforms for students to conduct comprehensive scientific investigations and engage in scientific practices, particularly for phenomena that are difficult to observe in real-world settings (Vergara et al., 2022). In addition, the Yazici and Nakiboglu (2024) highlight that VLs enable students to visualize underlying processes and mechanisms in natural phenomena that are not directly observable, thus supporting the development of accurate mental models for understanding complex, abstract concepts.

Previous research has highlighted the benefits of virtual labs for improving student learning performance. For example, Nolen and Koretsky (2018) found that students in virtual labs demonstrated deeper engagement, contributed more actively to group learning, had more opportunities to integrate prior knowledge, and showed greater interest in engineering problem solving than students in traditional labs. Similarly, Husnaini and Chen (2019) observed that virtual labs were more effective than physical labs in facilitating students' understanding of complex scientific concepts and improving their self-efficacy in scientific inquiry. However, some scholars argue that simply providing VLs alone does not necessarily result in optimal learning outcomes, given the inherent difficulties of scientific inquiry and the challenges posed by VL environments (Liu et al., 2021; Wang et al., 2022). Therefore, the selection of appropriate instructional strategies to support students in navigating scientific inquiry in virtual environments is essential (Banda & Nzabahimana, 2021). Among these strategies, inquiry-based learning (IBL) approaches occupy an important place in science education, and their implications and influence have been discussed in recent decades. For example, the review by Kamarudin et al. (2024) found that most studies on the effects of integrating technology and inquiry-based pedagogy showed positive effects on students' science learning, including improvements in conceptual understanding, scientific and thinking skills, perceptions of science, motivation and interest levels, and collaborative skills. IBL stands out as a widely recognized and effective approach because of its alignment with the core scientific practice of inquiry and its emphasis on student-centered learning (Kang & Keinonen, 2018). In addition, IBL promotes students' conceptual understanding and skill development by guiding them through an authentic inquiry cycle that includes planning and carrying out investigations, collecting data using appropriate technological tools, analyzing different interpretations, and communicating findings (Kamarudin et al., 2024).

Although it has been shown that combining IBL with VLs can effectively enhance students' science learning. For example, Zheng et al. (2024) demonstrated that using VLs for scientific inquiry activities significantly improved students' understanding of scientific concepts and their scientific epistemic beliefs. Students' observation time and inquiry strategies were significantly strengthened. In addition, Ogegbo and Ramnarain's (2022) study showed that integrating virtual interactive stimulation techniques into inquiry-based activities can be effective in increasing learners' deep understanding of scientific concepts. Furthermore, Kolil and Achuthan's (2024) study found that incorporating VLs into IBL chemistry learning reduced alternative conceptions and increased students' awareness of laboratory education through increased participation, improved learning outcomes and enhanced skills. However, the literature review showed that most of these studies only used VLs as experimental tools in the investigation phase of IBL, and teacher involvement was still needed to guide students in key phases of IBL, such as the orientation or conceptualization phases (Aktaş & Karamustafaoğlu, 2024; Galan et al., 2017; Kapici et al., 2022). Although this teacher-led guidance has facilitated the implementation of IBL to some extent, it has not achieved fully independent student-centered inquiry. In fact, traditional IBL practices often rely on direct teacher intervention in the scientific inquiry process, and students are not really equipped to engage in IBL learning fully independently under this model (Voet & De Wever, 2019).

The introduction of the Flipped Classroom (FC) model can effectively address this issue. Flipped classroom, as a student-centered pedagogy, emphasizes the advancement of knowledge transfer and exploration tasks, which enables students to focus on in-depth scientific investigations and problem-solving processes in the pre-class phase (Akçayır & Akçayır, 2018). By placing knowledge learning outside the classroom, students can apply and consolidate their knowledge more independently during the actual inquiry process, which is

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conducive to truly independent inquiry in the full sense of the word (Chen et al., 2024). Meanwhile, combining IBL with flipped classrooms not only supports students' scientific inquiry without teacher intervention but also fosters the scientific observation skills and facilitates the core skills needed in science learning and research, such as experimental design and manipulation, scientific analysis, and problem solving (Kolil & Achuthan, 2024). Therefore, this study proposed and developed a structured inquiry-based virtual lab approach (SIVL) and applied it to a flipped physics classroom for ninth grade students with the aim of enhancing their physics achievement, learning motivation, and inquiry skills. The developed SIVL allows students to conduct IBL independently before the in-class phase.

Research Focus

The virtual experiment developed and implemented in this study is based on the principles of voltammetry in the context of Ohm's law, as outlined in the Chinese ninth grade physics curriculum. Voltammetry is an experimental technique used to determine resistance values by measuring voltage and current and is categorized into two approaches: the internal ammeter method and the external ammeter method. A key challenge for ninth-grade students in mastering voltammetry is understanding the correct configuration of ammeters and voltmeters, as well as selecting optimal connections to minimize measurement errors. Students often struggle to assess how the internal resistance of the ammeter and voltmeter affects the measurements, which can lead to errors. In addition, students often confuse series and parallel connections, further complicating the experimental process and increasing the cognitive demands of understanding these circuits. Therefore, this study focused on designing and implementing an SIVL within a flipped physics classroom for ninth grade students to increase students' knowledge of voltammetry and improve their motivation and inquiry skills.

Research Aim and Research Questions

The developed SIVL aimed to provide a safe, controlled, and reproducible environment in which students can engage in self-directed learning during the pre-class phase. The SIVL involves all stages of the IBL, promoting students' deeper understanding of voltammetry and encouraging independent inquiry. The stages of IBL traditionally include orientation, conceptualization, investigation, conclusion, and discussion. In line with these stages, the SIVL in this study was designed to support students' progression through the stages of IBL, adapted to the specific physics content covered: orientation, hypothesis generation, experimentation and data interpretation, decision, and reflection (Pedaste et al., 2015). The discussion phase was deliberately excluded from this study as the SIVL was designed for students to independently participate in IBL during the pre-class phase in a flipped classroom, emphasizing self-directed exploration over collaborative discourse.

In this VLs environment, students have the opportunity to design and test different experimental setups, experiment with both internal and external ammeter configurations, and observe and record changes in measurement errors over different resistance levels. Meanwhile, this approach enables students to formulate hypotheses and explanations based on observed patterns in internal resistance. By adjusting parameters such as voltage, current, and resistance, students can independently discover relationships within the data, analyze optimal configurations, and thereby enhance their understanding of voltammetry. In addition, this study also aimed to examine whether the proposed SIVL method could facilitate students' knowledge of voltammetry and improve their motivation and inquiry skills through an experimental design. The research questions that guided this study were as follows:

- RQ_1: Do students using the Structured Inquiry-Based Virtual Lab (SIVL) in a flipped physics classroom demonstrate higher achievement in physics compared to those using a GVL or a Traditional Flipped Classroom (TFC)?
- RQ_2: Does the use of SIVL in a flipped physics classroom lead to greater learning motivation among students compared to the use of GVL or TFC in a flipped physics classroom?
- RQ_3: Do students using SIVL in a flipped physics classroom demonstrate more advanced inquiry skills compared to those using GVL or TFC?

These questions aim to assess the comparative effectiveness of SIVL in enhancing student achievement, motivation and inquiry skills within a flipped physics classroom.

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Research Methodology

General Background

A quasi-experimental design was used with 120 ninth grade students from three intact classes in a lower-secondary school located in central China. There were two experimental groups and one control group in this study: students using SIVL in a flipped physics classroom (SIVL-FC group), students using GVL (GVL-FC group), and a control group using the TFC (TFC group). This experiment was conducted in the spring semester of 2024 in a lower-secondary school in central China. The main steps of the experimental procedure were as follows: First, pre-tests to assess physics knowledge and learning motivation were conducted for all three groups to establish baseline levels. Next, the experimental group completed the physics learning tasks independently using the SIVL and the GVL, while the control group completed the physics learning tasks independently by using the TFC method. Following these interventions, post-tests were administered to assess students' physics achievement, learning motivation, and inquiry skills. To analyze the results, an analysis of covariance (ANCOVA) with post-hoc tests was conducted to examine potential statistical differences between groups in terms of physics achievement, learning motivation, and inquiry skills, with a significance level of .05.

Participants

The participants in this study were 120 ninth-grade students aged 14 to 15, including 43 girls and 67 boys, from three intact classes in a lower secondary school in central China. The three classes were selected using a one-stage cluster sampling method, which allowed for an efficient selection of intact groups, minimizing disruption to the students' regular schedule and ensuring that the natural classroom environment remained intact. In addition, one-stage cluster sampling was appropriate as it provided a randomized and practical approach to obtaining a representative sample within the school, allowing a straightforward comparison of the effects of the different instructional interventions across similar ninth grade physics classes. The three classes were randomly assigned to experimental and control groups with 40 students in each group. The teacher for all three groups of students was the same one with eight years of experience in teaching physics. The teacher is an expert on using educational technology, regularly attends seminars on the design and use of educational technology, and is well-versed in the integrated implementation of technology in class.

Ethical considerations were thoroughly addressed in this study. Prior to the experiment, informed consent forms were distributed to both the students and their parents or guardians to ensure that all parties were fully aware of the purpose and procedures of the study. Students were informed of their right to withdraw from the experiment at any time without penalty and were assured that their performance in the experiment would not affect their grades in the physics course. To maintain confidentiality, each student was given an identification number to make their data anonymous throughout the study. At the end of the experiment, the developed app was made available to all students to ensure equitable access and to address any concerns about fairness.

Procedures

The SIVL design procedure

This study developed SIVL by using the Nobook platform, and SIVL consists of three interconnected databases, which include the Learning Materials Database, the Inquiry-Based Learning Database, and the Learning Tests Database, as shown in Figure 1. SIVL provides broad compatibility across multiple platforms and devices, including those running on iOS and Android systems. When students access the SIVL on their devices, these databases integrate seamlessly to provide comprehensive support for inquiry-based learning in physics.

The Learning Materials Database provides (a) basic theoretical content on voltammetry, primarily through text and video; (b) virtual apparatus for voltammetry experiments, such as voltmeters, ammeters, resistors, and other essential equipment; and (c) interactive features, including tools for connecting wires and testing apparatus functionality.

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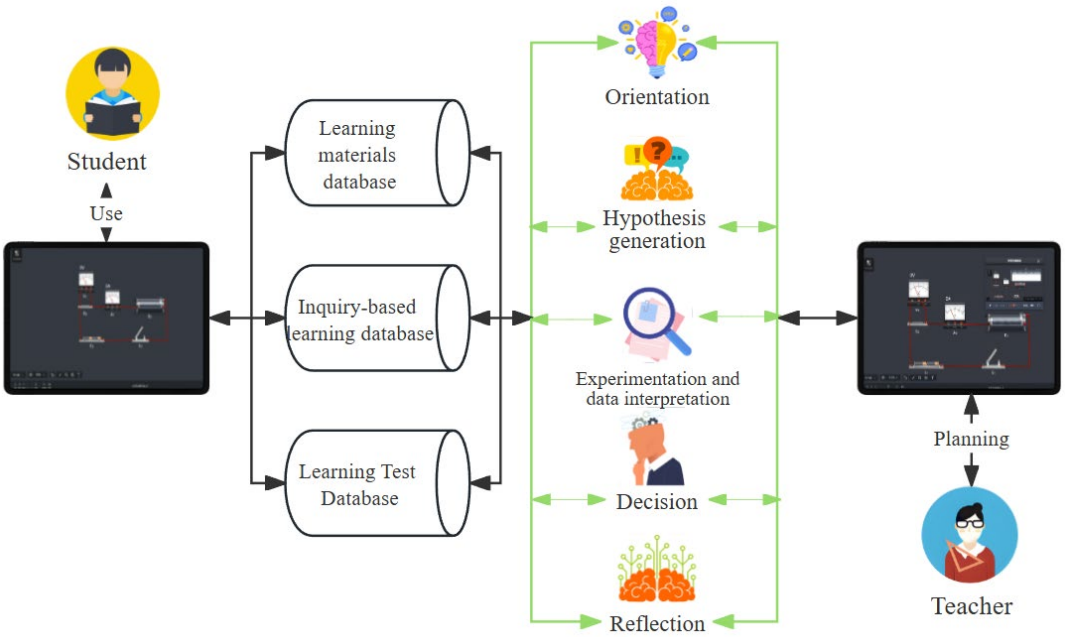
The Learning Test Database focuses on the single-choice and open-ended questions used in the hypothesis generation phase, as well as all tests in SIVL.

Figure 1
System Architecture of SIVL



The Inquiry-Based Learning Database is designed to facilitate students' independent engagement with the inquiry-based learning process. Supported by the Learning Materials and Learning Tests databases, this component guides students through the core stages of inquiry-based learning: orientation, hypothesis generation, experimentation and data interpretation, decision making and reflection.

Orientation phase: This phase introduces students to the basic theoretical concepts of voltammetry and is designed to help students contextualise the experiment and understand its learning objectives. The interface provides text descriptions along with diagrams of the circuit structure, providing an easy to understand introduction to the basic principles of voltammetry. It also provides practical guidance on circuit assembly and outlines the necessary precautions to help students engage with the material and prepare for future tasks. As shown in Figure 2, SIVL uses circuit diagrams and dialogue boxes to illustrate the principles of voltammetry and the purpose of the experiment, guiding students to a full understanding of the context of the experiment.

Hypothesis generation phase: During the hypothesis generation phase, SIVL encourages students to formulate their predictions about the results of the resistance measurements before conducting the experiment. The system is designed with multiple-choice and open-ended questions that allow students to record their hypotheses, as shown in Figure 3. For example, multiple-choice question 1: 'When measuring resistance using the internal and external connection methods, which connection do you think may result in a greater measurement error?'. Open-ended question 1: 'In a voltammetry experiment, if the internal resistance of both the voltmeter and the ammeter cannot be ignored, which method (internal or external) would you choose to minimize the measurement error? This interaction allows students to prepare for the next part of the experiment and form their own research hypothesis based on the experimental question by thinking about the experimental variables and their possible effects before the experiment.

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Figure 2
The Interface of Orientation Phase

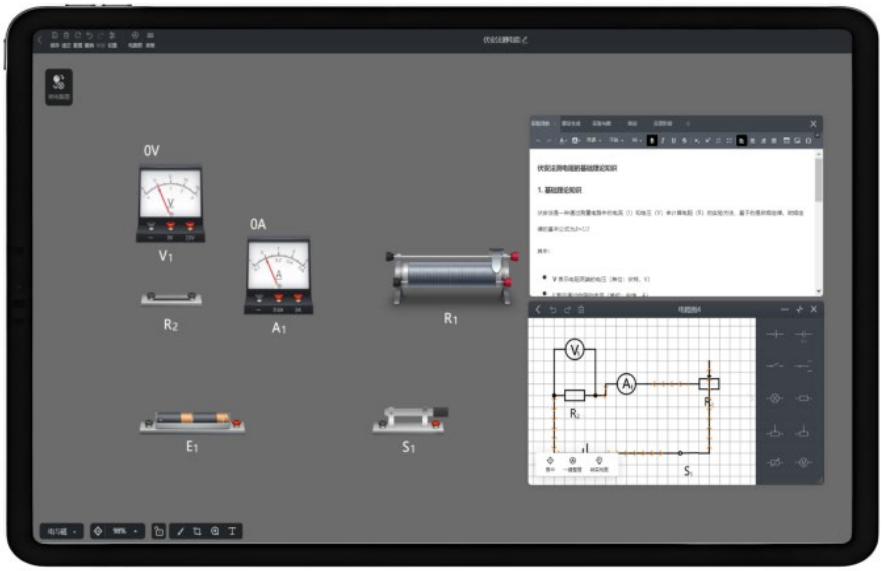
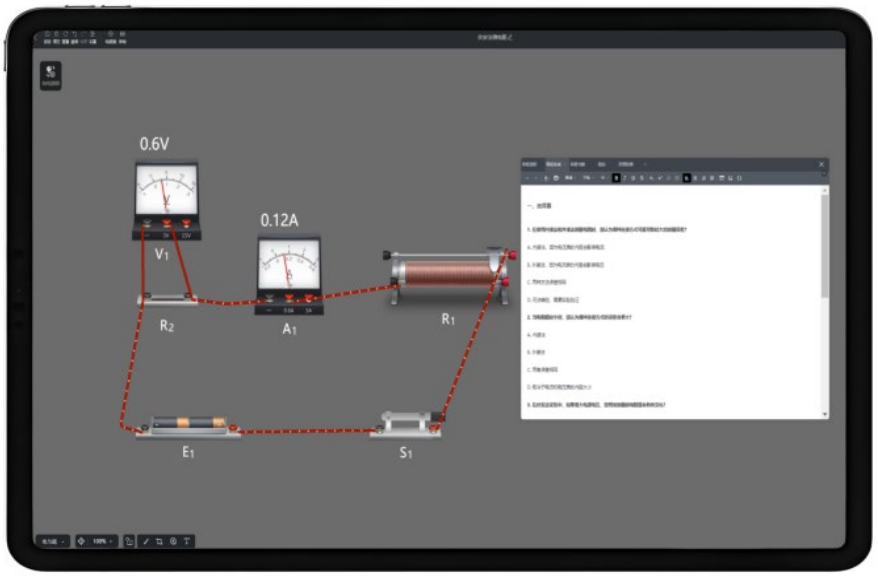


Figure 3
The Interface of Hypothesis Generation



Experimentation and Data Interpretation phase: This phase is the core of SIVL, where students gain hands-on experience with virtual laboratory equipment, including a power supply, resistors, an ammeter, a voltmeter, and connecting wires. SIVL allows students to construct circuits based on the voltammetric method, supporting both internal and external connections, with operational guidance to help students select the appropriate configuration. Students can select from a range of resistor values and record voltage and current data throughout the experiment.

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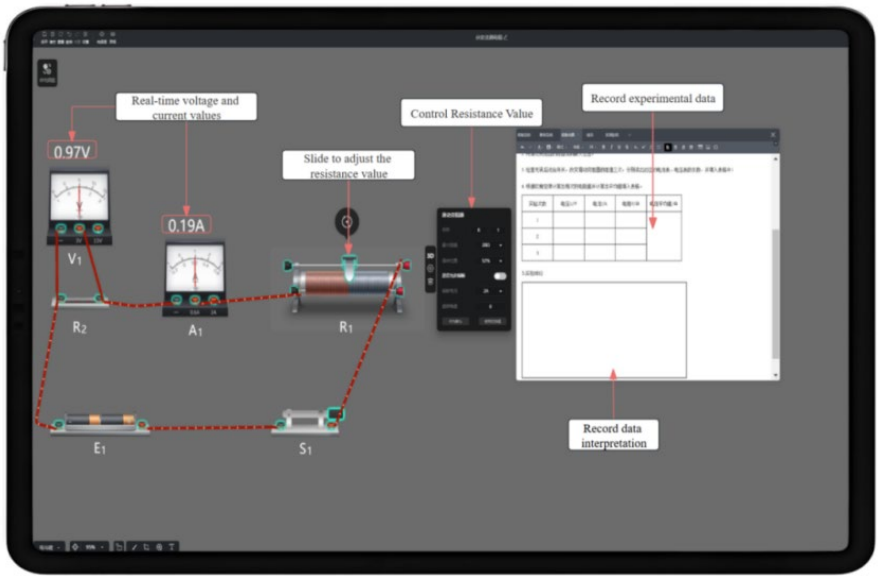
To facilitate data analysis, the SIVL provides real-time data logging and graphing capabilities, allowing students to visualize trends and changes in experimental data. As shown in Figure 4, students can adjust the resistance of the sliding rheostat as required and systematically document their observations and conclusions in a structured table. This approach enhances students' understanding of experimental dynamics and the relationship between key variables in voltammetry.

Figure 4
The Interface of Experimentation and Data Interpretation Phase



Decision phase: SIVL guides students through the analysis of their experimental results, enabling them to calculate resistance values based on measured voltage and current data and to evaluate the error differences between different connection methods. The system provides tools for data comparison, analysis, and icon-based visualization to help students determine which connection method minimizes error most effectively, as shown in Figure 5. This design encourages students to make informed judgments based on experimental data, gain insight into the optimal connection method for voltammetric resistance measurement, and formulate well-supported conclusions.

Reflection phase: SIVL prompts students to summarize their learning and the challenges they encountered during the experiment, encouraging them to record factors that may have influenced the results, such as the effect of the instrument's own resistance on the measurements and the relationship between resistance, voltage, and current. A reflective journal provided by the system allows students to record insights, uncertainties, and areas for further research, as shown in Figure 6. This phase is designed to encourage critical thinking and help students to reflect on their learning journey and build a deeper and broader knowledge of the experimental process and its underlying principles.

After the design of the SIVL was completed, this study conducted alpha testing, beta testing and usability testing to validate its effectiveness and usability, and after two rounds of modifications, the final SIVL passed the various tests. Table 1 summarizes the content and the test results.

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Figure 5
The Interface of Decision Phase

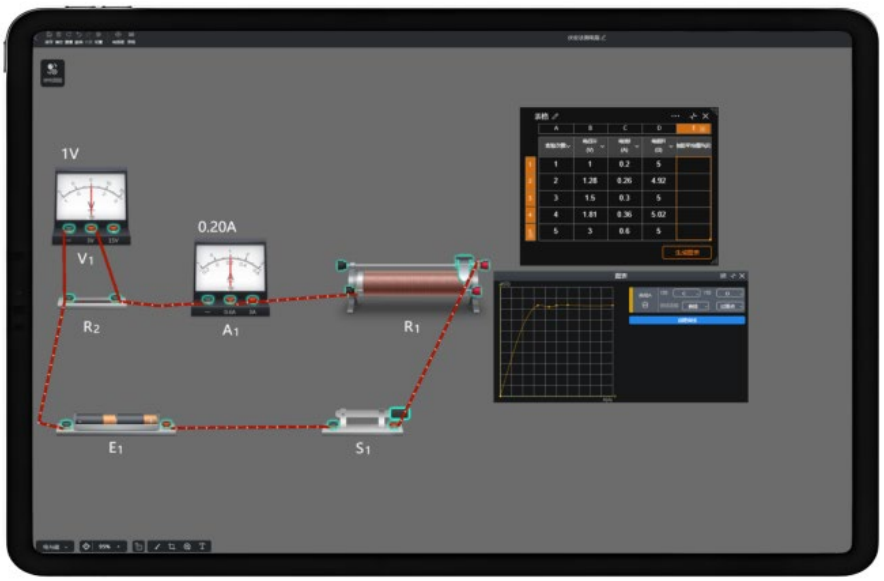

Figure 6
The Interface of Reflection Phase

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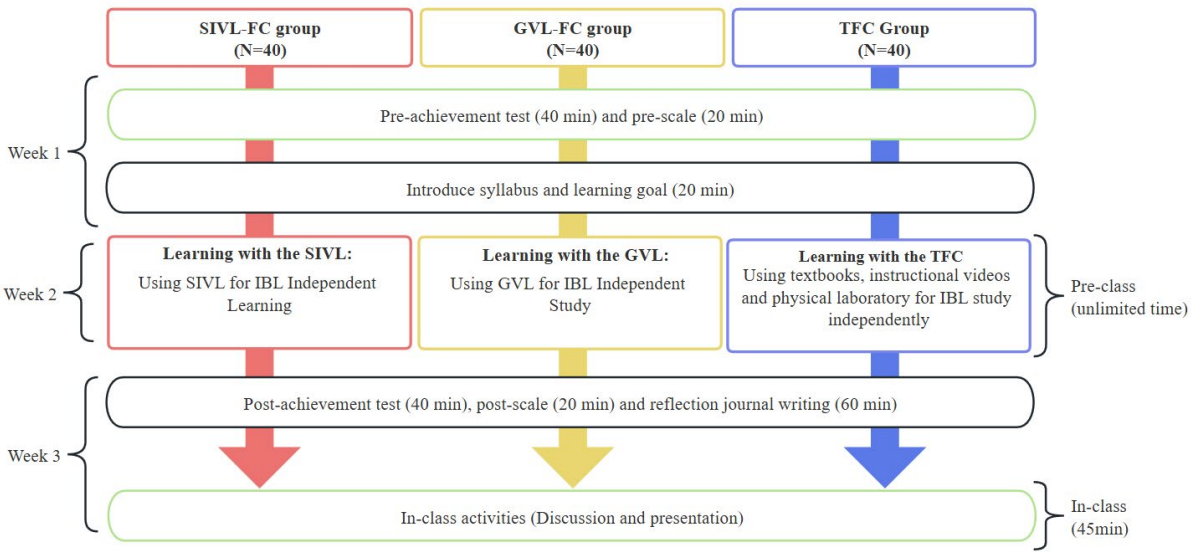
Table 1
The Contents and Results of the Tests

Test Types	Participants	Test contents	Score (%)	Criteria
Alpha Testing	SIVL Development Team	Test whether the system functions properly, the interface is friendly, and the content is presented correctly.	91.32	Very good
Beta Testing	Selected students and teachers	Identify problems and further enhance users' experience when using the system in the field	89.45	Very good
Usability Testing	Selected students and teachers	Evaluate the user experience of SIVL in order to guarantee that its design fulfills students' and teachers' needs in preparation for its official launch.	93.54	Very good

Experimental Procedures

The experiment procedures are shown in Figure 7. In the first week, participants were given a pre-achievement test (40 minutes) as well as a pre-scale (20 minutes) to assess their baseline level of physics achievement and learning motivation. In addition, the teacher introduced students to the learning objectives for voltammetric resistance measurement through a 20-minute briefing session.

Figure 7
Experimental Procedures



In the second week, students engaged in independent learning about voltammetry using different learning methods based on their group assignment. Students in the SIVL-FC group used the SIVL, which has built-in inquiry-based learning features, allowing them to complete the inquiry process independently. Students in the GVL-FC and TFC groups, on the other hand, were provided with an Inquiry-Based Learning manual with identical guidance to support their inquiry. The GVL-FC group used a General Virtual Lab (GVL) for this purpose, while the TFC group relied on textbooks, instructional videos and physical laboratory (PL) equipment for the study of voltammetry. The experimental group had the flexibility to study at any time and from any place during this pre-class phase. Meanwhile, the students in the control group could use the PL as needed. It is important to emphasize that the VLs used by both SIVL-FC and GVL-FC groups contain identical learning content. The main difference is that the VLs in the GVL-FC group have no embedded IBL processes.

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In the third week, students were first required to complete a post-achievement test (40 minutes), a post-test scale (20 minutes) and reflection journal writing (60 minutes). Students in the same group then have a class discussion and presentation (45 minutes), which provides an opportunity to consolidate and share learning experiences.

Research Instruments

This study used pre- and post-tests of Voltammetry Knowledge Achievement Test (VKAT) to assess students' knowledge acquisition. The test was developed based on the core concepts of Ohm's Law for ninth grade students, with items structured according to Bloom's (1964) taxonomy of cognitive skills: knowledge, comprehension, application, and analysis. The final test consisted of 10 multiple-choice and 5 fill-in-the-blank questions, with each question worth 1 point, for a total of 15 points, to assess students' basic knowledge and comprehension. In addition, 2 calculation questions (worth 5 points each) assessed students' application and analytical skills, for a total of 10 points. Moreover, a single analysis question worth 5 points further assessed students' ability to perform in-depth analysis. So, the VAKT has a maximum score of 30 and a minimum score of 0. To establish content validity, an associate professor of physics and three experienced teachers with more than seven years of teaching experience each conducted an expert evaluation using the Item Content Validity Index. The Scale-level Content Validity Index (S-CVI) was 0.91 and 0.93 for the pre-and post-test, respectively, which indicates high content validity. Modifications were made to items the experts rated as lowly relevant, and the final version of the test was approved by all experts.

The Physics Learning Motivation Scale (PLMS) used in this study was adapted from the work of Chen et al. (2024) and modified to fit the specific content of the study. The PLMS is a 5-point Likert scale that measures intrinsic motivation (items 1–5) and extrinsic motivation (items 6–10). Examples of items to measure intrinsic motivation include "I believe that studying physics is worthwhile because it increases my ability." (item 1). Items that measure extrinsic motivation include: "No matter if I enjoy physics or not, I will learn a lot, as I don't want to disappoint my instructor." (item 6). The Cronbach's α of the PLMS is .86, with intrinsic motivation at 0.85 and extrinsic motivation at .88, suggests that the scale has a high degree of internal consistency.

This study used Reflection Journal Writing (RJW) to assess students' inquiry skills. The RJW questions were developed collaboratively by three experienced lower secondary physics teachers, each having at least seven years of teaching experience, together with an associate professor of physics. After three rounds of revisions, the team finalized and approved the content of the RJW. The RJW was structured according to the Inquiry-Based Learning (IBL) process, which has five key dimensions: question formulation, hypothesis generation, experimental design, data collection and analysis, and conclusion and reflection. Each dimension contains two questions, for a total of 10 questions. A detailed scoring rubric for inquiry skills is also provided with the RJ, with each question worth up to 1-5 points and specific criteria for each score level. To ensure the reliability of the scoring, an inter-rater reliability test was conducted in which each rater independently scored the responses of 30 students. The test yielded a reliability coefficient of 0.93, indicating high inter-rater reliability. The score range for RJW is 0-50, with higher scores demonstrating better inquiry skills.

Data Analysis

This study primarily used one-way ANCOVA with post-hoc tests to examine whether there were significant differences in physics achievement and learning motivation between the three groups, using pre-test scores for both physics achievement and learning motivation as covariates. In addition, a one-way ANCOVA with post-hoc tests was conducted to determine if there was a significant difference in inquiry skills between the three groups, as inquiry skills were only assessed in the post-test. Homogeneity of variance and homogeneity of regression slope tests were carried out before running the ANCOVA. Similarly, the homogeneity of variance was tested before conducting the ANCOVA. A significance level of .05 was used for all statistical tests in this study.

Research Results

Physics Learning Achievement

ANCOVA was performed in this study after confirming that both the homogeneity of regression slopes ($F = 1.45$, $p = .238 > .005$) and the homogeneity of variance ($F = 2.44$, $p = .092 > .005$) assumptions were satisfied. As shown in Table 2, there was a significant difference in physics learning achievement between the students in

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the three groups (F = 158.66, p <.001, η^2 =.732). Post hoc LSD analyses were performed to identify specific differences in learning achievement. The results showed that the adjusted mean score of 23.59 for the SIVL-FC group was significantly higher than that of the GVL-FC group (Adj. Mean = 19.92) and the TFC group (Adj. Mean = 16.99) (p <.001). These results suggest that students in the SIVL-FC group achieved better physical learning achievements than those in the other two groups. Meanwhile, the GVL-FC group performed better than the TFC group in physical learning achievements.

Table 2
ANCOVA Results for Physics Learning Achievement Between the Three Groups

Group	N	M	SD	Adj. M	F	p	η^2	Post Hoc
SIVL-FC	40	23.28	2.28	23.59	158.66	.000	.732	(1) > (2)
GVL-FC	40	20.02	2.69	19.92				(1) > (3)
TFC	40	17.20	1.60	16.99				(2) > (3)

Learning Motivation

This study first tested for homogeneity of variance and regression slopes for the post-test scores on overall learning motivation, intrinsic and extrinsic motivation. These tests confirmed that the data met the assumptions required for conducting ANCOVA, as shown in Table 3.

Table 3
Test Results for Homogeneity of Variance and Regression Slopes

Test	Test Type	Variable (Post-test)	F	p	Decision
Homogeneity of variance	Levene's test	Learning motivation	.420	.658	Accepted
		Intrinsic motivation	2.21	.114	Accepted
		Extrinsic motivation	.222	.901	Accepted
Homogeneity of regression slopes	Tests of between-subjects effects	Learning motivation	1.480	.232	Accepted
		Intrinsic motivation	.330	.720	Accepted
		Extrinsic motivation	.898	.155	Accepted

The study found significant differences in learning motivation between the groups (F = 96.59, p <.001, η^2 =.625), as shown in Table 4. LSD analysis indicated that the SIVL-FC group demonstrated significantly higher overall learning motivation (Adj. Mean = 3.90) compared to both the GVL-FC group (Adj. Mean = 3.44) and the TFC group (Adj. Mean = 3.34), with p <.001. In addition, the GVL-FC group showed greater motivation than the TFC group (p <.001).

Table 4
ANCOVA Results for Learning Motivation Between the Three Groups

Variable	Group	N	M	SD	Adj. M	F	p	η^2	Post Hoc
Learning motivation	(1) SIVL-FC	40	3.88	0.26	3.90	96.59	.000	.625	(1) > (2)
	(2) GVL-FC	40	3.46	0.24	3.44				(1) > (3)
	(3) TFC	40	3.35	0.29	3.34				(2) > (3)

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Variable	Group	N	M	SD	Adj. M	F	p	η^2	Post Hoc
Intrinsic motivation	(1) SIVL-FC	40	3.97	0.39	3.98	120.89	.000	.676	(1) > (2)
	(2) GVL-FC	40	3.45	0.35	3.43				(1) > (3)
	(3) TFC	40	3.15	0.33	3.15				(2) > (3)
Extrinsic motivation	(1) SIVL-FC	40	3.80	0.35	3.82	18.76	.000	.244	(1) > (2)
	(2) GVL-FC	40	3.48	0.34	3.50				(1) > (3)
	(3) TFC	40	3.55	0.35	3.54				

For intrinsic motivation, this study also revealed a significant difference among the groups (F = 120.89, p <.001, η^2 =.676), as shown in Table 4. The LSD results showed that students in the SIVL-FC group were significantly more intrinsically motivated (Adj. Mean = 3.97) than those in the GVL-FC group (Adj. Mean = 3.45) and the TFC group (Adj. Mean = 3.15), with p <.001. The GVL-FC group also outperformed the TFC group in intrinsic motivation (p <.001).

For extrinsic motivation, significant differences were observed across the groups as well (F = 18.76, p <.001, η^2 =.244). LSD analysis showed that the SIVL-FC group had significantly higher extrinsic motivation (Adj. Mean = 3.82) compared to both the GVL-FC (Adj. Mean = 3.50) and TFC (Adj. Mean = 3.54) groups, with p <.001. However, extrinsic motivation was not significantly different between GVL-FC and TFC groups (p = .186 > .05), as shown in Table 4.

Inquiry Skills

Table 5
ANCOVA Results for Inquiry Skills Between the Three Groups

Variable	Group	N	M	SD	F	p	Post Hoc
Inquiry skills	(1) SIVL-FC	40	39.15	2.08	153.23	.0001	(1) > (2)
	(2) GVL-FC	40	33.67	2.69			(1) > (3)
	(3) TFC	40	29.53	2.58			(2) > (3)

Reflective journal writing was used in this study to assess students' inquiry skills. After confirming that the homogeneity of variance test (F = 1.95, p = .147 > .05) met the assumptions, an ANCOVA was conducted. The significant differences were found between the groups in inquiry skills (F = 153.23, p < .001). As shown in Table 5, LSD showed that the mean inquiry skills score of the SIVL-FC group (39.15) was significantly higher than GVL-FC group (33.67) and the TFC group (29.53), with p <.001. In addition, the GVL-FC group had significantly higher scores than the TFC group (p < .001).

Discussion

For research question 1, this study found that integrating SIVL into the pre-class phase of a flipped physics classroom significantly improved the learning achievement of ninth grade students. The IBL process embedded in SIVL, which includes orientation, hypothesis generation, experimentation, data interpretation, decision-making, and reflection, not only supports the acquisition of physics knowledge but also encourages deeper thinking, exploration, and problem solving. This structured approach promotes active questioning, hypothesis testing, and analysis throughout the experiment, leading to a deeper understanding and application of physics concepts, which ultimately improves learning achievement. In addition, the seamless integration of IBL with SIVL minimizes the need for students to switch between different resources, reducing cognitive load and al-

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lowing students to focus fully on the experimental process and concept understanding. In contrast, both the GVL and TFC groups provide students with an inquiry-based learning manual, but students in these groups must follow the manual independently. This reliance on an external manual may fragment the inquiry process and weaken the coherence between steps. Moreover, students in the GVL and TFC groups tend to passively follow the manual's instructions and lack the structured, internalized inquiry experience that SIVL provides, which may limit the depth of their learning and affect their learning achievement. This finding is consistent with Chen et al.'s (2024) study, which demonstrated that the virtual lab (VL) group outperformed the hands-on group in knowledge performance in an IBL setting. Similarly, the study's findings are also in line with Kolil and Achuthan (2024), who found that VLs play an important role in supporting IBL and improving student achievement and performance. The study's findings also support the view of Reyes et al. (2024), who suggested that VLs provide scalable and safe opportunities for science IBL and enhance comprehension of scientific concepts and improve learning outcomes.

For research question 2, this study found that implementing SIVL in a flipped physics classroom significantly increased students' motivation, both intrinsic and extrinsic. Students in the SIVL-FL group had more opportunities to independently engage in inquiry-based learning (IBL) activities, which allowed them to set up experiments, generate hypotheses, and draw conclusions based on their understanding of voltammetry during the orientation phase. This autonomy fosters curiosity, independence, and critical thinking—key factors that drive intrinsic motivation as students feel a sense of ownership and accomplishment through self-directed discovery. In addition, SIVL provides real-time feedback based on students' data input, allowing them to observe the cause-and-effect relationships between resistance, current, and voltage directly in the experiment. This immediacy enhances students' sense of achievement and progress, thereby increasing intrinsic motivation. Furthermore, timely feedback allows students to refine their learning strategies, further supporting their motivation. This finding is consistent with studies by Al-Nakhle (2022) and Alnaser and Forawi (2024), who found that incorporating VLs into inquiry-based learning environments significantly increased students' intrinsic motivation. This finding also supports the work of Şen and Erdoğan (2016), which demonstrated that inquiry-based laboratory applications positively affect students' intrinsic motivation.

In terms of extrinsic motivation, the SIVL provides students with clear objectives and measurable outcomes, allowing them to directly observe how their efforts contribute to academic performance. The SIVL environment reduces students' fear of failure and encourages them to experiment with new approaches. By repeatedly formulating and testing hypotheses in an IBL environment, students build confidence and increase their aspirations to achieve higher grades, thereby increasing their extrinsic motivation. Although a review of the literature revealed that IBL-based science learning enhances extrinsic motivation, this study was unable to locate research examining the combined effects of IBL and VLs on extrinsic motivation. Future studies could explore this area further to obtain a deeper understanding of the effects on students' motivation.

Regarding research question 3, this study found that the SIVL-FC group scored the highest in terms of inquiry skills, followed by the GVL-FC group, while the TFC group performed the worst. The reason for this result is that SIVL effectively integrates the key processes of IBL during the experiment and provides continuous support and feedback to the students. Within the SIVL environment, students were able to structure their inquiry activities from orientation, hypothesis generation, interpretation of experiments and data, decision making and reflection. The seamless integration of the entire process not only makes the inquiry process more coherent but also allows students to think deeply and make adjustments at each step. In addition, real-time feedback helps students to validate or correct their results in a timely manner, thereby improving their inquiry skills. Furthermore, since SIVL integrates the different processes of IBL into a unified platform, students do not have to switch frequently between different resources and can therefore focus more on experimental operations and conceptual understanding, which is important for improving inquiry skills.

In contrast, although the GVL-FC group also provided a VL environment, students could only learn by referring to the IBL manual, as the IBL process was not integrated. In addition, the lack of coherent guidance and timely feedback hindered the systematic and effective nature of the inquiry activities. Students in the TFC group had access to knowledge through instructional videos and textbooks, as well as free access to the PL in the pre-class phase, but without the structured process for guided inquiry, this remained a significant challenge for them.

The findings of this study support Husnaini and Chen's (2019) study, which revealed that guided inquiry-based VL was more effective in improving difficult concepts and scientific inquiry skills. Additionally, our findings

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are consistent with Ifthinan and Atun's (2019) study, which found that students who used inquiry-based VL had greater inquiry skills. However, this is in contrast to previous research that concluded inquiry-based virtual labs and hands-on labs were as effective in improving students' knowledge of science concepts and inquiry skills in lower-secondary school (Kapici et al., 2022).

Conclusions and Implications

This study designed and developed an SIVL by using Nobook platform and applied it in a flipped physics classroom to teach ninth-grade students about voltammetric resistance measurement. The results of this research showed that the use of SIVL in flipped classrooms significantly improved students' learning achievement, inquiry skills, and both intrinsic and extrinsic motivation. It was the structured integration of the whole inquiry-based learning process into the VL environment that led to these improvements. This included orientation, hypothesis generation, experimentation, data interpretation, decision making, and reflection.

These findings confirm the potential of SIVL as an innovative model for science education, which provides teachers with a powerful tool to encourage active engagement, critical thinking and deeper conceptual understanding. Importantly, this study has shown that embedding IBL within VL can address the challenges related to fragmented inquiry processes in traditional physics classrooms and help students achieve better learning outcomes.

This research has several implications for educational practice. First, this study encourages educators to integrate SIVL or similar inquiry-based virtual tools into their curricula to improve student achievement and maintain motivation. In addition, this study lays the groundwork for future research to explore the use of SIVL in other STEM disciplines and its impact on other variables such as engagement, critical thinking skills, and long-term retention. This study fills a gap in the existing literature, confirms the effectiveness of SIVL in the flipped classroom, and provides useful insights for the advancement of STEM education.

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Declaration of Interest

The authors declare no competing interest

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