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Physics

BEYOND THE TEXTBOOK: REVIVING THE SPIRIT OF EXPERIMENTAL PHYSICS IN INDIAN SCHOOLS AND COLLEGES

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ABSTRACT Experimental work is backbone of physics learning, supporting theoretical models with observable phenomena while developing measurement skills, scientific reasoning and evidence-based thinking. However, in India students often perform laboratory exercises to fulfil assessment requirements rather than investigate physical phenomena independently. This paper examines the factors contributing to declining student engagement in experimental physics at school and undergraduate levels and proposes an educator-centred framework to revitalise laboratory learning. Drawing on literature on practical science education, inquiry-based learning and virtual experiments, the paper identifies key challenges, including procedural experiments, examination-driven assessment, limited apparatus access, weak connections with real-life applications, fear of failure, inadequate preparation time and excessive reliance on digital tools. It argues that declining engagement results not only from student attitudes or infrastructure limitations but also from pedagogical practices, assessment methods and institutional constraints. In Indian schools and colleges labs most of educators often emphasizes on time bound completion of experiments aligned to the standard known results rather than permitting the students to explore and innovate. An integrated framework combining guided inquiry, hands-on participation, authentic measurement, uncertainty analysis, contextual applications, digital tools and competency-based assessment is proposed. Its relevance to the National Education Policy 2020 and Indian educational institutions is discussed. A 90-day implementation plan and mixed-methods research design are outlined to evaluate its effectiveness and guide future efforts to strengthen experimental competence and scientific temperament.

KEYWORDS : Physics Education; Experimental Learning; Laboratory Engagement; Inquiry-Based Learning; Scientific Temperament; Practical Assessment; Teacher Education; Virtual Laboratories; NEP 2020.

INTRODUCTION

Physics is an experimental science in which observation, measurement, mathematical modelling and the testing of hypotheses are closely interconnected. Laboratory work therefore has a distinctive role in physics education. It can help students understand physical concepts, acquire practical skills, recognise the limitations of theoretical models and appreciate how scientific knowledge is developed through evidence [2]

Nevertheless, the presence of a laboratory in a school or college does not necessarily ensure meaningful experimental learning. Students may attend practical classes, follow prescribed instructions, record observations and submit practical notebooks without developing a strong desire to investigate physical phenomena independently. In some settings, successful completion of the prescribed experiment appears to receive greater emphasis than understanding the scientific reasoning behind it [6] .

This concern warrants careful investigation. Declining interest should not automatically be treated as a universal or statistically established trend across all schools and colleges. Its extent may vary with educational level, institutional resources, curriculum, teaching practices and student background. However, the possibility that routine laboratory practices are failing to stimulate curiosity deserves serious attention from science educators. [5]

Recent research provides a useful basis for examining this problem. In a systematic literature review of practical work in science education, Oliveira and Bonito examined its potential to integrate practical skills with conceptual understanding while highlighting limitations in the ways practical work is implemented. Nicol et al. [5] reviewed students' perspectives on science laboratory learning and identified the importance of considering students' experiences and perceptions of laboratory activities. Research on combining real and virtual experiments further suggests that the educational design of laboratory work deserves attention [8]. These findings indicate that the educational value of laboratory work depends not merely on whether experiments are conducted, but also on how students engage with them.

The challenge has become more complex in an educational environment characterised by digital videos, virtual simulations, online practical records and generative artificial intelligence. Such tools can support learning, but they may also reduce the perceived need to undertake direct experimental work when students can access ready-made procedures, observations and conclusions. Research on virtual experiments and the integration of real and virtual laboratory experiences provides a basis for examining the appropriate educational roles of these technologies [8].

The present paper examines these concerns from the perspective of educators, with particular attention to practical and resource-conscious interventions suitable for Indian schools and undergraduate physics departments.

1.1 Objectives

The objectives of this paper are:

1. To identify pedagogical, assessment-related, institutional and technological factors that may contribute to reduced engagement in experimental physics.
2. To examine how the design of practical classes influences student curiosity, participation and experimental competence.
3. To propose strategies that teachers and college departments can implement without necessarily requiring substantial additional expenditure.
4. To examine the complementary roles of physical experiments, simulations and artificial intelligence.
5. To develop an educator-centred framework and a research design for evaluating interventions aimed at improving student engagement.

1.2 Research Questions

The paper addresses the following questions:

- What factors may discourage students from actively performing physics experiments?
- How do conventional practical teaching and assessment practices influence student participation?
- Which teaching strategies are most promising for promoting curiosity, independent investigation and experimental reasoning?
- How can educators integrate digital resources without displacing meaningful hands-on learning?
- How can institutions evaluate whether laboratory reforms improve student engagement and competence?

2. Methodology

This paper adopts a conceptual literature-review approach. It draws on selected peer-reviewed research reviews and studies concerning practical science education, student experiences in laboratories, inquiry-based learning, physics laboratory instruction and combinations of physical and virtual experiments. It also considers the National Education Policy 2020 as a relevant policy framework for Indian education [3].

Priority is given to literature published between 2022 and 2025, supplemented by relevant earlier research where necessary to establish the educational context. The selected sources include a systematic review of practical science education [6], a review of student perceptions of laboratory learning [5], research on combining real and virtual experiments [8], a systematic review of open inquiry [1],

research on students' experimental competence through inquiry-based laboratory approaches [4], and a review of virtual experiments in physics education [7].

The literature is examined thematically to identify recurring educational issues, potential mechanisms affecting engagement and practical interventions relevant to school and undergraduate physics.

This is a narrative conceptual review, not a systematic review or a new empirical investigation. It does not claim exhaustive database coverage, original participant data or measured intervention effects. The explanations and proposed framework are intended to inform subsequent empirical research.

3. Why Experimental Engagement Matters in Physics Education

The educational purpose of a physics laboratory extends beyond verification of textbook relationships. Well-designed experimental activities can support several interconnected outcomes. Research on physics instructional laboratories and practical science education highlights the importance of examining laboratory activities in terms of their educational purposes and learning outcomes [2, 6].

3.1 Conceptual Understanding

Experiments provide opportunities to compare theoretical predictions with observed behavior. For example, investigating the period of a simple pendulum allows students to connect measurements with the relationship between period and length and to examine the assumptions underlying the mathematical model.

When students only reproduce expected values, the opportunity to examine the meaning and limitations of the relationship may be lost. Practical work should therefore connect experimental observations with conceptual understanding rather than treat measurement and theory as separate activities [6].

3.2 Experimental and Measurement Skills

Practical work develops competence in apparatus assembly, instrument selection, calibration, measurement, data recording, graph construction and error estimation. These skills require active practice and cannot be acquired fully through observation alone. The development of experimental competence through inquiry-oriented laboratory approaches is an important area of science education research [4].

3.3 Scientific Reasoning

Real experiments often produce imperfect or unexpected results. Investigating these discrepancies requires students to distinguish random variation from systematic error, consider alternative explanations and evaluate the reliability of evidence.

Laboratory activities can provide opportunities for students to develop these abilities when they are required to interpret evidence rather than merely reproduce prescribed procedures [2, 6].

3.4 Curiosity and Scientific Temperament

An experiment can create an opportunity for students to ask questions, make predictions and challenge their existing understanding. Such experiences are important for cultivating a willingness to investigate rather than simply accept established explanations.

Student perceptions of laboratory learning should be considered when designing activities intended to promote curiosity, participation and positive learning experiences [5].

3.5 Transfer of Knowledge

When laboratory activities are connected to practical problems involving electronics, materials, energy, environmental monitoring or everyday devices, students can better appreciate the relevance of physics beyond examinations.

These benefits are not automatic. Practical work is most educationally productive when students are intellectually engaged with the experiment as well as physically involved in carrying it out [2, 6].

4. Factors that May Contribute to Declining Engagement

4.1 Procedural and Verification-Oriented Practical Work

A common weakness of conventional practical teaching is the emphasis on reproducing a prescribed sequence of steps. Students may receive the objective, apparatus list, formula, procedure, observation table and expected conclusion before entering the laboratory.

Under these conditions, the task can become one of reproducing an established answer rather than investigating a question. Students have little reason to formulate predictions or decide what evidence would support a conclusion.

Oliveira and Bonito [6] examined the implementation of practical work in science education and highlighted issues concerning its educational design. Research on physics instructional laboratories has also examined recurring approaches to laboratory instruction and directions for future development [2]. This literature supports the need to examine not only the presence of practical work but also its educational design.

Recommended Response: Introduce a question or prediction before providing the complete procedure. Gradually transfer responsibility to students by allowing them to choose variables, compare methods and explain their observations.

4.2 Examination-driven Assessment

When practical assessment focuses primarily on the final numerical answer, the neatness of a record or the reproduction of a standard procedure, students are likely to prioritise these requirements.

An experiment may then be treated as an examination task rather than an opportunity to understand the physical world. Unexpected results can become a source of anxiety rather than a reason for investigation.

Recommended Response: Assess the quality of measurements, apparatus handling, reasoning, data interpretation, error analysis and the ability to explain discrepancies. Practical records should support assessment rather than serve as its principal evidence.

4.3 Limited Individual Participation

Large classes and insufficient apparatus may prevent students from receiving adequate hands-on experience. In group experiments, one student may assemble the apparatus while others record observations or copy results.

Although collaborative learning can be valuable, it should not result in a few students acquiring all the practical skills.

Recommended Response: Organise small groups with rotating responsibilities. Ensure that each student handles the apparatus, records or analyses data and answers individual questions. Where equipment is limited, use rotating stations and low-cost experimental kits.

4.4 Weak Connections with Real-world Applications

Experiments can appear irrelevant when students cannot connect them with everyday phenomena, technological devices or problems in their surroundings.

For example, electrical measurements may be more engaging when connected to sensors, household devices, battery performance or energy use. Similarly, optics experiments can be linked to spectacles, cameras and solar applications.

Recommended Response: Introduce each experiment through a familiar phenomenon or practical problem. Use the application to motivate the investigation and return to it when interpreting the results.

4.5 Fear of Failure and Lack of Confidence

Students may avoid participation when they fear damaging apparatus, making incorrect measurements or being criticised for results that differ from expected values.

This fear is particularly damaging because experimental work necessarily involves uncertainty, adjustment and occasional failure.

Recommended Response: Establish a supportive laboratory culture in which students are expected to identify and explain errors. Educators should distinguish careless work from honest experimental uncertainty and reward thoughtful troubleshooting.

4.6 Constraints on Teacher Preparation and Institutional Support

Inquiry-oriented practical teaching requires time for preparation, apparatus maintenance, safety planning, student discussion and

assessment. Heavy workloads, crowded timetables and limited technical support can make conventional demonstrations or tightly prescribed procedures more attractive.

The development of inquiry-based laboratory approaches and experimental competence requires attention to how practical activities are designed and implemented [4, 6].

Recommended Response: Provide shared experiment plans, reusable low-cost kits, technical assistance, collaborative lesson development and professional development focused on practical pedagogy.

4.7 Limitations of Laboratory Infrastructure

Some schools and colleges lack sufficient apparatus, reliable consumables, functional instruments or dedicated laboratory time. These limitations can restrict opportunities for independent experimentation.

However, lack of expensive equipment should not be confused with the absence of all possibilities for practical learning. Many foundational experiments in mechanics, sound, optics, magnetism and basic electronics can be performed using affordable materials, provided safety and measurement quality are maintained. [Fig. 1]

Fig.1 ***Reusable and Low-cost Physics Experimental Kits Manufactured Locally for Foundational Mechanics and Optics Learning***

Recommended Response: Conduct an audit of existing equipment, repair usable instruments, develop inexpensive experimental kits and prioritise apparatus that permits repeated student use.

4.8 Digital Resources and the Substitution of Observation for Experimentation

Videos, simulations and virtual laboratories provide valuable opportunities to visualise processes, practise procedures and explore conditions that are difficult to reproduce physically. Their educational value should not be dismissed.

In a systematic review of combining real and virtual experiments in science education, Wörner et al. [8] examined the educational potential of integrating the two approaches. Complementing this, Wang et al. [7] reviewed virtual experiments specifically within physics education, drawing attention to their instructional role and highlighting critical issues concerning the assessment of student learning beyond rote memorization. The important distinction is between using digital tools to enrich investigation and using them to avoid investigation altogether.

Recommended Response: Adopt a sequence in which students predict an outcome, explore it through a simulation, test it experimentally and explain any differences. Virtual work should supplement physical experiments wherever the latter are feasible and educationally appropriate.

4.9 Generative Artificial Intelligence and Ready-Made Practical Records

AI tools can produce explanations, experimental procedures, observation tables and conclusions rapidly. When students submit such material without performing or understanding the experiment, the resulting record may provide little evidence of learning.

Nevertheless, AI can also support the development of hypotheses, the identification of possible sources of error and the comparison of theoretical and experimental relationships.

Recommended Response: Require students to explain their own data, repeat a measurement, modify an apparatus or defend an interpretation orally. Encourage transparent and responsible use of AI while ensuring that students remain accountable for the experimental evidence they present.

4.10 Insufficient Student Voice

Laboratory reforms may be designed without systematically examining how students experience practical classes. Their concerns about equipment, instructions, confidence, workload and relevance may consequently remain unaddressed.

Nicol et al. [5] reviewed students' opinions, views and perceptions of science laboratory learning, supporting the importance of taking student perspectives into account when examining laboratory experiences.

Recommended Response: Use short anonymous questionnaires, student discussions and observation of laboratory participation to identify barriers and evaluate whether reforms are effective.

5. An Educator-centred Framework for Revitalising Experimental Physics

The preceding discussion suggests that improving laboratory engagement requires a coordinated approach rather than a single intervention. Inquiry-oriented laboratory teaching and the development of experimental competence provide a useful foundation for designing such an approach [4, 6].

The following framework is proposed for schools and undergraduate colleges.

5.1 The Predict–Investigate–Analyse–Explain Model

The proposed PIAE model has four interconnected stages.

Stage 1: Predict

Students are introduced to a physical question and asked to predict the outcome. They explain their reasoning before observing the result.

Stage 2: Investigate

Students assemble or operate the apparatus, identify the quantities to measure, collect data and repeat measurements where appropriate.

Stage 3: Analyse

Students organise data, plot graphs, estimate uncertainty and compare their results with theoretical expectations.

Stage 4: Explain

Students interpret the findings, investigate discrepancies and propose improvements or further experiments.

This model is a proposed pedagogical framework, not a validated intervention. Its effectiveness should be evaluated through classroom implementation and empirical research. Its emphasis on investigation and experimental competence is consistent with the educational objectives examined in research on inquiry-based laboratory approaches [4].

5.2 Example: Redesigning the Simple Pendulum Experiment

In a conventional experiment, students may measure the period at different lengths and calculate the acceleration due to gravity.

Under the Proposed Framework:

1. Students predict whether changing the bob's mass will affect its period.
2. They investigate using bobs of different masses while controlling the length and release angle.
3. They measure the time for several oscillations, repeat the measurements and compare the results.
4. They explain whether the observations support the theoretical prediction and consider possible measurement errors.
5. They extend the investigation by examining the relationship between the square of the period and the length.

The experiment now develops conceptual understanding, measurement competence, uncertainty analysis and independent reasoning without requiring expensive apparatus.

5.3 Progressive Development of Student Independence

Inquiry should be introduced progressively rather than by expecting inexperienced students to conduct completely open-ended investigations immediately.

Level	Student activity	Principal educational objective
1. Demonstration	Observe a phenomenon and discuss a prediction	Curiosity and initial understanding

2. Guided practical	Follow a procedure while explaining decisions	Instrument handling and measurement
3. Structured inquiry	Investigate a question using supplied equipment	Evidence-based reasoning
4. Guided independent investigation	Select variables or modify a procedure	Experimental planning
5. Open investigation	Formulate a question, design a method and defend findings	Independence and scientific competence

The appropriate level depends on student age, prior experience, safety requirements and curriculum objectives. Open inquiry should not be assumed to be universally superior to guided inquiry. Dah et al. [1], in their systematic review of open inquiry and student learning in science, provide a basis for critically examining its educational effects rather than assuming that the most open form of inquiry is automatically the most effective.

6. Improving Practical Assessment

Assessment strongly influences how students approach experiments. A revised system should reward both practical competence and scientific reasoning.

The following illustrative rubric can be adapted to institutional regulations.

Component	Suggested Weight
Understanding the question and predicting the result	10%
Apparatus handling and safe experimental practice	20%
Measurement quality and data recording	20%
Graphs, calculations and uncertainty analysis	15%
Interpretation and scientific reasoning	20%
Troubleshooting and suggested improvements	10%
Honest reporting and collaboration	5%
Total	100%

The rubric is a proposal and requires testing for reliability, fairness and suitability for different practical courses.

Three principles are particularly important.
First, an unexpected result should not automatically be treated as evidence of poor performance. Students should receive credit for identifying and investigating plausible causes.
Second, a well-presented practical record should not be accepted as sufficient evidence of individual competence. Direct observation and short oral questions are necessary.
Third, assessment should reflect the intended learning outcomes. Where a practical is designed to develop instrument handling, that skill should be observed directly; where the objective is experimental reasoning, students should be required to interpret and defend their data.

These principles are consistent with the broader need to align practical activities with their intended educational outcomes [2, 6].

7. Implications for Schools and Undergraduate Colleges in India

The National Education Policy 2020 emphasises experiential learning, hands-on activities, exploration, critical thinking and a movement away from rote learning [3]. These priorities provide a policy basis for strengthening experimental science education.

Implementation, however, requires practical measures at different educational levels.

7.1 School Education

At school level, educators should prioritise curiosity, observation and the ability to conduct simple investigations.

Useful Measures Include:
- Low-cost activities using familiar materials.
- Science clubs and student-led demonstrations.
- Small-group experiments with rotating roles.
- Connections between textbook concepts and everyday phenomena.
- Assessment based on observation, explanation and practical participation.

Teachers should ensure that students gradually acquire the skills needed to conduct experiments safely and independently. These measures are compatible with an educational emphasis on practical work and active student engagement [3, 6].

7.2 Undergraduate Physics Education

At undergraduate level, laboratory activities should progress towards greater independence and more rigorous measurement [10].

Possible Interventions Include:
- Replacing selected verification experiments with investigative questions.
- Introducing uncertainty budgets, calibration and reproducibility.
- Encouraging students to compare measurement techniques.
- Developing small research projects using existing departmental equipment.
- Integrating sensors, electronics, materials science and environmental measurements where relevant.
- Requiring students to defend their experimental methods and conclusions. [Fig.2]

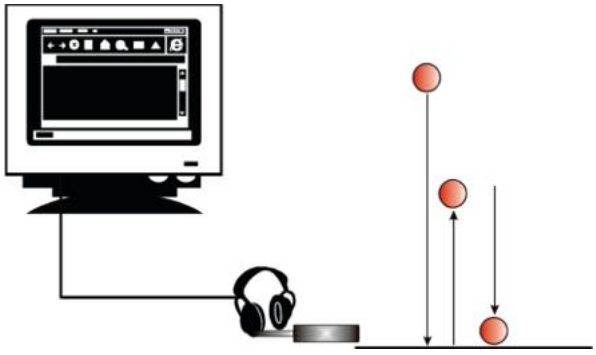

Fig2. Interactive Data-logging and Parameter-testing Window within a Virtual Physics Laboratory Software Module.

Undergraduate students should learn not only how to obtain a result but also how to judge its reliability and determine the limitations of the method used. Developing experimental competence through inquiry-oriented laboratory teaching is particularly relevant to these objectives [4].

7.3 Teacher Development and Institutional Leadership

Institutional support is essential. Teachers need time, practical resources and professional opportunities to improve their laboratory teaching.

Departments can develop shared banks of experiments, conduct peer-observation sessions, organise workshops on inquiry-based teaching and recognise effective practical instruction.

Laboratory improvement should therefore be treated as a teaching-and-learning priority, not solely as an equipment-purchase exercise. Research examining practical work and laboratory instruction supports the importance of considering the educational design of experiments alongside the resources available [2, 6].

8. A proposed 90-day Implementation Programme

A practical implementation programme can begin with a small number of experiments and expand after evaluating the results.

Phase I: Diagnosis (Days 1–30)
- Conduct a baseline survey of student interest and confidence.
- Observe laboratory sessions to determine who performs each task.
- Identify experiments dominated by copying or mechanical repetition.
- Select three to five experiments for redesign.
- Record existing resource and timetable constraints.

Phase II: Intervention (Days 31–60)
- Introduce the Predict–Investigate–Analyse–Explain model.
- Provide each student with meaningful hands-on participation.
- Use short oral questions and direct observation.
- Introduce one open-ended challenge per week.
- Collect feedback from students and teachers.

Phase III: Evaluation (Days 61–90)
- Repeat the student survey.
- Assess students' ability to explain and modify an experiment independently.

- Compare practical reasoning and measurement skills with baseline performance.
- Document implementation difficulties.
- Revise the approach before extending it to additional classes.

The programme should be regarded as a pilot. Changes observed during a short implementation period cannot, by themselves, establish long-term effectiveness or prove that the intervention caused any improvement.

9. Proposed Empirical Research Design

The framework can be tested through a mixed-methods study involving schools and undergraduate colleges.

9.1 Research Questions

1. Does inquiry-oriented practical teaching improve student engagement compared with conventional practical instruction?
2. Does it improve students' experimental reasoning, measurement competence and ability to interpret unexpected results?
3. How do students perceive the relevance, difficulty and enjoyment of laboratory work?
4. Which institutional and teacher-related factors influence implementation?

9.2 Study Design

A quasi-experimental design could compare classes using the proposed intervention with classes following conventional practical teaching. Where feasible, classes or institutions should be assigned to conditions randomly. Otherwise, baseline differences should be measured and considered during analysis.

The intervention group would use inquiry-oriented practical activities, structured student participation and process-based assessment. The comparison group would continue with its usual practical teaching, subject to applicable curriculum and institutional requirements.

Both groups should undertake comparable experiments and be assessed using equivalent instruments. The emphasis on inquiry and experimental competence is informed by research on inquiry-based laboratory approaches [4].

9.3 Data Collection

Data could be collected through:

- A student engagement questionnaire administered before and after the intervention.
- An experimental competency rubric.
- Direct observations of student participation.
- Practical reasoning questions based on unfamiliar experimental situations.
- Interviews or focus groups with students and teachers.
- Records of apparatus access, practical attendance and implementation fidelity.

The questionnaire and assessment rubric should be piloted before use. Their validity and reliability should be evaluated rather than assumed. Student perspectives should be incorporated into the evaluation, given the relevance of students' reported experiences to laboratory learning [5].

9.4 Data Analysis

Quantitative analysis could compare pre-intervention and post-intervention scores within and between groups, accounting for baseline differences and class-level clustering where appropriate.

Qualitative interviews and observations could be analysed thematically to identify changes in confidence, perceptions of relevance, barriers to participation and teacher experiences.

Effect sizes and confidence intervals should be reported alongside statistical significance. The study should also examine whether outcomes differ by school or college level, prior experience, resource availability and other relevant contextual factors.

9.5 Ethical Considerations

Participation should follow institutional ethical requirements. Students should receive appropriate information about the study, and consent or assent should be obtained as required. Data should be anonymised or pseudonymised, and participation in research should not unfairly affect academic assessment.

No numerical findings should be reported until data have actually been collected and analysed.

10. Limitations

This paper has several limitations.

First, it is a conceptual review based on selected literature rather than an exhaustive systematic review. The selection of literature may therefore omit relevant studies.

Second, the paper does not present original survey data from Indian schools or colleges. Consequently, it cannot establish the prevalence, magnitude or causes of declining experimental interest in any specific population.

Third, the proposed framework and assessment rubric have not been validated through an intervention study. Their suitability may vary according to age, curriculum, laboratory facilities and institutional constraints.

Fourth, findings from international research may not transfer directly to all Indian educational settings. Differences in class size, assessment systems, teacher preparation, language and infrastructure require contextual consideration.

Finally, student engagement is multidimensional. Participation in an experiment, enjoyment of practical work, conceptual understanding and long-term interest in science are related but distinct outcomes. They should be measured separately where possible.

These limitations reinforce the need for empirical studies in diverse Indian schools and undergraduate institutions.

11. CONCLUSION

Experimental physics education faces a challenge when laboratory participation becomes primarily procedural, examination-oriented and disconnected from scientific inquiry. However, it would be premature to attribute declining engagement to a single cause or to students' attitudes alone. The design of practical activities, assessment methods, access to apparatus, teacher support and the use of digital resources may all influence how students experience laboratory learning [2, 5, 6].

Research on practical science education, student perceptions of laboratory learning, and the integration of real and virtual experiments suggests that the educational value of practical work depends on meaningful participation, the integration of hands-on skills with conceptual understanding and attention to students' experiences [5, 6, 8]. Combining physical and virtual experiments may offer additional benefits when each is used for an appropriate educational purpose [8].

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