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# The Effect of Virtual Laboratory and Self Regulated Learning on Students' Practical Skills and Cognitive Knowledge in Undergraduate Chemical Engineering Education

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## ABSTRACT

**Background.** Virtual laboratories allow repeatable procedural practice, while self-regulated learning (SRL) may be associated with achievement.

**Purpose.** This study compared practical skills and cognitive knowledge for hands-on laboratory (HOL) practice integrated with a virtual laboratory (VRL) versus HOL supported by PowerPoint (PPT), and tested SRL and strategy × SRL effects.

**Method.** This quasi-experimental 2 × 2 pretest-posttest study included 69 Chemical Engineering undergraduates at Tribhuwana Tunggadewi University (HOL + VRL, n = 36; HOL + PPT, n = 33). SRL was high for 40 and low for 29 students. Outcomes were analysed using MANOVA and univariate follow-up tests.

**Results.** Pillai's Trace showed multivariate effects of strategy, V = .341, F(2, 64) = 16.570, p < .001, and SRL, V = .552, F(2, 64) = 39.494, p < .001. Strategy effects were significant for cognitive knowledge, F(1, 65) = 16.504, p < .001, $\eta p^2$ = .202, and practical skills, F(1, 65) = 21.540, p < .001, $\eta p^2$ = .249. SRL effects were significant for cognitive knowledge, F(1, 65) = 52.500, p < .001, $\eta p^2$ = .447, and practical skills, F(1, 65) = 38.125, p < .001, $\eta p^2$ = .370. The strategy × SRL interaction was not significant multivariately, V = .001, F(2, 64) = 0.017, p = .984, or univariately (cognitive p = .906; practical p = .878).

**Conclusion**. The use of virtual laboratory media positively contributes to students' practical and cognitive learning outcomes in laboratory-based learning. Self-regulated learning also plays an important role in influencing students' achievement. Therefore, the development and wider accessibility of virtual laboratory media are recommended to support more effective science learning in higher educatioDescriptive means favoured HOL + VRL across SRL levels. These findings require cautious interpretation because covariance/variance assumptions were not fully met and the analysed outcome metric must be confirmed.

## KEYWORDS

Virtual Laboratory, Self Regulated Learning, Practical Skills, Cognitive Knowledge

## INTRODUCTION

Learning outcomes are one of the main indicators used to evaluate the effectiveness of the educational process and to determine changes in students' knowledge, attitudes, and skills after participating in learning activities

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(Degeng & Triretnoningrum, 2025). In higher education, particularly in engineering education, learning outcomes are not limited to cognitive achievement but also include psychomotor competencies that reflect students' practical skills and professional readiness. In Chemical Engineering education, these two domains are closely related because students are required not only to understand theoretical concepts but also to apply them through laboratory practical activities (Gai & Kim, 2026). Therefore, the effectiveness of laboratory-based learning is an important aspect in achieving the competencies expected of Chemical Engineering graduates. Laboratory learning in Chemical Engineering programs often faces many challenges related to student readiness, communication barriers, and limitations in practical experience (Bewota, 2026). According to preliminary observations made at the Chemical Engineering Study Program of Tribhuwana Tunggadewi University, many students come from geographically remote areas in Eastern Indonesia and Kalimantan, where access to laboratory facilities and science-based learning experiences are relatively limited. As a result, about 70% of students have minimal prior experience with laboratory activities before entering university. This condition creates difficulties in understanding laboratory procedures, handling scientific instruments, and applying theoretical concepts during practical sessions. In addition, differences in linguistic background and communication styles often lead to misunderstandings between lecturers and students during teaching activities, making laboratory teaching less effective and increasing the risk of procedural errors and laboratory accidents.

The rapid development of educational technology has encouraged the integration of digital learning media to support a more effective and flexible learning environment. Learning media functions as a communication tool that facilitates the transfer of information from educators to students and helps students build knowledge through various forms of representation (AECT, 2018). In recent years, digital learning environments have increasingly emphasized an interactive and technology-enabled approach to learning that combines theoretical understanding with practical experience (Zou et al., 2023). Meanwhile, future learning trends will be greatly influenced by the integration of technology and AI, where these digital tools are expected to encourage student motivation and involvement through project- and experiential learning approaches (Liu & Zhong, 2025). Educational technology has evolved from content-based teaching to an integrated, interactive, and flexible learning environment supported by digital media (Hustanto et al., 2024).

One widely discussed innovation in science and engineering education is the virtual laboratory (VRL), a software-based simulation environment that supports repeated experiments, visualization, and interactive learning without requiring direct physical interaction with laboratory equipment (Mottelson et al., 2021). Virtual laboratories allow students to rehearse procedures, observe simulated processes, and revisit concepts in a flexible setting (Hillmayr et al., 2020; Lakka et al., 2023). Previous studies have reported benefits for conceptual understanding and learning efficiency (Siahaya et al., 2024). Nevertheless, virtual laboratories are generally best treated as complements to, rather than complete replacements for, physical laboratory work because engineering students must also develop practical competencies and psychomotor skills (Asare et al., 2023; Th. et al., 2022). Hands-on laboratory activities remain important for developing procedural understanding, technical skills, and safety awareness (Agustian et al., 2022). Integrating virtual preparation with direct laboratory practice may therefore combine the flexibility of simulation with experience using physical equipment.

In addition to technological factors, learner characteristics may shape how students benefit from digital learning environments. Self-regulated learning (SRL) refers to learners' capacity to

plan, monitor, and evaluate their learning (Zimmerman, 2000). It includes cognitive, metacognitive, and motivational processes that support strategic learning and persistence (Astuti & Rozikin, 2024). Although previous research has examined virtual laboratories in relation to conceptual understanding and achievement, a relevant gap remains in evaluating observed laboratory performance alongside cognitive outcomes while also examining SRL and its interaction with instructional strategy (Seufert, 2026; Hsu & Lee, 2026). Written tests can assess conceptual knowledge, but they cannot by themselves capture the execution of laboratory procedures, equipment handling, and safety-related performance. A performance-based rubric is therefore needed alongside a cognitive test to represent both outcome domains (Agustian et al., 2022). The contribution of the present study is to compare HOL + VRL with HOL + PPT and to examine the main effects of instructional strategy and SRL, as well as their interaction, on both practical laboratory skills and cognitive knowledge. Cognitive load and scaffolding are considered possible explanatory perspectives in the discussion; neither construct was measured directly in this study.

This study addresses practical and pedagogical challenges in Chemical Engineering education, particularly where students have diverse prior laboratory experiences. It compares hands-on laboratory practice integrated with a virtual laboratory (HOL + VRL) against hands-on laboratory practice supported by PowerPoint (HOL + PPT) and examines outcomes at high and low levels of SRL. The study is guided by three hypotheses: H1: instructional strategy has a statistically significant multivariate effect on practical laboratory skills and cognitive knowledge; H2: SRL level has a statistically significant multivariate effect on the two outcomes; and H3: instructional strategy and SRL interact significantly in their effects on the two outcomes.

## RESEARCH METHODOLOGY

This study employed a quantitative quasi-experimental design with a pretest-posttest non-equivalent control group structure. Because students were enrolled in pre-existing classes, participants could not be randomly assigned to treatment groups (Setyosari, 2020). A 2 × 2 factorial arrangement was used: instructional strategy had two levels (HOL + VRL and HOL + PPT), and SRL was categorized into high and low levels. The dependent variables were practical laboratory skills and cognitive learning outcomes.

**Table 1.** 2x2 Factorial Research Design

| | | Learning Strategies | |
|---|---|---|---|
| | | HOL + VRL ($X_1$) | HOL + PPT ($X_2$) |
| Self-Regulated Learning | High (Y1) | (X1,Y1) | (X2,Y1) |
| | Low (Y2) | (X1,Y2) | (X2,Y2) |

The independent variable was instructional strategy, with two conditions: hands-on laboratory practice integrated with a virtual laboratory (HOL + VRL) and hands-on laboratory practice supported by a PowerPoint presentation (HOL + PPT). SRL was treated as a second factor and categorized into high and low levels using questionnaire scores. The dependent variables were cognitive learning outcomes and practical laboratory skills.

The population comprised undergraduate students enrolled in the Chemical Engineering Study Program at Tribhuwana Tunggadewi University who were taking Chemical Engineering Operations in the third and fifth semesters. A total of 69 students participated: 36 students in the experimental group (HOL + VRL) and 33 in the control group (HOL + PPT). These allocations are consistent with the Chapter IV descriptive tables and the supplied SPSS output. The classes were

not randomly assigned because they had been formed before the study. Both groups studied fluid systems and separation techniques in Chemical Engineering Operations. The supplied analyses classified 40 students as having high SRL and 29 as having low SRL.

The instruments comprised an SRL questionnaire, cognitive achievement tests, observation sheets, a practical laboratory performance rubric, virtual-laboratory media, instructional materials, and laboratory manuals. The SRL questionnaire was used to categorize students into high- and low-SRL groups. Cognitive outcomes were measured using essay-based pretests and posttests on Chemical Engineering Operations, including fluid mechanics and separation processes. Practical laboratory skills were assessed through laboratory performance, practice reports, and final laboratory examinations. The SRL questionnaire consisted of 36 items adapted from Zimmerman's self-regulated learning framework. Each item was rated on a five-point Likert scale to assess students' self-regulated learning characteristics. The responses were used to determine students' overall SRL scores, which served as the basis for classifying participants into high- and low-SRL groups. This classification enabled the examination of differences in cognitive achievement and practical laboratory performance between students with different levels of self-regulated learning.

Before implementation, all research instruments except the self-regulated learning (SRL) questionnaire underwent expert validation to assess their content appropriateness and alignment with the intended learning outcomes. The SRL questionnaire consisted of 36 items adapted from Zimmerman's established self-regulated learning framework, with responses rated on a five-point Likert scale. Because the questionnaire was adapted from an established framework, no separate expert feasibility assessment was conducted for this instrument. The remaining instruments, including cognitive achievement tests, observation sheets, the practical laboratory performance rubric, virtual-laboratory media, instructional materials, and laboratory manuals, were evaluated by educational and subject-matter experts and were deemed feasible for use. Relevant validity and reliability procedures were conducted for the applicable instruments before data collection. The study procedures consisted of three major phases: preparation, implementation, and evaluation. During the preparation phase, the researcher developed the instructional materials, virtual-laboratory media, assessment instruments, and learning scenarios. The applicable validity and reliability procedures were also completed during this phase. In the implementation phase, students first completed the SRL questionnaire and pretest assessments before participating in the instructional treatment.

**Table 2.** Learning Syntax

| Stages | Learning Procedure | Teaching Activities |
|---|---|---|
| 1 | Orient learners to problems | The teacher explains the learning objectives, explains the necessary logistics, and motivates the learner to be actively involved in problem-solving activities |
| 2 | Organizing learners for learning | Teachers divide into groups, helping learners define and organize problem-related learning tasks |
| 3 | Guiding individual and group investigations (VRL preparation) | Students gather information, explore laboratory procedures in the virtual simulation, discuss predictions, and then carry out the corresponding hands-on experiment. The instructor guides the inquiry and reinforces safe procedures |
| 4 | Developing and Presenting Work Products and Exhibits | Teachers assist learners in planning and preparing appropriate work such as: final reports, videos, models, and help them share their assignments with others |
| 5 | Analyze and evaluate the problem-solving process | Teachers help learners to reflect and evaluate the investigations and learning processes they use. |

The instructional procedure followed the problem-based learning stages adapted from Arends (2012): orienting students to the problem, organizing students for learning, guiding individual and group investigations, developing and presenting work, and analyzing and evaluating the problem-solving process. VRL was integrated primarily during the investigation stage, before students entered the physical laboratory. Students used the simulation to explore the sequence of procedures and operational processes, after which they conducted hands-on activities. Lecturers facilitated the investigations, supported students' problem solving, and guided reflection.

Data collection was conducted over one academic semester, lasting approximately six months, in accordance with the academic calendar of the Chemical Engineering Study Program. The data collection procedures included administering pretests, distributing the self-regulated learning (SRL) questionnaire, observing students during laboratory learning activities, assessing practical laboratory skills, and administering posttests. Although pretests were administered before the instructional intervention, pretest scores were not included in the statistical hypothesis testing. The analysis used posttest scores for cognitive learning outcomes and post-intervention assessment scores for practical laboratory skills. Data analysis consisted of prerequisite testing and hypothesis testing. Before hypothesis testing, the normality of the outcome data was examined using the Kolmogorov–Smirnov test, while the homogeneity of error variances was assessed using Levene's test. The equality of covariance matrices was also examined using Box's M test. All prerequisite tests were evaluated at a significance level of 0.05. The research hypotheses were tested using Multivariate Analysis of Variance (MANOVA) with SPSS. MANOVA was selected because the study examined two dependent variables simultaneously: cognitive learning outcomes and practical laboratory skills. The analysis assessed the main effects of instructional strategy and self-regulated learning, as well as their interaction, on both dependent variables.

Some methodological limitations must be acknowledged. First, the use of non-random groups can limit the generalization of findings and introduce potential selection bias. Second, this research was conducted in a university context and focused specifically on Chemical Engineering students, limiting its wider application to other disciplines. Third, differences in students' previous laboratory experience and digital literacy may have affected their performance during the intervention. Nevertheless, this study provides valuable insights into the integration of virtual laboratory environments and self-regulated learning in improving students' cognitive and psychomotor learning outcomes.

## RESULT AND DISCUSSION

This study investigated the effects of virtual laboratory-assisted practicum and self-regulated learning (SRL) on students' cognitive learning outcomes and practical laboratory skills in Chemical Engineering education. The analysis involved 69 undergraduate students who were divided into two instructional groups: a live lab integrated with a virtual lab (HOL + VRL) and a live lab integrated with a PowerPoint presentation (HOL + PPT). The participants were also categorized into high and low independent study groups based on the results of the questionnaire. Descriptive statistical analysis showed that students who followed the HOL+VRL learning strategy consistently achieved higher scores in both practical laboratory skills and cognitive learning outcomes compared to students in the HOL+PPT group. Students with high SRL also performed much better than students with low SRL in both dependent variables. Specifically, students in the HOL+VRL and high SRL groups obtained the highest average scores for practical laboratory skills (M = 85.09) and cognitive learning outcomes (M = 82.76), while the HOL + PPT group with low SRL obtained the lowest scores in both domains.

**Table 3.** Descriptive Statistic Practical

Dependent Variabel: Practical Learning Outcomes

| Instructiona Groups | SRL | N | Mean | Std. Deviation |
|---|---|---|---|---|
| Controls (HOL+PPT) | High | 19 | 79.31 | 3.315 |
| | Low | 14 | 71.15 | 3.292 |
| Experiments (HOL+VRL) | High | 21 | 85.09 | 3.318 |
| | Low | 15 | 77.33 | 9.465 |

**Table 4.** Descriptive Statistic Cognitive

Dependent Variabel: Cognitive Knowledge

| Instructiona Groups | SRL | N | Mean | Std. Deviation |
|---|---|---|---|---|
| Controls (HOL+PPT) | High | 19 | 78.40 | 4.244 |
| | Low | 14 | 70.25 | 4.805 |
| Experiments (HOL+VRL) | High | 21 | 82.76 | 4.965 |
| | Low | 15 | 74.88 | 3.931 |

**Table 5.** Box'M varians-kovarians

Box's Test of Equality of Covariance Matrices[a]

| | |
|---|---|
| Box's M | 34.606 |
| F | 3.623 |
| df1 | 9 |
| df2 | 32329.856 |
| Sig. | .000 |

Tests the null hypothesis that the observed covariance matrices of the dependent variables are equal across groups.
a. Design: Intercept + Strategi_Pembelajaran_Praktikum + SRL + Strategi_Pembelajaran_Praktikum * SRL

The MANOVA indicated statistically significant multivariate effects of instructional strategy, Pillai's Trace = .341, $F(2, 64) = 16.570$, $p < .001$, and SRL level, Pillai's Trace = .552, $F(2, 64) = 39.494$, $p < .001$. The instructional strategy × SRL interaction was not statistically significant, Pillai's Trace = .001, $F(2, 64) = 0.017$, $p = .984$. Thus, the combined profile of cognitive knowledge and practical skills differed by instructional strategy and SRL level, but the analysis did not detect a multivariate interaction. A non-significant interaction does not establish that the effects are equivalent; it indicates only that an interaction was not detected in this sample.

The supplied SPSS "Tests of Between-Subjects Effects" output provides follow-up univariate results for each outcome (Table 8). Instructional strategy was significant for cognitive knowledge, $F(1, 65) = 16.504$, $p < .001$, partial $\eta^2 = .202$, and practical skills, $F(1, 65) = 21.540$, $p < .001$, partial $\eta^2 = .249$. SRL was significant for cognitive knowledge, $F(1, 65) = 52.500$, $p < .001$, partial $\eta^2 = .447$, and practical skills, $F(1, 65) = 38.125$, $p < .001$, partial $\eta^2 = .370$. The strategy × SRL interaction was not significant for cognitive knowledge, $F(1, 65) = 0.014$, $p = .906$, partial $\eta^2 = .000$ (rounded), or practical skills, $F(1, 65) = 0.024$, $p = .878$, partial $\eta^2 = .000$ (rounded).

Assumption checks warrant caution. Box's test was significant, Box's M = 34.606, $F(9, 32329.856) = 3.623$, $p < .001$, indicating unequal covariance matrices. Levene's test was not significant for cognitive knowledge, $F(3, 65) = 1.047$, $p = .378$, but was significant for practical skills, $F(3, 65) = 6.595$, $p = .001$, indicating unequal error variances for that outcome. The findings are therefore interpreted cautiously, particularly the univariate practical-skills result; a robust sensitivity analysis would strengthen the evidence.

**Table 5.** Multivariate Tests of Instructional Strategy (HOL + VRL vs. HOL + PPT)

| Effect | Value | F | Hypothesis df | Error df | Sig. |
|---|---|---|---|---|---|
| Pillai's Trace | .341 | 16.570[b] | 2.000 | 64.000 | .000 |
| Wilks' Lambda | .659 | 16.570[b] | 2.000 | 64.000 | .000 |
| Hotelling' Trace | .518 | 16.570[b] | 2.000 | 64.000 | .000 |
| Roy's Largest Root | .518 | 16.570[b] | 2.000 | 64.000 | .000 |

**Table 6.** Multivariate Tests of Self-Regulated Learning (SRL)

| Effect | Value | F | Hypothesis df | Error df | Sig. |
|---|---|---|---|---|---|
| Pillai's Trace | .552 | 39.494[b] | 2.000 | 64.000 | .000 |
| Wilks' Lambda | .448 | 39.494[b] | 2.000 | 64.000 | .000 |
| Hotelling' Trace | 1.234 | 39.494[b] | 2.000 | 64.000 | .000 |
| Roy's Largest Root | 1.234 | 39.494[b] | 2.000 | 64.000 | .000 |

**Table 7.** Multivariate Tests of the Instructional Strategy × SRL Interaction

| Effect | Value | F | Hypothesis df | Error df | Sig. |
|---|---|---|---|---|---|
| Pillai's Trace | .001 | .017[b] | 2.000 | 64.000 | .984 |
| Wilks' Lambda | .999 | .017[b] | 2.000 | 64.000 | .984 |
| Hotelling' Trace | .001 | .017[b] | 2.000 | 64.000 | .984 |
| Roy's Largest Root | .001 | .017[b] | 2.000 | 64.000 | .984 |

**Table 8.** Univariate Tests of Instructional Strategy, SRL, and Their Interaction

| Source | Dependent Variable | Type III Sum of Square | df | Mean Square | F | Sig. | Partial Eta Square |
|---|---|---|---|---|---|---|---|
| Main | Practical Skills | 1686.390[a] | 3 | 562.130 | 20.148 | .000 | .482 |
| Effect | Cognitive Knowledge | 1431.735[b] | 3 | 477.245 | 23.256 | .000 | .518 |
| Error | Practical Skills | 1813.496 | 65 | 27.900 | | | |
| | Cognitive Knowledge | 1333.908 | 65 | 20.522 | | | |
| Total | Practical Skills | 433970.900 | 69 | | | | |
| | Cognitive Knowledge | 415168.880 | 69 | | | | |
| Corrected | Practical Skills | 3499.886 | 68 | | | | |
| Total | Cognitive Knowledge | 2765.643 | 68 | | | | |

The corrected models accounted for 51.8% of the variance in cognitive knowledge ($R^2 = .518$, adjusted $R^2 = .495$) and 48.2% of the variance in practical skills ($R^2 = .482$, adjusted $R^2 = .458$), according to the supplied SPSS output

These findings suggest that virtual lab-assisted teaching provides meaningful support to improve student understanding and laboratory performance. The higher performance achieved by the HOL+VRL group can be explained by the virtual lab's ability to provide a repeatable simulation experience, procedural visualization, and opportunities for students to explore laboratory activities before entering the actual laboratory environment. Virtual labs help students reduce procedural uncertainty and increase familiarity with laboratory equipment and processes. These findings support previous research showing that virtual labs improve students' conceptual understanding, learning flexibility, and readiness in science and engineering education (Mihăilă et al., 2025). The results are also consistent with Dale's Experiential Cone theory, which suggests that learning becomes more meaningful when students engage in hands-on, concrete experiences rather than purely abstract teaching. Through VRL-assisted learning, students can interact with simulations and procedural representations before conducting actual experiments, allowing them to build a stronger conceptual and procedural understanding (Ukhurebor et al., 2025). While virtual labs cannot

completely replace physical lab experiences, virtual labs serve effectively as a preparation and reinforcement tool that increases students' readiness and confidence during hands-on activities (Danmali et al., 2026).

The significant multivariate effect associated with SRL is consistent with a social-cognitive view in which learners plan, monitor, and evaluate their cognition, motivation, and behavior during learning (Zimmerman, 2000). In the descriptive results, students classified as having high SRL scored above those classified as having low SRL. The univariate tests also showed statistically significant SRL effects on cognitive knowledge and practical skills. The strategy × SRL interaction was not significant in the multivariate test ($p = .984$) or in the separate univariate tests for cognitive knowledge ($p = .906$) and practical skills ($p = .878$). These results do not prove that the effects are exactly the same across SRL levels; they show that the analyses did not detect a significant interaction in this sample.

A possible explanation can be considered through Cognitive Load Theory: a well-designed simulation may make procedural information more visible and repeatable, reducing the need for novice learners to hold multiple unfamiliar steps in working memory while they build task schemas (Sweller, 1988). In addition, sequenced prompts, visual cues, and instructor guidance can function as scaffolds that help learners perform a task before they can manage all steps independently (Wood et al., 1976). These are plausible mechanisms for the observed pattern, not measured findings: this study did not directly assess cognitive load, scaffold use, or changes in SRL. The non-significant interaction therefore cannot be attributed to reduced extraneous cognitive load on the basis of these data; future research should measure these mechanisms directly. The assumption tests also found unequal covariance matrices and unequal error variance for practical skills, so that outcome requires cautious interpretation.

The contribution of this study is its joint examination of cognitive knowledge and practical laboratory performance alongside SRL in a quasi-experimental comparison of HOL + VRL and HOL + PPT. The multivariate tests and univariate follow-up tests showed significant main effects of instructional strategy and SRL, while none of the interaction tests was significant. Because the classes were not randomized and the practical-skills variance assumption was not met, the magnitude and generalizability of the effects should be treated cautiously.

Several limitations should be acknowledged. First, the quasi-experimental design used non-randomized groups, which may introduce selection bias and limit causal generalization. Second, the study was conducted at one institution with Chemical Engineering students, limiting generalizability to other disciplines and settings. Third, the intervention lasted one semester, so long-term outcomes remain unknown. Fourth, Box's test indicated unequal covariance matrices and Levene's test indicated unequal error variance for practical skills; this weakens the assumptions underlying the reported tests and warrants robust sensitivity analysis.

Future studies are recommended to involve larger and more diverse participant populations across multiple institutions and disciplines. Further research may also explore longitudinal effects of virtual laboratory implementation, investigate additional moderating variables such as motivation and digital literacy, and integrate more advanced immersive technologies such as augmented reality or artificial intelligence-based adaptive laboratory systems. Such developments may contribute to more personalized and effective engineering learning environments in the future.

## CONCLUSION

This study found significant multivariate effects of instructional strategy and SRL level on the combined outcomes of practical laboratory skills and cognitive knowledge. Follow-up univariate

tests indicated significant main effects of instructional strategy on cognitive knowledge and practical skills and significant main effects of SRL on both outcomes. Descriptive means were higher in the HOL + VRL condition than in the HOL + PPT condition at both SRL levels. The strategy × SRL interaction was not statistically significant in the multivariate or univariate analyses. These results support considering virtual laboratories as preparatory complements to hands-on practice, while recognising that the study does not establish equivalent effects across SRL levels or definitive causal effects.

The study contributes to technology-enhanced engineering education by considering cognitive knowledge and observed practical performance together and by examining SRL alongside instructional strategy. It highlights the potential value of combining digital simulation with physical laboratory experience rather than replacing hands-on practice. Future studies should document the platform and instrument properties, specify pretest/posttest scoring and analysis decisions, and test whether cognitive load or scaffolded guidance helps explain the learning patterns. Robust analyses should also be considered when homogeneity assumptions are violated.

For practice, virtual laboratories may be used to prepare students for physical experiments by allowing them to rehearse procedures and revisit simulated processes. Institutions should align simulations with the actual laboratory protocol and safety requirements, while retaining supervised hands-on work to assess real equipment handling and procedural competence.

## DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work the author(s) used Perplexity in order to Article Search. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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## AUTHORS' CONTRIBUTION

Author 1: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Writing - original draft.
Author 2: Conceptualization; Methodology; Supervision; Validation; Writing - review and editing.
Author 3: Project administration; Resources; Supervision; Validation; Writing - review and editing.
Author 4: Methodology; Supervision; Validation; Writing - review and editing.

## DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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