

Integration of Virtual Lab-Based Learning Media in Improving Practical Skills and Student Engagement in Computer Network Engineering

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Abstract: This study investigates the integration of learning media using virtual labs to improve practical skills and student engagement in Computer Network Engineering at Institut Teknologi dan Bisnis Bina Sarana Global. A quasi-experimental design was conducted in an experimental class using virtual labs and in a control class using the traditional practicum. Participants consisted of 62 students. Data were collected with pretest–posttest assessments of practicum skills and an evidence-rated engagement questionnaire. The results showed a great increase in the experimental class. Then, using a series of independent-samples t-tests, we compared the posttest practical skill scores between the experimental ($M = 85.42$, $SD = 6.31$) and control class practice ($M = 78.11$, $SD = 7.04$), $t(60) = 4.21$, $p < .001$, and a large effect size ($d = 1.06$). In addition, a comparison of the groups' mean scored on short-answer scoring revealed that students were more engaged with the material in the experimental group ($M = 4.32$, $SD = 0.41$) than compared to students in the control group ($M = 3.87$, $SD = 0.46$), $t(60) = -3.78$, $p < .001$. In general, they are effective in providing laboratory practice to master concepts, demonstrate bad practices, troubleshoot, and in encouraging active participation in learning. Implementation Read This Teaching Note: Virtual labs are recommended as an active research-based practicum model in engineering to enhance student learning outcomes.

Keywords: virtual laboratory, practical skills, student engagement, digital learning media.

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■ INTRODUCTION

This growing demand for more creative educational solutions is especially evident in areas such as computer networking engineering, where students need substantial theoretical knowledge to address the industrial challenges they may encounter. Standard classroom approaches in computer networking engineering are limited because limited lab access and safety concerns make it difficult to ensure equal opportunity. Most importantly, repeated hands-on software practice requires accuracy when students undertake it in rapid succession within a single time frame. These restrictions may also prevent students from gaining vital skills, leaving them uncertain and/or incapable of even basic practical expertise in computer networking (J. Li & Liang, 2024).

One possible approach to overcome these limitations is integrating virtual laboratory platforms specifically designed for Computer Network Engineering. Applications such as Cisco Packet Tracer, GNS3, EVE-NG, and Mininet enable students to design network topologies, configure routers and switches, assign IP addresses, test connectivity, analyze network traffic, and troubleshoot configuration errors through interactive simulations. These platforms provide immediate feedback and on-demand access, allowing students to repeatedly practice network installation, configuration, and troubleshooting without damaging physical equipment or disrupting operational networks (Abdrabou & Shakhathreh, 2021). This functionality supports experiential learning by connecting theoretical concepts with authentic

networking tasks in a safe, controlled environment. Consequently, virtual laboratories can strengthen students' practical competence, problem-solving skills, and confidence in managing increasingly complex computer network systems.

Further, the pedagogical potential of virtual labs is grounded in contemporary educational theories such as constructivist learning theory. Indeed, virtual labs are themselves rich interactive experiences that encourage active engagement with the materials, enabling students to construct knowledge through inquiry-based learning and hands-on experimentation (Wastira & Tekad, 2025). Computer Network theory is often viewed as a very abstract topic; these digital platforms can help spur students' interest and commitment to their learning, which may wane during a traditional lecture. Immersive Virtual Labs: Because of their immersive nature, these virtual labs offer an interactive (rather than passive) exploration. Typical classes remain observational, which again aims to help students understand the concepts of Computer Networking Engineering.

Even real lab implementations have significant benefits, but they vary across educational levels in Indonesia when abstracting virtual implementations! Additionally, the teacher's resistance to this shift has been identified as the principal barrier to determining whether any of these approaches will offer improvement and efficiency, as teachers are habituated to traditional approaches or worry about students who may not be able to use technologies appropriately or correctly in the context of their content areas (Wut & Xu, 2021). Nevertheless, empirical evidence shows that these virtual labs complement practical training, maintain practical skills, and enhance academic performance and student engagement when used alongside actual labs in engineering education. In addition, these immersive virtual worlds are a meaningful supplement to conventional approaches when well executed (Sharma et al., 2022).

Another option that may help students gain practical skills and supplement information engineering training is virtual laboratories. These tools have been shown to let students practice Computer Network design, implementation, and troubleshooting repeatedly, without limitations, compared to traditional physical labs. Students match course labs, and this iterative practice is key to developing skills for professional problems, where one must move from theory to practice. Although most traditional instructional methods in information engineering education, among other areas, face many challenges in developing students' practical skills, virtual laboratories offer a promising, innovative alternative. These tools support hands-on exploration, boost engagement, and align with current pedagogical practices. The benefits of virtual labs in improving educational outcomes support more exploratory work and an evidence-based approach to measurement in authentic learning environments.

This study aims to determine the effectiveness of virtual lab media on practical skills and student engagement among Computer Network Engineering students at Institut Teknologi dan Bisnis Bina Sarana Global. The study uses quasi-experimental methods to compare outcomes for students who use virtual labs with those who use only an orthodox practicum. More specifically, the study aims to determine whether integrating a virtual lab results in measurable improvements in practical skills (Computer Network, measurement accuracy, and troubleshooting) and increases in behavioral, emotional, and cognitive engagement. The study further aims to examine students' perceived usability of virtual labs and the extent to which Virtual Labs create a more friendly learning environment.

Accordingly, this study investigates the effectiveness of virtual laboratory-based learning in enhancing practical skills and student engagement in Computer Network Engineering. Specifically, it addresses the following research questions:

1. To what extent does virtual laboratory-based learning improve students' practical skills in designing, configuring, testing, and troubleshooting computer networks compared with conventional laboratory instruction?
2. Does virtual laboratory-based learning produce higher levels of behavioral, emotional, and cognitive engagement than conventional laboratory instruction?
3. How do students perceive the usability, benefits, and challenges of virtual laboratories in supporting their Computer Network Engineering learning experiences?

The context of virtual labs is very important for understanding the instructional design, curriculum plan, and technology integration strategies of the Information Engineering Study Program at Institut Teknologi dan Bisnis Bina Sarana Global. The need to refocus the equation of engineering education is pressing, and utilizing digital learning innovations, including assessment tools and methods closely linked to educational engagement strategies, may provide greater opportunities for students to be better prepared for the challenges they will face in their professional or academic future. More broadly, the results of this study provide recommendations not only for updating lab-based instruction at institutions that host engineering programs but also for the literature on educational technology in engineering disciplines.

■ METHOD

Research Design

This study employed a quasi-experimental, non-equivalent pretest–posttest control-group design to evaluate instructional effects in intact classrooms where individual randomization was impractical (H. Chen et al., 2024; Wang et al., 2026). A mixed-methods approach combined quantitative outcome comparisons with qualitative evidence of students' experiences (Koçan et al., 2024a). Quantitatively, pretest and posttest scores were compared between students

receiving Virtual Laboratory-based instruction and those receiving conventional laboratory instruction, consistent with comparative virtual-laboratory research (J. Li & Liang, 2024). Qualitatively, interviews examined experimental-group students' perceived benefits, challenges, and learning experiences to explain the quantitative patterns (Koçan et al., 2024b). Both groups followed identical learning outcomes, practical competencies, assessment criteria, and instructional time.

Population and Samples

The population comprised undergraduate students enrolled in the Computer Network Engineering course within the Information Engineering Study Program at the Bina Sarana Global Institute of Technology and Business. Purposive sampling was used to select two intact classes from the 13 available course sections. The classes were selected based on the following comparability criteria: enrollment in the same course and semester, exposure to the same syllabus and instructional content, instruction by the same lecturer, and comparable prior experience with computer network laboratory activities. All students in the two selected classes participated, producing a sample of 62 students. One intact class of 32 students was designated as the experimental group and received virtual laboratory-based instruction. In contrast, the other class of 30 students was designated as the control group and received conventional laboratory instruction.

Following the intervention, 12 students from the experimental group were selected for semi-structured interviews using stratified purposive sampling. The selection aimed to represent variation in learning outcomes: four students with high performance, four with average performance, and four with low performance. These categories were determined using students' total posttest scores on the practical-skills

assessment rubric, rather than GPA, pretest results, or previous assignment scores. The rubric assessed network design and configuration, testing and measurement accuracy, and troubleshooting ability.

The 32 experimental-group students were ranked by total posttest scores and divided into three approximately equal groups. Students in the upper third were classified as high-performing, those in the middle third as average-performing, and those in the lower third as low-performing. Four students were then randomly selected from each category. When identical scores occurred at a category boundary, all students with the same score were included in the eligible pool, and selection was conducted randomly. This procedure ensured objective participant classification while capturing diverse experiences of virtual laboratory-based learning.

Research Instrument

Researchers used a mixed-methods design to assess the impact of integrating a virtual lab on

students' practical skills and engagement. An analysis of available, officially standardized instruments that met the requirements indicated above was conducted to select the survey instruments for this study based on their alignment with the study objectives and previous validity and reliability checks reported in the literature. Quantitative data were collected using a rubric for practical skills assessment and an engagement questionnaire, while qualitative data were collected through an observation checklist and semi-structured interviews. The practical rubric tool evaluated the technical competencies of students during laboratory sessions, while the student engagement questionnaire surveyed behavioral, emotional, and cognitive engagement on a 5-point Likert scale (1 = Strongly Disagree; 2 = Disagree; 3 = Neutral; 4 = Agree; and 5 = Strongly Agree). Qualitative methods used to supplement quantitative findings, in terms of providing descriptions about students' learning behaviors, experiences, and perceptions of using the virtual laboratory. Table 1 presents an overview of the research instruments.

Table 1. Summary of research instruments

Instrument	Purpose	Components / Indicators	Scale / Participants	Validity & Reliability
Practical Skills Assessment (Rubric)	To measure students' technical competencies in Computer Network Engineering tasks.	• Network configuration and assembly competence • Measurement and configuration accuracy • Troubleshooting ability • Interpretation of network behavior	Performance rubric	Validated by three subject-matter experts; Inter-rater reliability, Cohen's $\kappa = 0.82$
Student Engagement Questionnaire	To assess students' behavioral, emotional, and cognitive engagement during learning activities.	• Behavioral engagement (participation, effort) • Emotional engagement (interest, motivation) • Cognitive engagement (focus, strategy use)	Five-point Likert scale: 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly Agree	Adapted from established engagement frameworks (W. Li, 2024; Wang et al., 2025; Zhang, 2026); Cronbach's $\alpha = 0.89$
Observation Checklist	To document observable learning behaviors during	• Task participation • Attention during instruction • Interaction with virtual lab features	Observation of all 62 students throughout six instructional sessions	Expert-reviewed for clarity and content relevance

	instruction.	Collaboration during practical activities		
Semi-Structured Interview Guide	To explore students' perceptions of virtual lab usage and learning experiences.	• Perceived usefulness • Benefits and challenges • Engagement and motivation • Suggestions for improvement	12 purposively selected students (4 high-, 4 moderate-, and 4 low-performing students); 20–30-minute interviews	Content validity confirmed through expert review; findings triangulated with observations and quantitative results

Data Collection

Data were systematically collected across six instructional sessions to document changes in both the skills being taught and students' levels of engagement over the course of the intervention. The combination of pretests, posttests, observations, and interviews provided a rich context for exploring how integrated virtual labs might have influenced learning gains. Although

both the experimental and control groups received similar instructional content, the practicum media differed. During the data-collection phase, the researcher established baseline equivalence, examined learning experiences during the intervention, and measured changes following instruction. Table 2. Overview of the different data collection phases and their activities.

Table 2. Summary of data collection procedures

Phase	Description	Activities Conducted
Pretest Phase	Establish baseline equivalence between groups.	• Practical skills pretest administered to both groups. • Engagement baseline survey completed by all participants.
Intervention Phase	Implement instructional treatments for each group over 6 sessions.	Experimental group: – Used virtual lab tools (Multisim, Tinkercad). – Conducted guided simulations and independent Computer Network exploration. Control Group: – Used traditional tools (breadboards, multimeters, power supplies). – Completed parallel tasks without simulation aids.
Blended Practicum Integration	Provide hands-on reinforcement for both groups.	• All students performed a final physical practicum to apply skills acquired during the intervention.
Posttest Phase	Assess learning gains and capture qualitative insights.	• Practical skills posttest administered to both groups. • Engagement survey re-administered. • Semi-structured interviews were conducted with selected students.

Data Analysis

To provide an in-depth analysis and understanding of the effects of virtual lab integration on students' practical skills and engagement, data were analyzed using a combination of quantitative and qualitative methods. SPSS was used to analyze quantitative data and identify shifts in practical skills and engagement levels. To evaluate pretest–posttest gains within each group, paired-samples t-tests

were conducted; independent t-tests compared posttest scores between the experimental and control groups. Effect sizes were computed as Cohen's *d* to quantify the practical equivalence of observed differences. To evaluate improvements in specific practical skill components, percentage improvement was calculated for each subskill by comparing the mean pretest and posttest scores. Where Posttest Mean represents the average score obtained after

the virtual laboratory intervention and Pretest Mean represents the average score before the intervention. This metric indicates the relative increase in performance for each practical skill component, allowing comparison of learning gains across different competencies. Higher percentages indicate greater improvement attributable to the instructional intervention

Qualitative interview data were analyzed thematically in NVivo following Braun and Clarke's six phases: transcript familiarization, initial coding, theme generation, theme review, theme definition and naming, and report production (J. Li et al., 2025). Representative quotations were selected to substantiate each theme and preserve participants' perspectives (Lim et al., 2025). The resulting themes were compared with quantitative patterns to identify convergence, complementarity, or divergence between the datasets, consistent with mixed-methods integration procedures (Bird et al., 2022). Analytical triangulation strengthened

the credibility of the findings by using simple quantitative evidence from observation notes to validate qualitative data against statistics.

■ RESULT AND DISCUSSION

Improvement in Practical Skills

A structured rubric was used to score the performance of computer networking workshop tasks across different contingencies (e.g., relative competence in computer networking, correctness in measurement & analysis, effectiveness in troubleshooting). Both groups performed the same practical skills assessment at pretest and posttest. This design enabled the investigator to quantify whether performance improved or declined within each group and to compare virtual lab-based instruction with standard laboratory instruction. Tables 3 and 4 present descriptive and inferential statistics on the improvement in practical skills across both groups.

Table 3. Improvement in practical skills between experimental and control groups

Assessment	Group	Mean (M)	SD	Statistical Test	p-value	Effect Size (d)
Pretest	Experimental	67.81	7.23	$t(60) = 0.54$	0.592	0.14 (Small)
	Control	66.79	7.38			
Posttest	Experimental	85.42	6.31	$t(60) = 4.21$	< 0.001	1.06 (Large)
	Control	78.11	7.04			

The pretest results confirmed equivalent baseline practical skills between the experimental and control groups ($t(60) = 0.54$, $p = 0.592$, $d = 0.14$). Following the intervention, the experimental group achieved significantly higher posttest scores than the control group ($t(60) = 4.21$, $p < .001$), with a large effect size ($d = 1.06$), demonstrating the effectiveness of virtual laboratory-based learning in enhancing practical skills. To illustrate individual learning gains, students' pre-test and post-test practical skill scores were plotted on a scatter plot. The diagonal line ($y = x$) represents no improvement,

allowing comparison of learning progress between the experimental and control groups (see Figure 1).

Figure 1 shows that almost all data points are positioned above the diagonal line, indicating that students in both groups improved their practical skills after instruction. However, the experimental group shows consistently higher post-test scores and larger gains than the control group, with most students scoring above 85. In contrast, the control group exhibits more modest improvements and lower post-test scores. These visual findings are consistent with the statistical

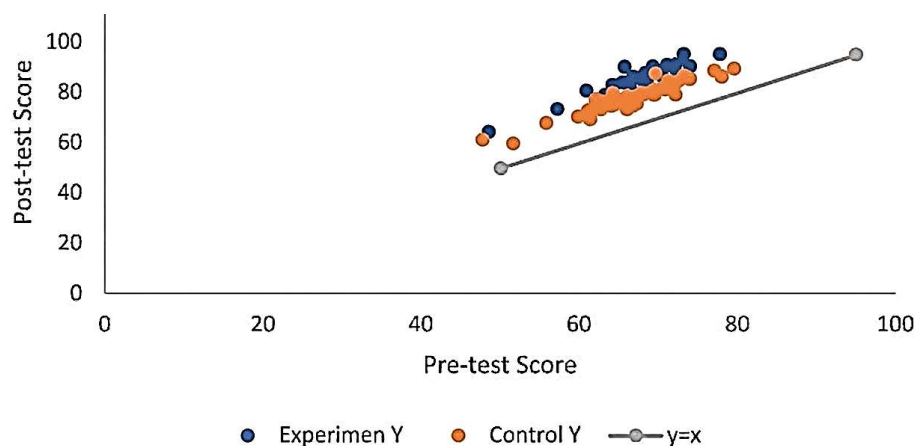


Figure 1. Scatter plot of pre-test and post-test practical skills for the experimental and control groups

results in Table 3, confirming that virtual laboratory-based learning produced significantly greater improvements in practical skills than conventional instruction ($t(60) = 4.21, p < .001$, Cohen’s $d = 1.06$).

A deeper dive into rubric scores also showed that three core skill components improved dramatically. Users reported the greatest improvement in their troubleshooting skills (28%), measurement accuracy (23%), and

Table 4. Subskill performance improvement in the experimental group

Skill Component	Pretest Mean	Posttest Mean	Improvement (%)
Troubleshooting	61.80	79.10	28.0
Measurement Accuracy	69.20	85.12	23.0
Computer Network Assembly	72.40	85.43	18.0

computer networking skills (18%). These results indicate that students gain a deeper understanding of computer networking behavior by actually practicing, receiving immediate feedback, and repeating this exercise as many times as needed in a low-risk virtual lab environment. As a result, students have improved procedural accuracy and confidence before working in physical lab environments. In other studies, we found that virtual lab integration effectively enhances practical skills in Computer Network Engineering and serves as a valuable supplement to traditional laboratory instruction.

Student Engagement Outcomes

Using a validated Likert-scale questionnaire, student engagement was assessed in three dimensions, behavioral, emotional, and cognitive, in pretest and posttest formats. This assessment enabled the researcher to examine differences in engagement beyond experimental or control differences, using percentage change for each engagement component. This result is presented in Table 5 as an engagement metric, along with corresponding statistical results demonstrating the impact of integrating virtual labs on student engagement.

Table 5. Student engagement scores for experimental and control groups

Engagement Measure	Assessment	Group	Mean (M)	SD	Statistical Test	p-value
Overall Engagement	Pretest	Experimental	3.46	0.43	$t(60) = 0.41$	0.684
		Control	3.42	0.45		

Behavioral Engagement	Posttest	Experimental	4.32	0.41	$t(60) = 3.78$	< 0.001
		Control	3.87	0.46		
	Pretest	Experimental	3.45	0.46	$t(60) = 0.36$	0.721
		Control	3.41	0.47		
Emotional Engagement	Posttest	Experimental	4.28	0.44	$t(60) = 0.44$	0.662
		Control	3.82	0.49		
	Pretest	Experimental	3.47	0.42	$t(60) = 0.39$	0.699
		Control	3.43	0.44		
Cognitive Engagement	Posttest	Experimental	4.35	0.40	$t(60) = 0.39$	0.699
		Control	3.90	0.45		
	Pretest	Experimental	3.46	0.44	$t(60) = 0.39$	0.699
		Control	3.42	0.46		
	Posttest	Experimental	4.33	0.41	$t(60) = 0.39$	0.699
		Control	3.89	0.44		

The pretest results indicated no significant differences in student engagement between the experimental and control groups ($p > .05$), demonstrating comparable baseline engagement. Following the intervention, the experimental group achieved significantly higher overall engagement than the control group ($t(60) = 3.78, p < .001$). Improvements were observed across behavioral,

emotional, and cognitive engagement, suggesting that the virtual laboratory fostered greater participation, motivation, and active learning throughout the Computer Network Engineering course. Comparison of practical skill scores using a standard bar chart (Boxplot), a visualization model that masks the distribution of individual data and the presence of outliers, as shown in Figure

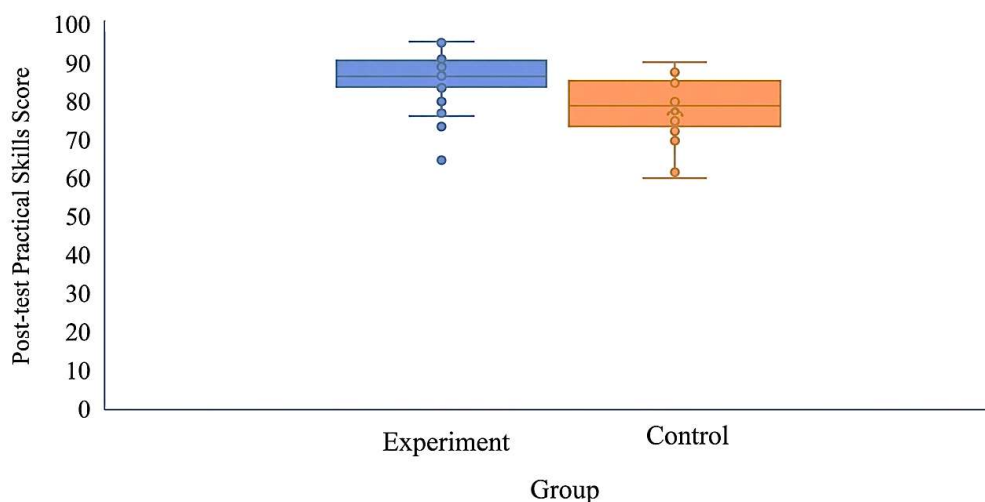


Figure 2. Practical skills posttest mean score

Figure 2 presents the distribution of post-test practical skills scores for the experimental and control groups using a boxplot. The experimental group had a higher median score than the control group, indicating better overall practical performance after the Virtual Lab

intervention. The first (Q1) and third (Q3) quartiles of the experimental group were also higher, showing that most students achieved better practical outcomes. Although both groups showed some variability, the experimental group's scores were more concentrated in the upper score range,

whereas the control group displayed a wider spread with several lower scores. A small number of outliers were observed in both groups but did not alter the overall distribution pattern. These findings visually support the statistical results, indicating that Virtual Lab-based learning substantially improved students' practical skills compared with conventional laboratory instruction.

However, a closer look at these drivers of engagement shows more even progress across behavior, emotion, and cognition. Regarding behavioral engagement, students in the experimental group spent significantly more time on their tasks, made a greater overall contribution (in simulated computer networking), and explored a wider variety of topics related to computer networks and systems (4, 5). Students experienced increased emotions, and because virtual simulations provided a supportive environment, they were more engaged and less anxious. Large effects were also found for cognitive engagement (greater attention and reasoning) and strategy use in exploring the Computer Network. That means you get High attraction scores for Virtual labs, as they provide live/error-free experiments, and for computer network models that are visually rich. It got students involved because they could see firsthand how changes in Computer Network configurations affected voltage, current, and

component behavior instantly, which raised questions and kept them engaged.

By facilitating engagement and learning, the ability to run experiments at any time of day, without needing equipment, led students to repeat them. The data we already have show that virtual labs not only boost student motivation and involvement but also support a more conceptual understanding of Computer Network Engineering. This justifies the need for virtual lab environments to improve students' engagement in Engineering Education.

Qualitative Findings

Qualitative data were collected through classroom observations and semi-structured interviews with 12 purposively selected students (4 high-performing, 4 moderate-performing, and 4 low-performing students) to complement and triangulate the quantitative findings. Interview transcripts were analyzed using NVivo 14 following Braun and Clarke's (2023) six-phase thematic analysis procedure. After coding and theme refinement, three overarching themes emerged: (1) Increased Conceptual Clarity, (2) Reduced Cognitive Load and Anxiety, and (3) Enhanced Motivation and Learning Autonomy (Braun & Clarke, 2023). Table 6 presents the frequency of participants (case count) contributing to each theme.

Table 6. NVivo coding matrix summary of qualitative themes (n = 12)

Theme	Representative Sub-themes	Case Count (n)	Participants (%)
Theme 1. Increased Conceptual Clarity	Better understanding of network concepts; visualization of network behavior; immediate feedback; easier troubleshooting	11	91.7%
Theme 2. Reduced Cognitive Load and Anxiety	Reduced fear of making mistakes; repeated practice; safe experimentation; increased confidence	9	75.0%
Theme 3. Enhanced Motivation and Learning Autonomy	Increased interest; self-directed learning; independent exploration; collaborative learning	10	83.3%

Theme 1. Increased Conceptual Clarity (11 of 12 participants; 91.7%)

The most frequently identified theme concerned improvements in students' conceptual understanding of Computer Network Engineering concepts. Eleven participants explained that the virtual laboratory enabled them to visualize network behavior, making abstract concepts easier to understand.

"The Virtual Lab helped me understand network topology and device configuration much more clearly. When I changed an IP address or routing configuration, I could immediately see the impact on network connectivity." (Participant E05)

"I finally understood how packets move through the network because I could observe the simulation in real time." (Participant E11)

Virtual laboratories provided dynamic visual representations that strengthened students' conceptual understanding of Computer Network Engineering principles. Immediate feedback and interactive simulations enabled students to connect theoretical knowledge with practical network behavior. Classroom observations further showed that students discussed routing, addressing, and troubleshooting with greater confidence and asked more analytical questions during practical sessions. These findings indicate that virtual laboratories functioned as cognitive scaffolds, facilitating meaningful conceptual learning.

Theme 2. Reduced Cognitive Load and Anxiety (9 of 12 participants; 75.0%)

Nine participants reported that virtual laboratory activities reduced stress and anxiety commonly experienced during conventional practical sessions.

"I was not afraid of making mistakes because I could reset the simulation whenever something went wrong."

(Participant E08)

"Working in the Virtual Lab made me more confident before entering the real laboratory." (Participant E02)

Students perceived the virtual environment as a psychologically safe learning space where they could freely experiment without damaging laboratory equipment or disrupting network devices. The ability to repeat activities, modify configurations, and immediately correct errors reduced extraneous cognitive load and allowed students to focus on understanding network concepts. Observations confirmed that students became more willing to explore alternative solutions and demonstrated greater confidence when solving complex networking problems.

Theme 3. Enhanced Motivation and Learning Autonomy (10 of 12 participants; 83.3%)

Ten participants described increased motivation and greater independence while using the virtual laboratory.

"Learning became much more interesting because I could explore different network configurations on my own." (Participant E07)

"Even after class, I continued practicing at home because the software was easy to access." (Participant E12)

The virtual laboratory's flexibility encouraged students to become more active and self-directed learners. Many participants voluntarily explored additional network scenarios beyond those required by the course and collaborated with peers to solve configuration problems. Classroom observations also revealed frequent peer discussions and independent experimentation. These findings suggest that virtual laboratories foster intrinsic motivation, promote autonomous learning, and encourage sustained engagement with Computer Network Engineering content.

Integration of Qualitative and Quantitative Findings

The qualitative findings strongly support the quantitative results. The high frequency of participants reporting improved conceptual understanding (91.7%), increased motivation (83.3%), and reduced cognitive load (75.0%) aligns with the statistically significant improvements observed in practical skills and student engagement. Together, these findings demonstrate that virtual laboratory media not only improve technical competencies but also enhance the cognitive and affective learning processes that underpin successful Computer Network Engineering education.

Virtual Labs Add Immensely in Hands on Skills

Today, virtual labs offer an interesting opportunity, as they allow students to access information without expensive physical materials. Based on previous descriptions, students who had a virtual lab atmosphere received considerably greater posttest scores than those assigned traditional course lab assignments (Rakhmawati et al., 2022). Virtual labs are introduced as meeting needs for both cognitive and procedural skills. These findings are consistent with prior research, which indicated that simulated environments have been successful because they provided learners repeated opportunities to practice and develop skills in the absence of physical resources (Rana et al., 2024).

A more detailed breakdown of troubleshooting, accurate measurement, and networking assembly shows large gains across many metrics. These enhancements mean that virtual labs not only improve understanding of the theory but also enable students to transfer what they have learned into practice (Y. Chen et al., 2024). It has been shown that this type of environment fosters hypothesis testing and iterative learning, which are hallmarks of skill acquisition in scientific education (Tuli et al.,

2022). Virtual tools enable students to engage in repeated processes that involve trial and error, leading to a deeper understanding of concepts and retention of key ideas (Sharma et al., 2022).

Notably, qualitative quotes from students testified to the promise of virtual labs. It has also been found that students find both instant feedback and visualization of circuit behaviors help them identify errors rapidly and deepen their understanding of principles (Lee et al., 2023). Interactive components and immersive technological features in virtual labs reduce risks in conventional physical lab scenarios, such as equipment failures and safety issues. Such low-risk experimentation is particularly important in fields that require tight tolerances, such as engineering and the physical sciences (Sakkas et al., 2025). This combination of quantitative data and qualitative student experiences supports the claim that virtual labs significantly enhance practical skills by providing a well-structured, immersive, and safe learning environment. Virtual labs are therefore poised to play a prominent role in how educational systems continue to grow and adapt their curricula to utilize technology, providing improved learning outcomes and a skilled student generation (Garrard & Beck, 2018).

Interaction and Visual Feedback Increase Student Engagement

Virtual labs also include interactive simulations that could increase student engagement in behavioral, emotional, and cognitive learning. All experiments demonstrate greater student engagement in mediated environments than in traditional learning situations. These findings support the theory that immersion in a virtual environment provides an interactive, engaging, and entertaining context for learning, which may reduce anxiety when learning complex scenarios such as Information Engineering (Tokatlidis et al., 2024).

Qualitative data to further explain that these virtual labs are interactive, with real-time visual feedback and easy manipulation, allowing learners to stay engaged. Students reported that they were happy to go through the processes and see what happened with their actions, thus engaging in active experimentation, which reinforced concepts (Dodevska et al., 2025). This principle is consistent with Multimedia Learning Theory, which holds that the presence of visual and interactive components in a learning environment increases cognitive processing by enabling students to build and solidify an understanding of material through perceptions from multiple pathways (Wekerle et al., 2024). In addition, the experience-based nature of these environments nurtures feelings of autonomy and competence, which are important aspects of Self-Determination Theory (SDT); studies have shown that these feelings contribute to greater intrinsic motivation (Huang et al., 2023).

In particular, multiple studies have confirmed the utility of visual feedback mechanisms. These feedback systems help determine responses at the task level and significantly impact whether students are willing to engage with the material. Studies indicate that gamified elements in educational settings may enhance student achievement and motivation, providing further support for the power of virtual environments (Chans & Portuguese Castro, 2021). The behavioral/cognitive engagement observed leads to a more enriching learning experience and improves overall academic performance and satisfaction (Almasri, 2024). Virtual lab environments can increase student engagement and support more in-depth cognitive processing through interactivity and immediate feedback. Equally important, the tools train in a way that both improves students' academic performance and inspires them to undertake more complex material with increased confidence, enabling an

interactive learning experience (Allcoat et al., 2021).

Reduced Cognitive Load Supports Deeper Learning

Virtual labs place less cognitive load on students, especially those who prefer a tentative learning experience. This decreases cognitive load comes from not needing to worry about how equipment works or the dangers that a researcher faces when something goes wrong during an actual experiment in the field. They allow students to explore complex concepts in a much more realistic, low-pressure environment without the risks associated with damaging equipment (Zhu et al., 2024). This leads to deeper engagement with the learning material and students reading for understanding rather than avoidance of errors (Chawla et al., 2023).

The same goes for Cognitive Load Theory, which describes pesky extraneous cognitive load as leading to barely formative learning outcomes. One effective method is combining automation of repetitive tasks with visual cues that guide students as they complete their activities. This brings us to virtual labs! If circuit configurations can be reset quickly and elements can be manipulated easily, students can focus on learning the relationships between concepts rather than struggling with the logistical issues of traditional lab environments (Teng et al., 2024). Moreover, the virtual environment that provides immediate feedback helps to create a stronger learning experience by allowing practice of low-stakes tasks repeatedly (Arango-Vasquez & Manrique-Losada, 2022).

Research supports the idea that these automated, supportive aspects of virtual learning environments may contribute to more efficient cognitive processing. Compared with standard practices, research shows that students using virtual labs experience lower cognitive load,

leading to deeper learning through engagement with the material (T. Li, 2025). Qualitative evidence indirectly supports the link between reduced cognitive load and learning performance by suggesting enhanced student confidence and competence with virtual simulations (Dai et al., 2023). Overall, studies show that virtual labs can be designed to enhance knowledge acquisition while helping students develop a deeper understanding of complex concepts with reduced cognitive load and greater ease in the learning process (Venn et al., 2023). Such a new capability for exploration and a safe digital space leads to more meaningful learning experiences (Siddiqui et al., 2025).

Virtual and Physical Labs Function Best as Complementary Tools

Integration of Virtual Labs and Physical Labs in Learner Contexts: A Lesson for the Future Abstract: Virtual labs are an attractive alternative to physical labs in engineering education if the purpose is high-quality learning. Despite the potential of virtual labs to improve cognitive abilities, such as reducing cognitive load and lowering anxiety at early learning stages, real-world labs that train your tactile skills for real-life application remain relevant (Osher et al., 2020). This combination also ensures that, with the conceptual grounding provided by a virtual environment, students still get their dose of practical experience as they work toward learning skills through hands-on training.

Research further supports that a simulation-based practice phase followed by hands-on tasks delivers an optimal instructional sequence compared with either mental or physical components alone. You will become acquainted with low-risk components of virtual replicas so that students can make mistakes and learn ideas without damaging gear. The physical labs then give you the empirical experience with real objects and tools that will reinforce that knowledge (Weis et al., 2024). These methodologies correlate with

strategies like Constructivism that support experiential learning with theory-practice integration (Wahyudi et al., 2024).

Moreover, this complementary approach is especially important in engineering programs that lack sufficient equipment (e.g., due to large class sizes). Such limitations in student personnel resources can be effectively overcome by blending available learning models to provide access to preparatory simulations, thereby enabling more students to actively participate in the process (Aghaee & Karunaratne, 2024). Educators can help students gain competencies more effectively and address logistical issues faced in an educational institute by combining traditional lab experiences with virtual technologies (Kang & Kim, 2021). The evidence strongly suggests that virtual labs can greatly enhance learning outcomes, but not as a replacement for physical labs. Instead, they should build on prior experience, adjust for special learning needs, and let students practice these skills repeatedly, all within protective environments. This mixed strategy ultimately results in a more holistic education that equips students much better to face future challenges posed by their professional outlooks (Della Spina & Viglianisi, 2021).

Theoretical Alignment Reinforces the Effectiveness of Virtual Lab Integration

Several theoretical frameworks complement this by showing positive gains in student learning from integrating virtual labs into educational interventions. Most importantly, constructivist learning theory prompts students to interact with what they study by making meaning from their own experiences and experiments. Virtual lab environments provide scaffolding that lets learners engage with and manipulate elements in the environment, enabling them to complete higher-level tasks through manipulation rather than rote memorization (Rey & Defensor, 2024). Second, the theory of Multimedia Learning is

consistent with evidence that dynamic simulation can enhance comprehension. By using different forms of media (both visual and auditory stimuli), these labs combine to construct diverse interactive spaces that offer a multisensory learning experience (Shkilev et al., 2024). It also uses a multimodal strategy to improve understanding of the instructional topic.

Cognitive Load Theory also fits here, as those in the experimental condition will almost certainly be less anxious and more focused, too. Virtual laboratories could reduce cognitive load, allowing learners to practice without fear of making mistakes or breaking equipment and to engage deeper cognitive resources (Bauer et al., 2025). This is consistent with the literature, where lower cognitive load also leads to better learning outcomes (Limanto et al., 2020). External virtual labs are also associated with the Technology Acceptance Models (TAM/UTAUT), which refer to the degree to which use and convenience affect users' acceptance of technology. Research demonstrates that students retain a favorable view of virtual labs, as new technologies benefit interactive and autonomous online learning styles (Rudhumbu, 2022). When students perceive them as effective and user-friendly, these tools motivate them to engage in the learning experience, an all-important prerequisite for positive learning outcomes (Enders et al., 2021). Together, these conceptual alignments form an almost bulletproof foundation for understanding how and why virtual labs boost learning outcomes.

■ CONCLUSION

This research examined the effect of Virtual Lab-based learning media on students' practical skills and engagement in the Computer Network Engineering course in the Information Engineering Program. Both quantitative and qualitative findings consistently show that virtual laboratories provide substantial educational benefits beyond conventional laboratory instruction. The results showed that students using virtual laboratory tools

(e.g., Multisim and Tinkercad) significantly outperformed their peers across multiple practical skill components, including troubleshooting, measurement accuracy, and computer network assembly. The large effect size (Cohen's $d = 1.06$) indicates that integrating virtual laboratories produced a substantial and educationally meaningful improvement in students' practical skills. Furthermore, students in the experimental group reported higher levels of behavioral, emotional, and cognitive engagement, while qualitative findings revealed greater motivation, confidence, and active participation during learning. These findings support integrating virtual laboratory media as an effective instructional approach to enhance both technical competence and student engagement in engineering education.

A second major find was that students performed better across all three aspects of engagement (behavioral, emotional, and cognitive). Interactive simulations and immediate visual feedback in the virtual labs increased curiosity, prolonged attention span, and motivation. Beyond quantitative findings, qualitative findings also showed that virtual labs reduced cognitive load and anxiety, and improved conceptual clarity and independent learning. Despite these findings suggesting substantial educational benefits, some limitations remain. The study used intact class groups with limited randomization. The period was brief and did not allow researchers to assess long-term retention. Students vary in their access to technology and the capability of their devices, which may skew results in larger implementations.

Future research may use random sampling, longer intervention duration, or examine the sustainability of conceptual retention and functioning in real-life scenarios. These studies highlight that, although virtual, these labs are not a replacement for conventional hands-on laboratories; they remain a useful and effective complement. Together, they strengthen skill mastery and engagement and support a quality

approach to modernized, flexible, learner-centered engineering education. For instructors, virtual labs are suggested as preparation for physical labs to help solidify students' conceptual understanding and reduce procedural errors. You might want to use guided simulation tasks that are very structured first, and then have students explore on their own at some point after that to give them more freedom in their learning. If possible, instructors should provide structured feedback during simulation activities to help students interpret circuit behavior and troubleshoot effectively.

■ **DECLARATION OF GENERATIVE AI USAGE IN THE WRITING PROCESS**

The authors used an AI-assisted language tool to improve grammar, readability, and manuscript organization. All research design, data analysis, interpretation, and conclusions were performed and verified by the authors, who take full responsibility for the final content of the manuscript.

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