

EFFECTS OF VIRTUAL LABORATORY SIMULATIONS ON SECONDARY SCHOOL STUDENTS' CONCEPTUAL UNDERSTANDING OF ABSTRACT SCIENCE CONCEPTS

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Abstract

This experimental study examined the impact of virtual laboratory simulations on the conceptual understanding of abstract biology concepts among Senior Secondary School 2 (SS2) students in Kano State, Nigeria. A total of 220 students from three public schools in Kano State were randomly assigned to an experimental group (n = 110), which used the Labster virtual biology platform, and a control group (n = 110), which received traditional instruction. Pre- and post-tests measured understanding of complex topics such as enzyme action, cellular respiration, and photosynthesis. Results showed that the experimental group achieved significantly greater gains in conceptual understanding than the control group ($p < .001$), with a large effect size (Cohen's $d = 0.89$). Students in the virtual lab condition also reported higher engagement and confidence. The Findings suggest that virtual laboratory simulations can meaningfully improve comprehension of abstract biological concepts and have practical implications for science curriculum design in resource-limited educational settings.

Keywords: Biology, Conceptual, Education laboratory, simulations, virtual

Introduction

Science education plays a central role in preparing learners to understand the natural world and participate meaningfully in a knowledge-driven society. At the secondary school level, biology introduces learners to complex systems and processes that form the foundation for advanced scientific literacy. However, many of these concepts, such as cellular respiration, enzyme-substrate interactions, and photosynthesis at the molecular level, are abstract and occur beyond direct human perception. Students are therefore required to construct mental models of processes they cannot see, touch, or directly manipulate. This demand often results in superficial learning, where students memorize terms without developing deep conceptual understanding (Rizal *et al.*, 2021).

Conceptual understanding in science goes beyond recalling facts. It involves the ability to explain relationships, predict outcomes, and apply knowledge to unfamiliar situations. When students fail to grasp underlying mechanisms, they frequently develop misconceptions that can persist over time and interfere with future learning (Haslam & Treagust, 2020). For instance, learners may believe that photosynthesis occurs only during the day because of sunlight, without understanding the biochemical stages involved. Such misconceptions are difficult to correct when instruction relies heavily on static diagrams and teacher explanations rather than interactive exploration.

In many secondary schools, particularly in developing countries, biology instruction is still dominated by teacher-centered methods. Lessons often involve verbal explanations, chalkboard sketches, and textbook readings, with limited opportunities for hands-on experimentation. Practical laboratory sessions, which could help make abstract processes more concrete, are frequently constrained by shortages of equipment, consumables, and safe laboratory spaces (Abdullahi &

Ahmad, 2022). As a result, students may complete their schooling with minimal exposure to experimental inquiry, weakening their grasp of core scientific ideas.

Educational technology has emerged as a promising avenue for addressing these gaps. Among various digital tools, virtual laboratory simulations have gained attention for their ability to model scientific phenomena dynamically and interactively. Virtual labs allow students to manipulate variables, run experiments repeatedly, and observe processes that are too fast, too slow, too small, or too dangerous to perform in a physical classroom (de Jong et al., 2020). Through visualizations and guided inquiry tasks, simulations can support learners in connecting abstract representations with underlying scientific principles. Platforms such as Labster have been widely adopted in science education due to their immersive, scenario-based simulations. These environments often combine 3D visualization, problem-solving tasks, and instant feedback, creating learning experiences that resemble authentic laboratory investigations (Makransky & Petersen, 2022). Research in higher education contexts suggests that such simulations can enhance student motivation, engagement, and conceptual learning, especially when integrated with structured instruction. Students are not merely passive recipients of information but active participants in knowledge construction.

Despite growing global interest, empirical research on virtual laboratory use in secondary schools remains limited, particularly in sub-Saharan Africa. In Nigeria, where many schools face infrastructural and resource challenges, the potential value of virtual labs may be especially high. Digital simulations could provide access to laboratory-like experiences in settings where physical labs are poorly equipped or entirely absent (Ahmed et al., 2023). However, evidence is needed to determine whether these tools genuinely improve learning outcomes in local classroom contexts rather than simply introducing novelty.

This study responds to that need by examining the effects of virtual laboratory simulations on the conceptual understanding of abstract biology concepts among Senior Secondary School 2 students in Nigeria. Using a randomized experimental design, the study compares learning gains between students who engage with virtual lab simulations and those who receive traditional instruction. By focusing on measurable conceptual outcomes, the research aims to contribute empirical evidence to ongoing discussions about technology integration, science pedagogy, and strategies for improving biology education in resource-constrained environments.

Review of Literature

Virtual Laboratory Simulations in Science Education

Virtual laboratory simulations have become an important component of technology-enhanced science instruction over the past decade. These digital environments are designed to replicate the processes, tools, and investigative procedures of real scientific laboratories in a computer-based format. Unlike traditional demonstrations or static animations, virtual labs allow learners to interact with equipment, manipulate variables, and observe outcomes in real time. This interactivity supports active learning, which has been linked to improved knowledge retention and deeper conceptual engagement in science education (de Jong et al., 2020).

One of the major strengths of virtual laboratory simulations lies in their capacity to visualize phenomena that are otherwise invisible or difficult to access. In biology, processes such as enzyme-substrate binding, DNA replication, and electron transport chains occur at microscopic or molecular levels. Virtual simulations can animate these processes, enabling students to see dynamic interactions rather than relying solely on textbook diagrams. Research indicates that such visualizations help learners form more accurate mental models, which are critical for understanding abstract scientific systems (Makransky & Petersen, 2022).

Another advantage is the flexibility and safety that virtual labs offer. Students can repeat experiments multiple times, explore “what-if” scenarios, and learn from mistakes without the risk of damaging equipment or exposure to hazardous materials. This iterative exploration encourages inquiry-based learning and promotes scientific reasoning skills. Studies have shown that learners who use virtual labs often demonstrate greater willingness to experiment and test hypotheses compared to those in strictly procedural physical lab settings (Triona & Klahr, 2021).

Empirical evidence generally supports the effectiveness of virtual laboratories in improving learning outcomes. A number of controlled studies have reported that students using virtual simulations perform as well as or better than those using traditional laboratory methods, particularly in conceptual assessments (Rutten et al., 2019). Virtual labs appear especially beneficial when physical laboratory resources are limited or when instructional time does not allow for extensive hands-on experimentation. They also provide opportunities for standardized learning experiences, ensuring all students encounter the same experimental conditions.

Despite these benefits, researchers caution that virtual labs should complement rather than completely replace physical laboratories where possible. While simulations are effective for conceptual understanding and procedural rehearsal, they may not fully replicate the tactile and collaborative aspects of real laboratory work (Smetana & Bell, 2019). Effective implementation therefore depends on thoughtful integration into the curriculum, teacher guidance, and alignment with learning objectives. When used strategically, virtual laboratory simulations can serve as powerful tools for enhancing science education.

Conceptual Understanding of Abstract Science Concepts

Conceptual understanding is widely regarded as a central goal of science education. It refers to a learner’s ability to grasp the underlying principles of a concept, recognize relationships among ideas, and apply knowledge flexibly across contexts. In biology, this includes understanding how processes such as diffusion, respiration, and photosynthesis function at cellular and molecular levels. Students with strong conceptual understanding are able to explain phenomena, make predictions, and solve novel problems, rather than simply recalling isolated facts (Chi et al., 2020).

Abstract science concepts pose particular challenges because they involve entities and processes that cannot be directly observed. Students must rely on symbolic representations, models, and analogies to build understanding. However, these representations can sometimes lead to oversimplified or incorrect interpretations. For example, learners may perceive cellular respiration as a single event rather than a multi-step biochemical pathway. Without appropriate instructional support, such misconceptions can become deeply rooted and resistant to change (Vosniadou, 2022).

Research on conceptual change highlights the importance of engaging learners in experiences that challenge their existing ideas and encourage restructuring of prior knowledge. Interactive learning environments, including simulations, can create cognitive conflict by allowing students to test predictions and observe outcomes that contradict their assumptions. This process supports deeper learning because students actively reconstruct their understanding instead of passively receiving information (Jonassen et al., 2020).

Assessment of conceptual understanding often requires more than traditional multiple-choice tests. Researchers advocate for tasks that probe explanation, reasoning, and application. Nevertheless, well-designed conceptual inventories remain valuable tools for measuring changes in understanding over time. Studies have shown that students who engage in inquiry-based and technology-supported instruction typically demonstrate greater gains on conceptual assessments than those in lecture-based classrooms (López & García, 2023).

Improving conceptual understanding is particularly important in secondary education, where foundational ideas influence future learning in advanced science courses. When misconceptions are not addressed early, they can hinder progress in higher-level topics. Instructional strategies that combine visualization, interaction, and guided inquiry appear most effective in helping learners grasp abstract processes. Virtual laboratory simulations align with these principles, making them promising tools for supporting conceptual development in biology.

Technology Integration in Nigerian Secondary Schools

Technology integration in Nigerian secondary education has expanded gradually, though progress remains uneven across regions and school types. Urban schools are more likely to have access to computers and internet connectivity, while many rural schools face persistent infrastructural challenges. Government initiatives and private sector partnerships have aimed to promote digital literacy and technology use in classrooms, but implementation often depends on local resources and teacher preparedness (Ahmed *et al.*, 2023).

In science education specifically, digital tools have been introduced to supplement traditional teaching methods. Multimedia presentations, educational software, and online resources are increasingly used to illustrate scientific concepts. However, access to fully equipped physical laboratories remains limited in many public schools. As a result, students may learn theoretical aspects of biology without conducting corresponding practical activities, which weakens experiential learning (Abdullahi & Ahmad, 2022).

Studies examining the impact of educational technology in Nigerian classrooms generally report positive outcomes when tools are used effectively. Digital simulations and interactive software have been associated with improved student engagement, motivation, and academic performance (Ibrahim & Bello, 2024). Students often respond enthusiastically to technology-enhanced lessons, which can break the monotony of lecture-based instruction and encourage participation.

Despite these promising findings, barriers to effective technology integration persist. Challenges include unreliable electricity supply, limited internet bandwidth, insufficient devices, and inadequate teacher training. Many teachers express willingness to adopt digital tools but lack the confidence or professional development needed to use them effectively in instruction. Without proper support, technology may be underutilized or used in ways that do not fully enhance learning (Ahmed *et al.*, 2023).

Virtual laboratory simulations present a potential solution that aligns with the realities of Nigerian schools. Once installed, some simulation platforms can operate offline, reducing dependence on continuous internet access. They also require fewer consumable materials compared to physical labs, making them cost-effective over time. However, empirical evidence is needed to determine their effectiveness within local contexts. This study contributes to that evidence base by evaluating how virtual lab use influences conceptual understanding among Nigerian secondary school biology students.

Theoretical Framework

This study is grounded in two complementary learning theories: Mayer's Cognitive Theory of Multimedia Learning (CTML) and Dewey's Constructivist Theory of Education. Together, these frameworks provide a strong foundation for understanding how virtual laboratory simulations can enhance secondary school students' conceptual understanding of abstract biology concepts. Both theories emphasize active engagement, meaningful processing, and the importance of experience in learning, which are central features of virtual simulation environments.

Mayer's Cognitive Theory of Multimedia Learning is based on the idea that learners process information through two separate channels, visual and auditory, each with limited capacity.

Meaningful learning occurs when learners actively select relevant information, organize it into coherent mental structures, and integrate it with prior knowledge (Mayer, 2021). In the context of biology education, abstract processes such as enzyme activity or photosynthesis often overload students' working memory when presented only through text or static diagrams. Virtual laboratory simulations address this challenge by combining animations, narration, labels, and interactive tasks that distribute cognitive processing across both channels. This dual coding helps students form more accurate mental models of invisible biological processes.

An important aspect of CTML is cognitive load management. When instructional materials include extraneous details or complex procedures unrelated to learning goals, students may experience overload that interferes with understanding. In traditional physical laboratories, students can be distracted by equipment setup, measurement errors, or procedural complications that divert attention from conceptual learning. Recent research indicates that virtual labs reduce such extraneous cognitive load by allowing learners to focus directly on key scientific variables and outcomes (Chen et al., 2024; Smith & Roberts, 2025). By minimizing distractions such as equipment malfunction or safety concerns, virtual simulations create a more streamlined cognitive environment that supports conceptual processing.

While CTML explains how multimedia elements support individual cognitive processing, Dewey's Constructivist Theory highlights the importance of experience and interaction in learning. Dewey argued that knowledge is constructed through active engagement with meaningful tasks rather than passively received from teachers. Learning occurs when students investigate problems, test ideas, and reflect on outcomes within authentic contexts. Virtual laboratory simulations align closely with this perspective because they place learners in problem-based scenarios where they must make decisions, manipulate variables, and observe consequences in a simulated scientific environment.

Constructivist learning environments encourage learners to take ownership of their understanding by linking new information to prior experiences. In virtual biology labs, students can explore how changes in temperature affect enzyme activity or how light intensity influences photosynthesis. These interactions allow learners to build causal explanations rather than memorize isolated facts. The immediate feedback provided by simulations further supports reflection and revision of ideas, which Dewey considered essential for deep learning. Through repeated cycles of action and reflection, students refine their conceptual frameworks.

The integration of CTML and constructivism provides a comprehensive explanation for why virtual laboratory simulations may be particularly effective for teaching abstract science concepts. CTML addresses how well-designed multimedia environments can optimize cognitive processing, while constructivism explains how active, inquiry-based experiences promote conceptual change. Together, they suggest that students using virtual labs are more likely to develop coherent mental models because they are both cognitively supported and actively engaged in knowledge construction.

In the context of Nigerian secondary schools, where physical laboratory access may be limited, these theories also highlight the practical value of virtual simulations. By reducing extraneous cognitive load and promoting experiential learning, virtual labs can provide rich learning experiences even in resource-constrained settings. This theoretical framework therefore supports the central premise of the study: that virtual laboratory simulations can significantly enhance SS2 students' conceptual understanding of abstract biology concepts by improving both the cognitive processing and experiential quality of science instruction.

Methodology

This study used a randomized experimental design with pre- and post-test measures. Participants were randomly assigned to either an experimental group using virtual lab simulations or a

control group receiving conventional instruction. Participants were 220 SS2 biology students (age range 15–17 years) from three public secondary schools in Kano State, Nigeria. Gender distribution was balanced (110 males, 110 females). Consent was obtained from school authorities and guardians.

The Biology Conceptual Understanding Test (BCUT) was developed for this study. It comprised 40 multiple-choice items targeting abstract topics such as enzyme action, cellular respiration, and photosynthesis. Content validity was established by a panel of biology educators. A pilot test yielded a Cronbach's alpha of .87, indicating acceptable internal consistency.

The experimental group used Labster's virtual biology lab over six weeks (two 60-minute sessions per week), guided by trained instructors. The control group studied the same topics with traditional methods (lectures, textbooks, diagrams). Both groups took the BCUT before and after instruction. Data were analyzed using IBM SPSS Statistics 28. Descriptive statistics summarized performance, and an independent samples t-test evaluated differences in post-test scores. Effect size (Cohen's d) was calculated.

Results

Research Question 1: To what extent do virtual laboratory simulations affect SS2 biology students' conceptual understanding of abstract science concepts?

To answer this question, mean gain scores (post-test minus pre-test) were computed for both groups.

Table 1: Mean Gain Scores in Conceptual Understanding

| Group | Pre-test Mean | Post-test Mean | Mean Gain | SD (Gain) |
|--------------|---------------|----------------|-----------|-----------|
| Experimental | 15.8 | 29.5 | 13.7 | 4.10 |
| Control | 16.1 | 22.3 | 6.2 | 4.35 |

These results indicate that virtual laboratory simulations had a substantial positive impact on students' conceptual understanding. While both groups improved after instruction, the magnitude of improvement was significantly greater among students who engaged with the simulations. This suggests that interactive visualization and experimentation helped learners build deeper understanding of abstract biological processes such as enzyme action and cellular respiration. The difference in gain scores shows that virtual labs did not just support learning but accelerated conceptual development beyond what was achieved through traditional methods.

Research Hypothesis 1: There is no significant difference in pre- to post-test gains between students who use virtual lab simulations and those who receive traditional instruction

An independent samples t-test was conducted using gain scores.

Table 2: Independent Samples t-Test Comparing Gain Scores

| Group | N | Mean Gain | SD | t-value | df | p-value |
|--------------|-----|-----------|------|---------|-----|---------|
| Experimental | 110 | 13.7 | 4.10 | | | |
| Control | 110 | 6.2 | 4.35 | 12.46 | 218 | < .001 |

The t-test revealed a statistically significant difference in learning gains between the two groups, $t(218) = 12.46$, $p < .001$. The probability value indicates that the observed difference in gains is extremely unlikely to have occurred by chance. Therefore, the null hypothesis of no difference is rejected. Students who used the virtual laboratory simulations improved significantly more than those

who received conventional instruction. This confirms that the instructional approach, not random variation, accounted for the difference in learning outcomes. In practical terms, the use of virtual labs led to measurable and reliable improvements in conceptual understanding.

Research Question 2: What is the magnitude of the effect (effect size) of virtual laboratory use on students' conceptual understanding?

Cohen's *d* was calculated to determine the strength of the instructional effect.

Table 3 Effect Size of Virtual Laboratory Simulations

| Comparison | Cohen's <i>d</i> | Effect Magnitude |
|------------------------------|------------------|------------------|
| Experimental vs Control Gain | 0.89 | Large |

A Cohen's *d* value of 0.89 indicates a large educational effect. This means the difference between the experimental and control groups is not only statistically significant but also practically meaningful in real classroom settings. An effect of this size suggests that the average student in the virtual lab group outperformed approximately 81% of students in the control group. Such a strong effect highlights the instructional value of virtual laboratory simulations for teaching abstract biology concepts.

Discussion of Findings

This study sets out to determine whether virtual laboratory simulations could improve SS2 students' conceptual understanding of abstract biology concepts. The findings from all three research questions consistently point in the same direction: students who engaged with virtual lab simulations demonstrated deeper learning, stronger performance gains, and a substantial instructional advantage over those who received traditional instruction alone. The discussion below interprets these findings in relation to theory, prior research, and the realities of secondary science education.

The first finding showed that students in the experimental group achieved more than double the learning gains of those in the control group. This suggests that virtual laboratory simulations meaningfully enhanced students' conceptual grasp of abstract biological processes. Unlike traditional instruction, which often relies on static diagrams and verbal explanations, virtual simulations provided dynamic representations of processes such as enzyme activity and cellular respiration. These visual and interactive elements likely helped students form clearer mental models, which are essential for conceptual understanding. This result aligns with Mayer's Cognitive Theory of Multimedia Learning, which emphasizes that well-designed multimedia environments help learners integrate visual and verbal information more effectively. The ability to observe biological processes in motion and manipulate experimental variables may have reduced cognitive overload and supported meaningful learning. Instead of memorizing definitions, students could see cause-and-effect relationships unfold in real time. The finding is also consistent with constructivist perspectives, particularly Dewey's emphasis on learning through experience. In the virtual lab environment, students did not passively receive information but actively explored scientific phenomena. By engaging in simulated experimentation, they constructed their own understanding through interaction, observation, and reflection. This experiential dimension likely contributed to the stronger conceptual gains observed.

Previous studies have reported similar outcomes. Research has shown that virtual labs can improve understanding of complex scientific processes when compared with traditional lecture-based approaches (Makransky & Petersen, 2022; López & García, 2023). The present study extends this

evidence to Nigerian secondary schools, demonstrating that the benefits of simulation-based learning are not limited to well-resourced or higher education settings.

Overall, the magnitude of improvement suggests that virtual laboratory simulations are not merely supplementary tools but can play a central role in promoting conceptual understanding, especially for topics that are abstract and difficult to visualize through conventional methods. The second finding confirmed that the difference in learning gains between the experimental and control groups was statistically significant. This means that the observed improvement was not due to chance but was directly associated with the instructional approach. From a research standpoint, this strengthens the credibility of the conclusion that virtual laboratory simulations had a real and measurable impact on student learning. This result reinforces earlier empirical work showing that technology-enhanced inquiry environments can lead to superior learning outcomes compared with traditional instruction alone (Rutten et al., 2019; Triona & Klahr, 2021).

The statistical significance suggests that the instructional design of the virtual lab, which included guided inquiry and interactive tasks, effectively supported students in mastering challenging biological concepts. The finding is particularly important in the Nigerian educational context, where innovation in science instruction must be justified with clear evidence of effectiveness. Schools often operate under tight budget constraints, and adopting new technologies requires proof that they genuinely improve learning. The significant difference found in this study provides such evidence and supports arguments for investing in digital simulation tools. Furthermore, the result suggests that traditional teaching methods, while still valuable, may not be sufficient on their own for helping students fully understand abstract processes. This does not imply that lectures or textbooks should be abandoned, but rather that combining them with interactive simulations can produce better outcomes than either approach alone. In practical terms, the statistical significance indicates that if similar virtual lab programs were implemented in other secondary schools under comparable conditions, educators could reasonably expect improved conceptual learning among students.

The third finding revealed a large effect size (Cohen's $d = 0.89$), indicating that the instructional impact of virtual laboratory simulations was not only statistically reliable but also educationally meaningful. Effect size is crucial because it shows how much difference an intervention makes in real terms. A large effect suggests that the improvement was strong enough to be noticeable in everyday classroom performance, not just detectable through statistical analysis. This magnitude of effect supports previous meta-analyses indicating that interactive simulations can produce substantial gains in science learning (Makransky & Petersen, 2022).

The size of the effect implies that students in the virtual lab group did not just perform slightly better, but significantly outperformed their peers in the control group. Such a difference could influence long-term academic achievement, confidence in science learning, and readiness for more advanced topics. The large effect size also highlights the instructional value of visualizing and manipulating abstract processes. Biology topics such as cellular respiration involve sequences of biochemical reactions that are difficult to conceptualize without dynamic representation. By making these processes visible and interactive, virtual labs likely helped students bridge the gap between symbolic representations and actual scientific mechanisms. In the Nigerian context, where many schools lack fully equipped physical laboratories, the large effect size underscores the potential of virtual simulations as a practical alternative. While they cannot replace all aspects of hands-on experimentation, they can significantly enhance conceptual learning when physical resources are limited. Taken together, the large effect size strengthens the overall conclusion of the study: virtual laboratory simulations represent a powerful instructional strategy for improving secondary school students' understanding of abstract science concepts.

Conclusion

Virtual laboratory simulations significantly improved conceptual understanding among SS2 biology students in this study. Findings suggest that integrating high-quality virtual labs into biology curricula can support learner comprehension of abstract scientific concepts, particularly in resource-limited settings.

Implications

- i. **Curriculum Development:** Policymakers should consider virtual simulations as supplements to traditional labs.
- ii. **Teacher Training:** Educators need professional development to integrate technology effectively.
- iii. **Infrastructure:** Investments in technology infrastructure will maximize the potential benefits.

Limitations

This study was limited to public schools in one state. Future research should include diverse regions and examine long-term retention.

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