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From Virtual to Real: Investigating the Gap Between Virtual Laboratory Learning and Real Laboratory Performance in Animal Physiology

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Abstract

This study aims to examine the performance gap between virtual laboratory-based instruction and real laboratory practicum in the Animal Physiology course. The research employed a mixed-methods approach with an explanatory sequential design, in which quantitative data were emphasized. The participants comprised 31 fifth-semester undergraduate students who engaged in two virtual laboratory sessions and two hands-on laboratory sessions conducted without additional instructor explanation. Laboratory performance was assessed across six dimensions of laboratory skills. The results indicate that procedural and psychomotor skills were in the moderate category, whereas data analysis, drawing conclusions, and presentation skills were in higher categories. Qualitative findings corroborate that virtual laboratories are effective in strengthening conceptual understanding, data literacy, and scientific communication; however, they are less effective in transferring technical and procedural skills to authentic laboratory contexts. Limited physical interaction with equipment, minimal sensorimotor feedback, and contextual discrepancies between simulation and real practice were identified as the primary contributing factors. This study concludes that virtual laboratories should be positioned as pre-laboratory scaffolding to support cognitive preparation rather than as substitutes for direct hands-on practicum. The implications of this study indicate that the integration of virtual laboratories and real laboratory practice should be designed complementarily so that the strengthening of conceptual understanding can be followed by the optimal development of students' procedural and psychomotor skills.

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INTRODUCTION

The rapid advancement of educational technology has driven the adoption of virtual laboratories as both alternatives and complements to science practicum in higher education. Virtual laboratories provide safe, efficient, and cost-effective experimental simulations and enable the visualization of complex biological processes that are difficult to observe directly (Bazie et al., 2024; Kashaka, 2024). In the context of biology education, virtual laboratories are effective for teaching complex and abstract biological topics, with the strongest impact on improving conceptual understanding, enhancing students' motivation, attitudes, and self-efficacy, and supporting the acquisition of basic laboratory skills. However, for certain physically procedural skills, integration with hands-on laboratory

practice remains necessary (Byukusenge et al., 2022; Mahendra & Killis, 2025). Virtual labs have also been reported to enhance students' motivation, learning accessibility, and engagement in science practicum activities, thereby strengthening the overall learning process (Mustapa et al., 2023)

Several studies have demonstrated that virtual laboratory–based learning contributes positively to students' conceptual understanding, data analysis skills, and higher-order thinking skills (Maksum et al., 2020). Virtual laboratories enable students to develop prior knowledge before entering a real laboratory practicum (Agustin et al., 2025). Virtual labs are frequently implemented as pre-laboratory exercises, allowing students to conduct experiments in a virtual environment prior to engaging in hands-on laboratory activities, thereby facilitating preparatory knowledge of procedures and underlying concepts (Kolodii et al., 2025).

However, despite this optimism, a fundamental issue remains insufficiently addressed: to what extent can learning acquired through virtual laboratories be effectively transferred to actual performance in real laboratory settings? Many studies predominantly focus on cognitive learning outcomes and students' perceptions, whereas psychomotor and procedural laboratory performance in authentic practicum contexts has been relatively underexamined (Chan et al., 2021). Consequently, there is a tendency to generalize that success in virtual environments automatically reflects readiness for performance in real laboratory contexts (Asyraaf et al., 2025).

In practice, the transition from controlled virtual environments to real laboratories, which require motor coordination, procedural precision, and proficient use of equipment, often presents challenges that cannot be fully represented by digital simulations (Halder & Banerjee, 2026; Saputra et al., 2026). While virtual laboratories enhance conceptual understanding, learner engagement, and access to simulated experimentation, they continue to face limitations in supporting the development of practical skills and their integration with physical laboratory contexts, particularly with respect to procedural skills that are not fully cultivated through digital simulations alone (Byukusenge et al., 2022).

A gap emerges when virtual laboratories are employed as pre-laboratory activities under the assumption that students who have learned experimental procedures virtually will be able to implement them independently in a physical laboratory practicum without additional guidance. Furthermore, several studies emphasize that manual skills, equipment handling, and experiences in managing technical errors are difficult to replicate through digital simulations due to limited sensory feedback and the idealized conditions of virtual environments, which fail to represent the complexity of authentic laboratory settings (Kapralos et al., 2022). Consequently, cognitive success in virtual spaces does not necessarily translate into performative competence in physical laboratory contexts. This issue is directly related to the theoretical problem of transfer of learning across contexts (Schunk, 2020)

In the context of science learning, psychomotor aspects constitute a foundational component of scientific skills that cannot be fully replaced by simulations. Direct hands-on experience with instruments and materials remains essential for developing motor coordination, procedural accuracy, and in situ experimental decision-making (Maksum et al., 2020). In addition, non-technical factors such as self-efficacy, motivation, and control over the learning environment influence students' readiness to engage in an authentic laboratory practicum (Schunk, 2019). These findings indicate the presence of a gap between virtual learning experiences and real laboratory performance that has not yet been systematically explored.

Based on these considerations, empirical investigation is required to explicitly examine the gap between virtual learning and real laboratory performance, not only in terms of

conceptual understanding but, more importantly, in students' performance skills during practicum activities. Accordingly, this study aims to investigate the extent to which learning through virtual laboratories can be transferred to actual laboratory performance, particularly in the Animal Physiology course. The findings are expected to contribute theoretically to the issue of transfer of learning in science education and to provide a pedagogical basis for positioning virtual laboratories more appropriately—as scaffolding for conceptual learning rather than as substitutes for direct hands-on laboratory experience.

METHODS

This study employed a mixed-methods approach with an explanatory sequential design, in which quantitative data were emphasized (QUAN emphasized) (Creswell & Clark, 2018). The initial phase involved the collection of quantitative data to assess students' laboratory performance following virtual laboratory–based instruction. Subsequently, students conducted an animal physiology practicum in a real laboratory setting without additional instructor guidance, under the assumption that the procedures and underlying concepts had been learned through the virtual laboratory.

Students' performance was evaluated using a laboratory performance assessment rubric encompassing six dimensions: (1) mastery of laboratory procedures, (2) use of instruments and materials, (3) execution of laboratory activities, (4) analysis of experimental data, (5) concluding experimental results, and (6) presentation of practicum outcomes. The instrument was validated through expert judgment to ensure content validity and was accompanied by structured scoring rubrics to minimize rater subjectivity. The overall research design is illustrated in Figure 1.

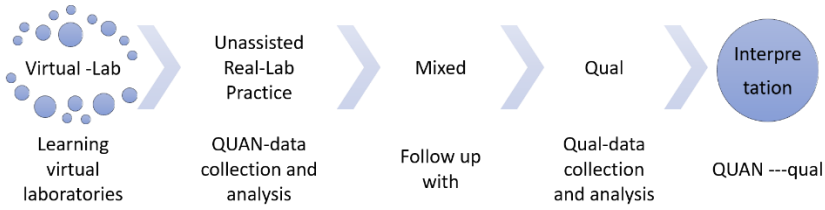

Figure 1 Research design

Qualitative data were collected to explain the quantitative findings through open-ended questionnaires that explored students' experiences, perceptions, and difficulties during the transition from virtual laboratories to real laboratory settings. The instructional intervention was conducted over four sessions, comprising two virtual laboratory sessions and two real laboratory practicum sessions conducted without additional instructor explanation. The participants consisted of 31 fifth-semester students from the Biology Education Study Program at a private university in Bandung, Indonesia.

RESULTS AND DISCUSSION

Students' laboratory performance was assessed after they completed virtual laboratory-based learning and subsequently carried out practicum activities in the real laboratory without additional instructor guidance. A more detailed presentation of the results is provided in Figure 2.

Figure 2 shows that students' mastery of laboratory procedures, skills in using instruments and materials, and execution of practicum activities received relatively lower scores, whereas higher scores were observed for data analysis, concluding, and presenting practicum results. These findings indicate a performance pattern in which higher-order cognitive skills exceed basic procedural and operational skills.

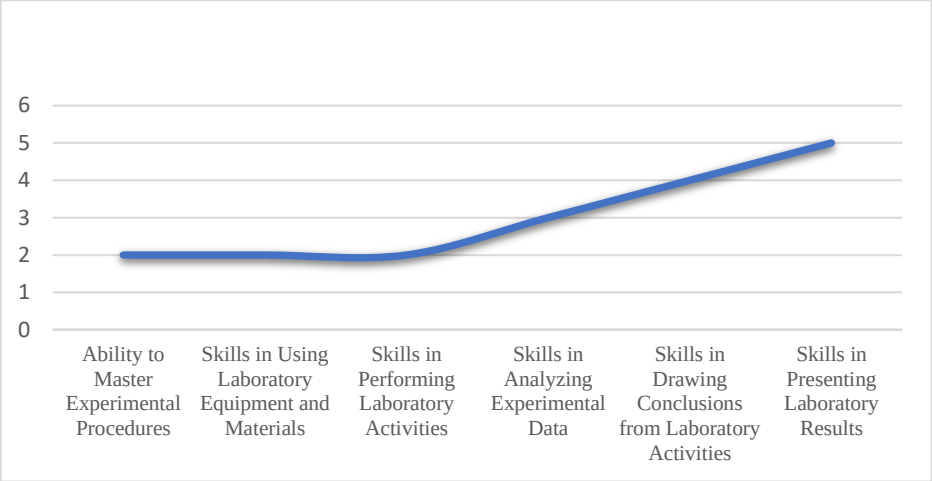

Figure 2 Students' psychomotor skills

The data reveal relatively low mean scores for procedural and operational dimensions, suggesting that students experienced difficulties in translating virtual procedural workflows into authentic laboratory contexts. Moreover, exposure to virtual laboratories did not fully facilitate motor readiness or accurate handling of real laboratory equipment. The skill of executing practicum activities tended to remain at a moderate level, reflecting a performance gap between virtual simulation and hands-on laboratory practice. These results indicate that virtual laboratories have not yet been able to fully substitute for direct laboratory experiences that provide physical interaction with equipment, materials, and real experimental processes.

However, in advanced cognitive domains such as data analysis, drawing conclusions from experimental results, and presenting findings, virtual laboratories were effective in bridging and strengthening students' conceptual understanding. In this context, virtual laboratories functioned as prior knowledge that trained students in information processing, critical thinking, and analytical reasoning, while also contributing positively to the development of scientific communication skills. Therefore, virtual laboratories are appropriately positioned as pre-laboratory (pre-lab) activities to facilitate students' cognitive readiness before engaging in hands-on laboratory practice.

Observational data and students' responses further indicated that virtual laboratories supported initial conceptual understanding before real practicum sessions were conducted. Nevertheless, several students reported difficulties in (1) adapting to the physical conditions of real laboratories, including more complex equipment and variable environmental factors; (2) determining procedural sequences independently without direct instructional scaffolding from instructors; and (3) handling technical errors that were not represented in virtual simulations. These qualitative findings help explain why procedural skills and equipment-handling scores tended to be lower than analytical and presentation skills.

The data indicate that virtual laboratories have not been effective in optimally transferring procedural skills to real laboratory contexts, as reflected in students' confusion in following work stages, weak mastery of procedural sequences, and the high level of instructor guidance required during practicum activities. These findings are consistent with reports that virtual simulations enhance engagement and conceptual understanding but are less effective in fostering procedural knowledge and manual skills due to limited direct interaction with equipment, minimal exposure to technical errors, and the idealized,

mechanistic nature of simulated environments (Kourtesis et al., 2021; Viitaharju et al., 2023; Andriani et al., 2024; Chen et al., 2024). Consequently, students are not sufficiently accustomed to dealing with variability and contextual problems in authentic laboratory settings, resulting in low practicum readiness despite prior engagement in virtual laboratory activities (Setyowati et al., 2024). Many students reported that they did not feel fully prepared even after practicing in virtual laboratories, as they had not experienced how procedures are actually enacted in real laboratory environments (Suryanti et al., 2019).

Skills related to the use of laboratory instruments and materials demonstrated relatively low achievement, even though students had practiced through virtual laboratories on topics such as cellular metabolism and cell division. Exposure to simulations and practicum videos supported the visualization of underlying mechanisms but was insufficient to develop the motor skills required for precise equipment operation. Other studies likewise report that familiarization with laboratory equipment through simulations does not fully bridge the gap in practical skill mastery in real laboratory contexts (Russo et al., 2025). Observational findings further indicate that students remained awkward in handling and using microscopes, pipettes, and graduated cylinders and, in some cases, misidentified the functions of instruments, despite having encountered their virtual representations. Practical skills have been shown to develop more effectively through direct hands-on practice than through virtual platforms (Haryoko & Jaya, 2018). The absence of sensorimotor feedback—such as tactile sensitivity to instruments, hand stability, and force control—constrains the development of operational competence (Ardhayantia et al., 2022; Siregar et al., 2022). In the context of the cell division topic, the high number of pre-practicum questions indicated insufficient operational readiness, which may be attributed to limited hands-on experience, contextual discrepancies in tools and procedures between simulations and physical laboratories, and weak independent problem-solving skills (Cai et al., 2020; Hamed & Aljanazrah, 2020; Kebande, 2024).

Skills related to the execution of practicum activities indicate that some students remained passive, hesitant to initiate actions, and tended to wait for further instructions, reflecting low self-confidence and limited motor readiness in authentic laboratory contexts. This condition is consistent with the view that students' engagement and the quality of practicum performance are influenced by self-efficacy, motivation, and structured learning environment support (Schunk, 2019). Self-confidence is associated with motor competence, whereby improvements in motor skills contribute to greater confidence in performing practicum tasks (Reyes-Acuca et al., 2020). These findings are further supported by evidence that motor competence is significantly related to self-esteem, which in turn affects students' willingness and autonomy in engaging in practical activities (Cakir et al., 2025)

Students' psychomotor performance was relatively weak, as reflected in hesitation and sequencing errors in basic activities such as stirring solutions, sampling, and timing observations, including among students with high theoretical achievement. These findings indicate that virtual laboratories are more effective in developing conceptual understanding than in training psychomotor skills. This result is consistent with previous studies reporting improvements in conceptual understanding and critical thinking through virtual laboratories, while the development and assessment of psychomotor skills remain limited and tend to be suboptimal (Safarati & Lubis, 2022; Udin et al., 2020). The limitations of simulations in providing sensorimotor feedback constrain the development of practical skills (Kapralos et al., 2022). whereas direct feedback plays a crucial role in procedural skill acquisition (Schunk, 2012). Direct hands-on experience with instruments and materials in physical laboratories remains irreplaceable by virtual simulations, as practicum activities require eye-hand coordination and the integration of conceptual understanding

that cannot be fully cultivated through computer-based interfaces alone (Maksum et al., 2020; Sinadia, 2021). Moreover, limitations in devices and internet connectivity weaken access to online practicum activities, slow down comprehension, and potentially hinder the attainment of learning objectives (Herlina et al., 2023). which in turn may reduce learning motivation due to technical frustration (Darwis & Hardiansyah, 2021).

In contrast, in the post-practicum phase, students demonstrated strong performance in data analysis, as reflected in their ability to read, interpret, and identify deviations in results with scientifically grounded justifications. Exposure to virtual laboratories that present structured datasets, interactive tables, automated graphs, and model visualizations strengthened students' data literacy and analytical reasoning (Lestari et al., 2023). Learning analytics support within virtual environments further facilitated the monitoring of performance and learning behaviors, contributing to the enhancement of analytical skills (Elmoazen et al., 2023). The integration of computational technologies in practicum activities, including software-assisted data processing, also contributed to greater analytical efficiency and higher-quality scientific argumentation among students (Tufino et al., 2023).

With respect to the skill of concluding practicum activities, students were able to formulate logical conclusions by linking experimental findings to biological concepts, relationships among variables, and hypothesis confirmation. The organization of information and the integration of practicum results within a conceptual framework are essential prerequisites for the development of higher-order reasoning (Schunk, 2012). Scenario-based laboratory simulations have been shown to enhance the quality of conclusion formulation by strengthening intrinsic motivation, self-efficacy, and conceptual understanding (Al-Nakhle, 2022). These findings are consistent with evidence indicating that virtual laboratories support the accuracy and depth of experimental conclusions (Celine et al., 2022) . Other studies further demonstrate that the use of virtual laboratory simulations in biology instruction improves students' ability to draw more accurate and in-depth experimental conclusions and facilitates a focus on scientific processes that integrate theory with experimentation (Bazie et al., 2024; Kolil et al., 2020; Makmal et al., 2024).Students' presentation skills of practicum results demonstrated positive outcomes, as reflected in increased confidence in explaining findings, constructing data-based arguments, and using appropriate scientific terminology, including the effective use of digital visualizations (e.g., graphs and diagrams). The flexibility afforded by virtual laboratories deepened conceptual understanding and refined students' argumentative skills, thereby enhancing the quality of scientific communication (Mahendra & Killis, 2025; Setiawan et al., 2025). The ability to manipulate experimental parameters within simulations further strengthened conceptual clarity and students' confidence in presenting results. In addition, immediate feedback provided by virtual learning environments facilitated the development of critical and creative thinking, as well as more effective scientific communication competencies (Dwi et al., 2024; Kapici et al., 2022).

The virtual laboratory and real laboratory activities are listed in Figure 3.

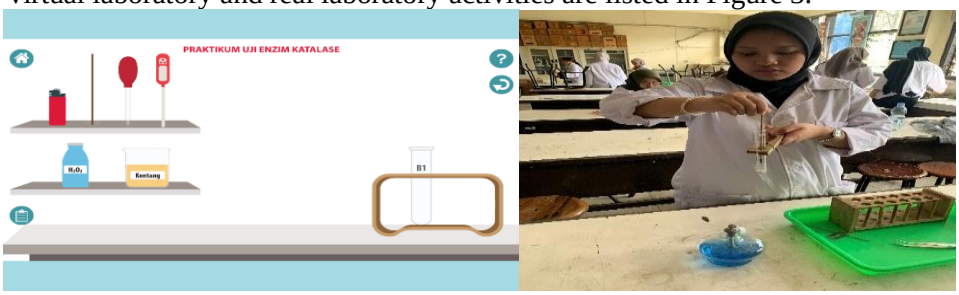

Figure 3 Virtual laboratory and real laboratory activities

Overall, virtual laboratories are more effective in strengthening cognitive and metacognitive skills (analysis, synthesis, and scientific communication) than in developing technical procedural skills and therefore remain suboptimal in supporting fluent performance in a real laboratory practicum. Accordingly, virtual laboratories are more appropriately positioned as conceptual scaffolding rather than as substitutes for physical laboratory experiences. Nevertheless, digital simulations enhance students' conceptual readiness and confidence and are associated with greater experimental efficiency and more accurate error identification. Future optimization of virtual laboratories should focus on enriching scenario design and integrating graduated procedural practice to strengthen skill transfer to authentic laboratory contexts.

CONCLUSION

Virtual laboratory-assisted learning was found to be effective in strengthening students' abilities in data analysis, conclusion formulation, and scientific communication. However, the transfer of procedural and psychomotor skills to the real laboratory context remains limited. Students still experienced difficulties in mastering procedural sequences, using laboratory equipment and materials, and performing practical activities that require hand–eye coordination. These findings indicate a performance gap between virtual simulations and real laboratory environments. Therefore, virtual laboratories are more appropriately positioned as scaffolding to support conceptual understanding and scientific reasoning rather than as a substitute for direct laboratory experience.

This study has several limitations. Laboratory performance assessment was conducted within a single practicum context and did not involve a direct comparison with learning groups employing different instructional approaches. Consequently, the findings primarily reflect the transfer of skills from a virtual laboratory environment to real laboratory practice within a limited context.

The implications of this study suggest that virtual laboratories should be utilized as a pre-laboratory learning medium to strengthen conceptual understanding, data analysis skills, and scientific reasoning before students enter the real laboratory. Nevertheless, practical learning should still provide hands-on experiences that allow students to practice equipment manipulation, motor coordination, and the implementation of experimental procedures in an authentic laboratory setting.

For future research, it is recommended to develop more integrative instructional designs that combine virtual laboratories with real laboratory practice. Such designs may emphasize procedural sequence training before laboratory sessions and provide brief preparatory briefings along with immediate feedback at the beginning of practicum activities to enhance students' procedural skill transfer.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS STATEMENT

Conceptualization: CT; methodology: CT; data collection: CT and FA; formal analysis: FA; original draft preparation: CT; reference collection: CT and FA; writing—review and editing: CT and FA; supervision: FA.

AI DISCLOSURE STATEMENT

During the preparation of this work, the authors used ChatGPT 4.0 (Artificial Intelligence) for language refinement and assistance with structuring certain sections of the manuscript. Following the use of this tool, the authors thoroughly reviewed, edited, and

validated the content to ensure accuracy and academic integrity. The authors take full responsibility for the final content of the publication and declare that the core research, data analysis, and interpretations were conducted without the aid of artificial intelligence.

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