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VIRTUAL LABORATORY IMPLEMENTATION IN MOLECULAR BIOTECHNOLOGY: CHANGE IN PROSPECTIVE BIOLOGY TEACHERS' SELF-SYSTEM AND MENTAL PROCEDURES

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ABSTRACT

Limitations in laboratory facilities and the demands of 21st-century learning require technology-based instructional innovations in molecular biotechnology courses. Therefore, the use of virtual laboratories has become a relevant solution for improving students' procedural skills and fostering the development of their self-system in a sustainable manner. The objective of this study is to observe the influence of and improvements in students' self-system and mental procedures during molecular biotechnology lectures using a virtual lab, as well as the relationship between these two variables. This study used two methods: an experimental single-group pretest-posttest design and a diary study. The research sample was selected purposively from two universities. The instruments used in this study were questionnaires, questions, and observation sheets. The research data were analyzed descriptively, using the Wilcoxon Signed-Rank test to test for differences in means, the Spearman's rho correlation test, and linear regression testing. The results showed a moderate increase in the self-system category (N-gain = 0.59) from 67.60 to 87.58 and in the mental procedural category (N-gain = 0.69) from 15.42 to 68.94. Both increases were significant, with p-values (0.000) > α (0.05) and an effect size of 0.87 in the large category. Both variables showed a significant relationship (ρ = 0.40) and a self-system contribution to 11.5% increase in mental procedures. The findings of this study indicate that the use of virtual labs in biotechnology lectures can significantly improve students' self-system and mental procedural abilities.

Keywords: virtual lab; self-system; mental procedures; molecular biotechnology

INTRODUCTION

One of the important factors that influences success in learning is students' ability to manage their learning process by utilizing various knowledge they already have, such as cognitive knowledge, metacognitive knowledge, and other important tools for assessing the learning process and progress (Panadero, 2017; Marantika, 2021; He et al., 2024). This ability is known as the self-system, a person's capacity to manage and evaluate important emotional and self-efficacy issues during learning. Self-system abilities do not develop naturally with age but require external stimulation and practice.

The concept of self-system was introduced by Marzano in 1993 and has a meaning almost identical to that of self-regulation proposed by Zimmerman and Pons (Marzano et al., 1993). In their taxonomy, the self-system is at the sixth, or highest, level in both the information domain and the mental and psychomotor procedures. According to Marzano, a person with a strong self-system can be identified through four indica-

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tors: examining importance, examining efficacy, examining emotional response, and examining motivation. The self-system is an important foundation for students as one of the 21st-century skills, enabling them to plan, monitor, and evaluate their learning methods so they can ultimately formulate appropriate strategies to overcome various obstacles (Yang & Li, 2023; Begum, 2025). Strengthening self-system and procedural skills among pre-service teachers aligns with Sustainable Development Goal 4 (SDG 4), which emphasizes quality education through improvements in educator competencies and technology-based learning approaches. In higher education, particularly in biology teacher education, self-regulation, reflective thinking, and procedural skills are essential components in fostering effective, adaptive, and sustainable learning processes (Kayacan & Ektem, 2019; Erwinsyah et al., 2025). Strengthening the self-system is very important for prospective biology teachers as they must master the correct biological concepts and prepare to teach them in the future (Maksimovć & Osmanović, 2019; Çeliker, 2021; Idris et al., 2025). Furthermore, empirical evidence indicates that self-system abilities remain insufficiently developed across different educational levels. None of the tenth-grade students assessed demonstrated adequate self-system abilities (Tuzzahra et al., 2022), whereas senior university students achieved only a moderate level of self-system ability (Idris et al., 2025). These findings suggest that the development of self-system competencies remains a persistent educational challenge and requires targeted instructional interventions. The demand to simultaneously integrate scientific, pedagogical, and self-system skills can be met if prospective teachers are actively involved in ongoing learning (Korpipää et al., 2020; Yerdelen et al., 2024).

One of the skills that prospective biology teachers must have in the future is procedural skills. Procedural skills enable a person to perform a series of systematic steps to complete tasks accurately and effectively. In the context of prospective biology teachers, the procedural skills referred to include designing experimental procedures, using tools and materials correctly, controlling variables, and analyzing and evaluating practical results (Sanduleac, 2024). Procedural skills are not only related to psychomotor or mechanical skills, but are rooted in procedural knowledge, or what we call procedural mental. Procedural mental is a cognitive representation that discusses a person's knowledge of the sequence of steps, actions, and conceptual considerations that underlie each procedure (Hurrell, 2021).

Various factors, including self-system ability, influence students' procedural abilities. Students with a strong self-system are predicted to be more systematic in carrying out procedures, more reflective, and better able to identify procedural errors, and more adaptive in using appropriate strategies, all of which are important components of procedural mentality. In addition, an increase in students' procedural knowledge can influence the self-system, particularly self-efficacy. Students with good procedural knowledge will be very confident (examining efficacy) in carrying out practical activities or learning processes (Boden et al., 2023).

Prospective teachers are a strategic group in education because they are prepared to be agents of change across all aspects of life (Pantić & Florian, 2015; Brown et al., 2021). The success of a country's education system begins with a university's ability to prepare qualified, adaptable prospective teachers (Schleicher, 2018). As future biology educators, teachers must not only be equipped with competent pedagogical and professional skills, but also procedural skills, including mental procedural and psychomotor skills, as well as competent self-system abilities (Maksimovć et al., 2015; Lauermann & König, 2016; Karlen et al., 2020; Alpaydın et al., 2022). Training and strengthening the self-system influence teaching styles that foster a pleasant classroom atmosphere and adapt to change and emerging technologies (Granziera et al., 2019; Juma, 2024).

For prospective biology teachers, some courses, such as molecular biology and molecular biotechnology, can be difficult to learn due to the complexity of the material, the interconnectedness of prior concepts, and their often theoretical instruction rather than practicum activities (Haberbosch et al., 2025). The 21st century is a time of massive, rapid biological development, including molecular biotechnology (Henry, 2022; Topcu et al., 2025). This development has had a significant impact across various fields, including agriculture, health, food, and industry (Adetunji et al., 2021; Tyczewska et al., 2023; Turetta et al., 2025). Teachers must be able to accommodate these developments so that prospective biology teachers are not only equipped with conceptual understanding but also have the mental and procedural skills to explain, demonstrate, and guide students in practical activities (Peker & Dolan, 2014; Fitriani et al., 2024). However, field conditions do not meet expectations. Limited infrastructure, unavailability of equipment and materials, and difficult practicum procedures result in learning being replaced by images or video simulations (Shambare et al., 2022; Poo et al., 2023; Mukagihana et al., 2025). This situation has the potential to hinder the development of self-systems and limit students' opportunities to practice procedural knowledge and performance during practicum activities.

Problems related to these practicum activities can be addressed by providing a simulated or virtual environment so students can experience them with low risk and cost (Alvarez, 2021). Virtual laboratories help students better master concepts, foster positive attitudes, and develop psychomotor skills (Saenz et al., 2019; Wu et al., 2022; Sapriati et al., 2023; Sujono et al., 2023). The integration of virtual laboratories into molecular biotechnology learning supports the implementation of Sustainable Development Goal 9 (Industry, Innovation, and Infrastructure) through adaptive, sustainable educational technology innovations that facilitate flexible, safe, and cost-effective learning experiences (Wahyuni et al., 2024). Furthermore, virtual laboratories have been reported to enhance students' procedural competencies, scientific reasoning, critical thinking, and inquiry-based learning skills by providing interactive environments that simulate authentic laboratory activities and promote active learning engagement (Noris et al., 2022). However, using poorly designed virtual labs to achieve the desired objectives will be futile. Virtual labs that are merely stimulating can lead students to be careless and to take them less seriously as tools to support their knowledge, attitudes, and psychomotor skills (Kapici et al., 2019; Byukusenge et al., 2023).

Various meta-analyses and systematic reviews have demonstrated that self-regulated learning plays a significant role in determining the effectiveness of digital learning and virtual learning environments (Atmojo et al., 2020; Theobald, 2021; Edisherashvili et al., 2022; Cheng & Yang, 2023). Virtual laboratories can enhance students' critical thinking skills, metacognitive skills, and overall learning outcomes (Ridlo et al., 2022; Ernita, 2024). Nevertheless, most existing studies have primarily focused on cognitive achievement and self-regulated learning in a broad sense, while investigations examining the relationship between self-system and procedural mental processes within virtual laboratory settings, particularly in molecular biotechnology courses, remain scarce.

Although previous studies have consistently demonstrated the effectiveness of virtual laboratories in improving learning outcomes, critical thinking, metacognitive skills, and self-regulated learning, several important gaps remain in the literature. First, most studies have focused primarily on cognitive achievement and general self-regulated learning outcomes, while the development of self-system components, such as examining importance, examining efficacy, examining emotional response, and examining motivation, has received limited attention. Second, procedural competence has frequently been examined from a psychomotor perspective, whereas the underlying mental procedures that guide procedural performance have rarely been investigated. Third, existing studies typically examine self-regulation and procedural skills as separate constructs, leaving the potential interaction between the self-system and mental procedures largely unexplored. Finally, despite the growing adoption of virtual laboratories in science education, empirical evidence from molecular biotechnology courses remains scarce, particularly in teacher education programs. These limitations indicate the need for research that simultaneously examines the development of the self-system and mental processes and explores their relationship within a virtual laboratory learning environment.

Based on these gaps, this study investigates the development of the self-system and mental procedures before, during, and after participation in a virtual laboratory-based molecular biotechnology course. Unlike previous studies that primarily focused on cognitive achievement, critical thinking, or self-regulated learning in general, this study adopts Marzano's self-system framework and examines its relationship with mental procedures within a virtual laboratory environment. The novelty of this study lies in (1) the simultaneous investigation of self-system and mental procedures, (2) the examination of their interrelationship, and (3) the application of these constructs within a molecular biotechnology course for prospective biology teachers. By addressing these gaps, the study contributes to a more comprehensive understanding of how virtual laboratory experiences support both affective and cognitive dimensions of learning.

METHODS

This study employed a single-group pretest–post-test design (Creswell, 2009). To enrich the research data, self-systems during learning were observed through study diaries to capture variables measured during the process through observation sheets (Ukrop et al., 2019; Robayo-Tamayo et al., 2020; Arndt & Rose, 2023). This study was conducted at two campuses and involved 72 undergraduate students enrolled in a Biotechnology course. A purposive sampling technique was employed to select participants, as only students enrolled in the course during the study period met the inclusion criteria and were directly involved in the learning intervention being evaluated. The sample consisted of 39 students from Campus A (4 males and 35 females) and 33 students from Campus B (4 males and 29 females). All research participants provided informed consent in accordance with the Human Research Ethics Committee of Universitas Pendidikan Indonesia (51/UN40.K/PT.01.01/2025).

This research was conducted over four weeks in a molecular biotechnology course, specifically on DNA isolation, electrophoresis, PCR, and gene transfer. This course used a virtual lab as a substitute for practicum activities. Pre-tests of the self-system and mental procedures were administered using a self-system questionnaire and mental procedures questions developed from Marzano's Taxonomy. Before class, students were socialized about how the learning process would take place. Each student received an account and password to log in to Libtrogen, a learning management system for this research. Libtrogen is a virtual laboratory designed to replace practicum activities in a wet lab, including DNA isolation, electrophoresis, PCR, electroporation, gene transfer with a gene gun, and gene transfer with Agrobacterium tumefaciens. At each meeting, students were given a worksheet with a mini project to complete in Libtrogen.

Libtrogen has three activities: concept exploration, virtual practicums, and assessments. In the concept exploration activity, students are trained to set objectives, measure prior knowledge, and complete self-assessments. The practicum activities are carried out weekly by following the procedures in the Virtual Lab feature. At the end of the practicum, students can see whether the procedures carried out were correct or incorrect. Students who completed the activities correctly continued the activity by filling out the provided worksheet, while those who completed the work incorrectly filled out a remedial form and repeated the same practicum. The remedial form helped students identify procedural errors. During the activity, researchers used several instruments to identify students' self-systems: observation sheets, performance observation sheets, and anecdotal notes. All these instruments served as a triangulation of the pre-test and post-test.

The instruments used in this study consisted of questionnaires, self-system observation sheets, and mental procedural questions developed from Marzano's Taxonomy. The self-system questionnaire consisted of 15 statements across 3 indicators: importance (5), efficacy (5), and emotional response (5). The self-system questionnaire used a Likert scale consisting of the options strongly agree, agree, disagree, strongly disagree, and very strongly disagree. Meanwhile, the mental procedural questions consisted of 11 multiple-choice items at varying cognitive levels. Both instruments were construct-validated by experts, with Aiken's values of 0.94 for the self-system instrument and 1 for the mental procedural questions, both of which were in the highly valid category. Meanwhile, based on empirical validity tests, both instruments are also in the valid and reliable category, with a reliability value of 0.78 for the self-system questionnaire and 0.75 for the mental procedural questions.

Data self-system and mental procedure abilities were categorized into five groups: excellent (81.00-100), good (61.00-80.99), moderate (41-60.99), poor (21.00-40.99), and very poor (<21). The data were analyzed using SPSS version 25, including a comparison of the pre-test and post-test using the Wilcoxon signed-rank test. The N-gain value distribution visualization was used to describe the distribution of improvements in students' self-system and mental procedures after the intervention. The average data for each self-system indicator at each meeting were visualized using a radar chart. In addition, the percentage change formula was used to see the percentage increase. Spearman's rho correlation test was used to see the correlation between the two variables. In contrast, the linear regression test was used to see the contribution of the self-system to the increase in mental procedures.

RESULTS AND DISCUSSION

Students' self-system and mental procedure abilities before and after attending molecular biotechnology lectures with virtual labs are presented in Table 1.

Table 1. Distribution of Prospective Biology Teachers' Self-System and Mental Procedure

	Self-System		**Mental Procedures**	
	Pre-test	**Post-test**	**Pre-test**	**Post-test**
Number of Students (N)	72	72	72	72
Minimum	53.33	74.67	0.00	32.69

Maximum	82.67	100	38.46	94
Average (Mean)	67.60	87.58	15.42	68.94
Standard Deviation	5.482	6.631	8.47	17.43

Table 1 demonstrates a clear improvement in both measured dimensions following the instructional intervention. The most substantial improvement was observed in the Mental Procedures dimension, indicating enhanced student performance in applying cognitive skills and completing tasks requiring higher levels of cognitive processing. Improvement was also evident in the Self-System dimension, suggesting positive development in students' affective characteristics and self-regulatory capacities throughout the learning process. These findings indicate that the intervention contributed not only to the enhancement of students' cognitive competencies but also to the development of self-management aspects of learning. Overall, the results suggest that the implemented instructional approach was effective in fostering improvement across multiple dimensions of student learning outcomes. The normality and homogeneity tests for the self-system and mental procedures are shown in Table 2.

Table 2. Normality and Homogeneity Test

	Self-System		Mental Procedures	
	Pre-test	**Post-test**	**Pre-test**	**Post-test**
Normality	Self-system data is normally distributed, while mental procedures data is not.			
(Kolmogorov-Smirnov Test)	.200	.189	.001	.018
Homogeneity	All data is homogeneous.			
Sig.	.427		.259	
Levene	7.800		1.284	

Table 2 shows that the self-system ability data in both the pre-test and post-test are in the normal category (P value > α), whereas the mental procedural ability data in both the pre-test and post-test are not normally distributed (P value > α). The homogeneity test results show that both data sets are homogeneous. To examine the mean differences between the two variables, the Wilcoxon signed-rank test was employed. In addition, the effect size was calculated using Cohen's *d*. The results are reported in Table 3.

Table 3. Wilcoxon Signed-Rank Test and Cohen's Effect Size

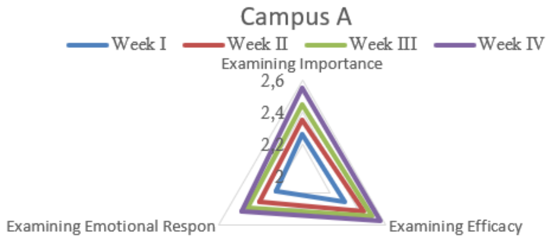
Variable	Z	P Value	Effect Size	Conclusion
Self-System	-7.350	.000	0.87	Very Large
Mental Procedures	-7.349	.000	0.87	Very Large

Table 3 shows that, based on the Wilcoxon Signed-Rank test, there is a significant difference between the pre-test and post-test for both the self-system and the mental procedural, with p-values (0.00) < α (0.05). In addition, Cohen's effect size test shows that both variables have an r value of 0.87, which is categorized as very large. These findings indicate that the use of virtual labs in molecular biotechnology lectures can not only significantly improve the self-system and mental procedural abilities but also has a strong practical effect.

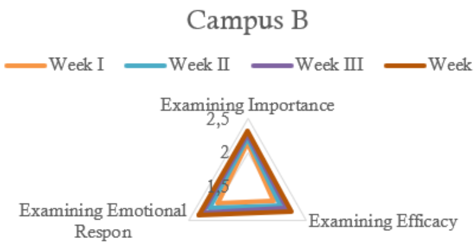
Figure 1. Distribution of Prospective Biology Teachers' Self-System and Mental Procedures (N-Gain)

Based on Figure 1, the students' self-system improved moderately, with the graph peaking at an N-Gain of 0.60 in the moderate category. Meanwhile, the peak of the mental procedural graph was at an N-Gain value of 0.70. The graphs above show that the virtual lab used during the study had different effects on the variables and research samples.

During the study, the development of the prospective biology teachers' self-systems was observed through observation sheets. These observations supported the primary data and confirmed the data obtained with events that occurred during the study. The study was conducted over four weeks, covering four main topics and six practicums. Throughout the study, students' self-system abilities increased each week, as shown in Figure 2.



(a)



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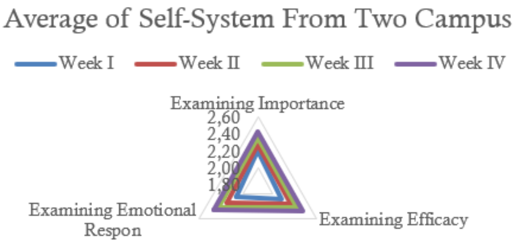

(c)

Figure 2. Development of Self-System in Each Week: (a) Campus A, (b) Campus B, and (c) Both Campuses

Figure 2a shows the development of the self-system of prospective biology teachers at Campus A during the intervention (4 weeks). Measurements were conducted weekly throughout the learning process using three indicators: importance, efficacy, and emotional response. At the first meeting, all three indicators had relatively balanced abilities with an average of 2.30 (scale 1-3), indicating that the students' self-system was in the moderate category. At the second meeting, indicators I and II increased, while indicator III showed a smaller change. The smaller increase is part of the initial adaptation to the learning process that is different from usual, in addition to the possibility of adjustments to the technology (virtual lab) used. At the third and fourth meetings, all indicators showed a significant increase, especially the examining efficacy indicator, which indicates that students are more competent in operating the virtual lab, understanding experiments, and connecting theory with practice, and that they have higher self-confidence after the experience and knowledge gained in the two previous meetings.

Figure 2b provides information on the development of the self-system at each meeting at Campus

B. In the first meeting, students' self-systems showed lower development, with an average of 2.06 (scale 1-3), compared to those in Campus A. At Campus A's first meeting, the highest indicator was I at 2.14, indicating that students had understood the general overview and the importance of the concepts to be learned from the beginning. However, they lacked self-confidence and emotional involvement, both of which were still developing. The increase in all indicators was gradual, but a different pattern emerged at the third meeting: the efficacy indicator began to increase sharply, as did the examining emotional response indicator. This indicates that students are increasingly enthusiastic and comfortable with the virtual lab and the learning process it supports. The self-system indicator value for all indicators was highest at meeting 4, with an average of 2.30, indicating that interventions with the virtual lab carried out during the learning process can help students clarify specific objectives, improve self-confidence, and help increase emotional involvement with lecturers, groupmates, or between groups in the ongoing learning.

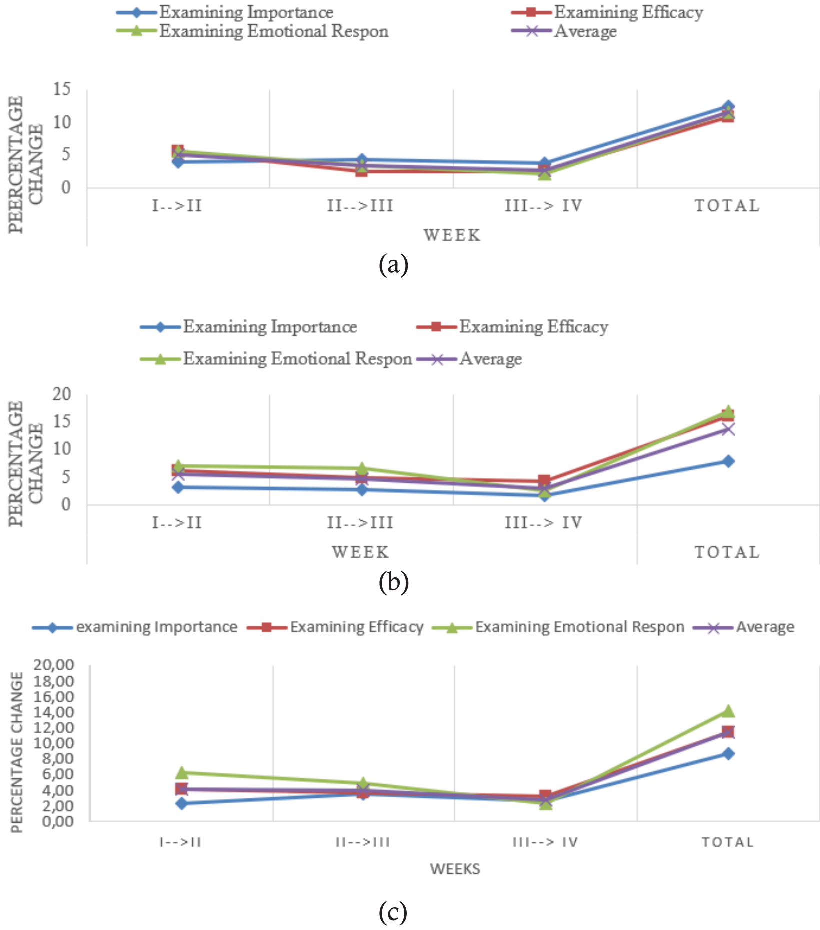

Figure 3. Percentage Change: (a) Campus A, (b) Campus B, and (c) Both Campuses

Figure 3a shows the percentage change in the self-system of prospective biology teachers over 4 weeks at two different campuses. At Campus A, the average increase in the percentage change in all indicators in the medium category (10%-20%) was 11,542. Across indicators, the largest increase was in the examining importance factor, followed by examining emotional response, and finally examining efficacy. At each meeting, the percentage of students who used the virtual lab during molecular biotechnology lecture activities changed. Based on the average change per meeting, the highest increase was from meeting I to meeting II (5.030), while the lowest was from meetings III to IV (2.722).

The percentage of changes in students' self-systems from each meeting at Campus B shows a different pattern and is higher than at Campus A, with an average of 13.641 in the medium category (Figure 2b). If we look at each indicator, the indicator that has the greatest change is the indicator examining emotional response with a percentage of 17.000 (medium), followed by the second indicator, namely examining efficacy with a medium category (15.979), while the lowest indicator with a small increase indicator (7.944) is in the indicator examining importance. Viewed from the meeting, the same pattern is observed at Campus B: meetings I and II show the largest increase. Figure 3 shows that, across both campuses, students' self-systems increased by 11.497% at each meeting. This means that during the use of the virtual lab, students experienced an increase in their self-systems in the medium category. The correlation test between the self-system and mental procedures is shown in Table 4.

Table 4. Correlation Test of Self-System and Mental Procedures

Variabel	ρ (Spearman)	P value	Conclusion
Self-system – Mental Procedures	.40	.004	Significant With Moderate Category

Based on the data in Table 4, the self-system has a significant relationship (p value (0.004) < value (0.05)) with mental procedural, with a moderate category (ρ = 0.4). To examine the influence of the two variables, a linear regression analysis was conducted on the relationship between the self-system and mental procedural, as shown in Table 5.

Table 5. Linear Regression Analysis Predicting Mental Procedural from Self-System

Predictor	B	SE B	β	t	p	R	R^2
Constanta	9.42	16.85	—	0.56	.578		
Self-System	0.58	0.19	.40	3.02	.003	.339	.115

Based on the data in Table 5, the regression analysis shows that the self-system contributes to a 11.50% increase in mental procedural ability. This means that strengthening the self-system will increase students' procedural mental ability.

The research findings show that the virtual lab significantly improved the self-system. This improvement indicates that the self-system is not a static attribute but rather a psychological aspect that can be trained, developed, and enhanced through specific treatments. This finding aligns with research suggesting that virtual reality can enhance the self-system in college students (De Rutté, 2024) and is closely related to learning independence (Lobos et al., 2024; Wu et al., 2025).

The improvement in self-efficacy during laboratory practicums is due to students' involvement in using equipment, observing phenomena, and working in teams. In comparison, virtual practicums train students through independent learning, for example, by evaluating key concepts to be learned, increasing motivation through enjoyable activities, building self-confidence through low-risk activities, and fostering self-control in completing practicums due to the unlimited time available (Korfiatis et al., 2023).

Self-system skills can develop when all of their components are systematically fostered through meaningful learning experiences. The development of the importance dimension requires students to recognize the value of concepts and skills for their academic achievement and future professional careers. Activities such as establishing laboratory objectives and identifying key concepts encourage students to anticipate learning goals, connect prior knowledge with new information, and relate scientific concepts to real-world contexts (Stoeckel, 2020; Spencer et al., 2024). From the perspective of Self-Regulated Learning (SRL) theory, these activities correspond to the forethought phase, during which learners set goals, evaluate task value, and develop strategic plans to achieve desired outcomes. Consequently, students are not merely following laboratory instructions; they are actively constructing an understanding of why the activities are important and how they contribute to their personal and professional development (Lobos et al., 2024; Wu et al., 2025). This process enhances students' perceived task value and strengthens their motivation to learn. Furthermore, by linking biotechnology concepts to future careers, students develop a clearer sense of purpose and relevance, a factor identified as critical for sustaining self-regulated learning and academic motivation (Makransky et al., 2019).

Numerous studies indicate that self-efficacy significantly influences learning behavior, persistence, and learning outcomes (Honicke & Broadbent, 2016; Meng & Jia, 2023). In a virtual lab setting, three important mechanisms contribute to its advantages in increasing self-efficacy. First, virtual labs provide a safe and risk-free environment, allowing students to experiment freely (Seifan et al., 2020; Viitaharju et al., 2023; Girmay et al., 2024) and to revise incorrect procedures (Liu et al., 2022; Vergara et al., 2022; Diwakar et al., 2023; Wu et al., 2025). Second, virtual labs also allow students to learn at their own pace (Chattopadhyay, 2025), adapt to their strengths and weaknesses, and receive continuous feedback. Finally, virtual labs are equipped with comprehensive and instructive guides, enabling students to perform effectively and reducing cognitive load (Gungor et al., 2022; Solikhin et al., 2022; Anom et al., 2024). These three aspects were key considerations in developing the virtual lab in this study. Throughout the study, these three aspects helped students develop confidence and be unafraid to try. If they did not perform well, they were allowed to retake the lab by completing a remedial form that helped identify their errors.

In every learning activity, whether in the classroom or in the laboratory, students experience positive or negative emotions (Simonton & Garn, 2020; Jerrim, 2022; Hu et al., 2024). Positive emotions such as curiosity, happiness, and satisfaction encourage increased student engagement in learning. Conversely, negative emotions such as fear, anxiety, sadness, and frustration will hinder learning success (Carmona-Halty et al., 2021; Chanpet et al., 2020; Rodríguez-Muñoz et al., 2021). In this study, the virtual environment focused primarily on fostering positive emotions by creating a comfortable, risk-free learning environment, providing challenges at different levels, and encouraging a sense of satisfaction and healthy competition (Ambusaidi et al., 2018; Dubovi, 2022; Patel, 2024). The success and failure features at the end of the practicum activity encouraged students to be brave and take risks while being cautious. Practicum activities in virtual labs provide students with the flexibility to learn anytime and anywhere, thereby reducing psychological stress during learning (Byukusenge et al., 2022; Salem & Lakwani, 2024).

The use of virtual labs in molecular biotechnology courses significantly improves students' mental procedures. Mental procedure skills are defined as the ability to remember, understand, and carry out simulated practicum activities before the actual laboratory activity (Saks et al., 2021; Sanduleac, 2024). The virtual environment allows students to observe and repeat procedures without time pressure, risks, or other limitations (Radianti et al., 2020). These findings align with cognitive rehearsal theory, which states that mentally repeating procedures can improve accuracy and fluency when practicum activities are conducted in a real-world setting (Sanduleac, 2024). The improvement in students' mental procedures can also be explained through constructivist learning theory. Constructivism posits that knowledge is actively constructed through interaction with learning environments rather than passively received from instructors.

Furthermore, virtual labs can reduce students' cognitive load when facing actual practicum activities (Sweller, 2011). For example, if a student makes an error converting units after the practicum has already been carried out, the practicum results will likely fail, requiring repetition and additional equipment and materials. Unlike virtual labs, students can repeat practicum activities continuously without worrying about material losses. Although virtual lab activities offer many advantages and can enhance students' cognitive processes, they cannot completely replace actual laboratory activities (Dyrberg et al., 2017; Radianti et al., 2020). Integration of the two is necessary to improve the quality of biotechnology learning for students.

Based on Figures 2 and 3, the two campuses show distinct patterns of self-system improvement. At Campus A, the importance indicator shows the largest increase, while at Campus B, the emotional response indicator shows the largest increase. Campus A shows a more cognitive-reactive pattern, indicating that students are aware of the importance of virtual labs in understanding biotechnology concepts and their implications for future skills. Meanwhile, Campus B shows a more affective-reflective pattern, indicating that interactive and visual experiences in the virtual laboratory increase students' interest and enthusiasm, which in turn can improve learning outcomes (Merchant et al., 2014). These differences confirm that virtual labs can enhance the self-system in different ways, either through cognitive-reactive or affective-reactive pathways.

Correlation tests indicate that the self-system is significantly related to students' mental procedures, accounting for 11.5%. In addition to the self-system, learning success is influenced by a range of factors. At least three factors influence student learning outcomes: institutional, social, and psychological/individual factors (Acosta-Gonzaga & Ramirez-Arellano, 2021; Nunes et al., 2023; Berhanu & Sewagegn, 2024). Students with more comprehensive learning facilities (Campus A) experienced a better learning experience. Its central location provided easier access to external resources, including industry, research institutions, and the scientific community. This access enriched students' learning contexts and increased the relevance of practicums to the real world, thereby increasing learning motivation (Dupont et al., 2015; Bowden et al., 2021). This enrichment has been shown to strengthen academic discussions, broaden perspectives, and enhance collective problem-solving skills

(Abouelenein et al., 2023). In addition to the factors mentioned, basic digital skills and readiness to embrace new technologies are crucial for the success of virtual lab implementation (Diwakar et al., 2023; Salimi et al., 2025). Initial support, including user orientation, instructional scaffolding, and technical guidance, is crucial for students to quickly enter a more meaningful stage of exploration and reflection.

In addition to positively influencing students' psychological and cognitive development, the implementation of virtual laboratories in this study also contributes to achieving Sustainable Development Goals (SDGs), specifically SDG 4 (Quality Education), by expanding access to inclusive and equitable learning opportunities, and SDG 9 (Industry, Innovation, and Infrastructure), by integrating innovative technological solutions into the educational process. The developed virtual laboratories support improved educational quality by enabling students to access learning activities anytime, anywhere. Furthermore, integrating virtual laboratories into the learning process provides students with valuable experience and mental preparedness to adapt to future technological and informational advancements.

Although this study shows that the use of virtual labs has a significant effect on the self-system and mental procedures, several limitations remain, including the absence of a control or comparison group, which limits the ability to compare conclusions. In addition, due to the relatively short duration of the study, the effects observed do not yet reflect the stability of the development of the self-system or mental procedures.

This study contributes to the literature by providing important theoretical, practical, and educational policy implications. From a theoretical perspective, the findings indicate that self-system and mental procedures are not static constructs but are shaped by variations in workload, virtual laboratory complexity, and the level of scaffolding provided. These findings support the view that appropriately designed virtual learning environments can foster both affective and cognitive dimensions of learning. From a practical perspective, the results offer guidance for optimizing the design and implementation of virtual laboratory learning environments to enhance students' self-regulation, self-efficacy, and procedural competencies. Furthermore, the findings support broader educational initiatives aimed at achieving Sustainable Development Goals 4 (Quality Education) and 9 (Industry, Innovation, and Infrastructure). The demonstrated effectiveness of virtual laboratories suggests that higher education institutions and policymakers should encourage the integration of technology-enhanced laboratory learning into science curricula to expand access to high-quality practical experiences, particularly in institutions with limited laboratory facilities. Strategic investments in digital infrastructure, faculty training, and virtual laboratory development may help reduce educational disparities while promoting innovation in higher education. Moreover, policies that foster students' self-regulation, self-efficacy, and procedural competencies can better prepare graduates for workplaces that are increasingly digital and technology-driven.

CONCLUSION

The results of the study indicate that the virtual laboratory in molecular biotechnology learning improves students' self-system and mental procedure abilities to a very good level. Based on the Wilcoxon Signed-Rank test, the increase was significant, indicating that the use of the virtual lab has a real influence on changes in students' self-system and mental procedures. Self-system improvement does not occur instantly but requires time and consistent practice. The correlation test shows that the self-system is significantly correlated with students' mental procedures. This means that students with a higher self-system will have better mental procedures. However, other factors that influence learning and instruction include social, motivational, and prior knowledge and experience.

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