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Evaluating Students' Performance and Perceptions Following Simulated Pharmacology Laboratories.

Evaluación del rendimiento y las percepciones de los estudiantes tras la implementación de laboratorios de farmacología simulados.

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Abstract.

Background: Traditional pharmacology education fails to bridge the gap between theoretical drug mechanisms and clinical application. This study evaluates the implementation of a simulated pharmacology laboratory as a pedagogical tool to enhance student achievement. **Methods:** A mixed-methods study was conducted across three student cohorts (n = 308). The simulation was integrated into: Principles of Disease I & II, Gastrointestinal (GI) System, and Nervous System & Special Senses modules. Performance was measured via pharmacology OSPE stations. Data were analyzed using SPSS, employing ANOVA and t-tests for gender-stratified quantitative results. Qualitative reliability was ensured through a thematic analysis of feedback from students, medical educators, and pharmacology experts. **Results:** Quantitative analysis revealed high levels of performance outcomes, particularly in the GI module (Mean 8.7 ± 0.1 for Patch 3 females). However, the Nervous System module consistently yielded lowest scores (Means < 7.0) across all patches, suggesting inherent conceptual complexity. Statistical significance was observed in Principles of Disease I ($p < 0.05$). Qualitatively, experts (n=10) praised the method's resource efficiency and cognitive alignment but cautioned against lack of biological variability inherent in digital models. Students reported increased self-efficacy, though gender-stratified feedback highlighted differing preferences for collaborative versus technical preparatory materials. **Conclusion:** Simulated pharmacology labs significantly support undergraduate learning outcomes in specific modular domains. While highly effective for visualizing drug-receptor interactions, a "hybrid" model incorporating real-world biological variability is recommended for complex neuropharmacology topics. These findings support the wider integration of simulation-based learning (SBL) as a stable, equitable pedagogical framework in medical curricula.

Keywords: Computer-based, Education environment, Outcome-based, Nervous system, Pharmacology.

Resumen.

Antecedentes: La enseñanza tradicional de la farmacología no logra acortar la brecha entre los mecanismos farmacológicos teóricos y su aplicación clínica. Este estudio evalúa la implementación de un laboratorio de farmacología simulado como herramienta pedagógica para mejorar el rendimiento académico de los estudiantes. **Métodos:** Se realizó un estudio de métodos mixtos en

tres cohortes de estudiantes (n = 308). La simulación se integró en los módulos de Principios de la Enfermedad I y II, Sistema Gastrointestinal (GI), y Sistema Nervioso y Órganos de los Sentidos. El rendimiento se midió mediante estaciones de ECOE (Examen Clínico Objetivo Estructurado) de farmacología. Los datos se analizaron con SPSS, empleando ANOVA y pruebas t para los resultados cuantitativos estratificados por género. La fiabilidad cualitativa se garantizó mediante un análisis temático de la retroalimentación de estudiantes, educadores médicos y expertos en farmacología. **Resultados:** El análisis cuantitativo reveló altos niveles de resultados de aprendizaje, particularmente en el módulo de GI (media de 8.7 ± 0.1 para las mujeres de la cohorte 3). Sin embargo, el módulo del Sistema Nervioso obtuvo de manera consistente las puntuaciones más bajas (medias < 7.0) en todas las cohortes, lo que sugiere una complejidad conceptual inherente. Se observó significación estadística en Principios de la Enfermedad I ($p < 0.05$). Cualitativamente, los expertos (n = 10) elogiaron la eficiencia de recursos y la alineación cognitiva del método, pero advirtieron sobre la falta de variabilidad biológica inherente a los modelos digitales. Los estudiantes informaron un aumento en la autoeficacia, aunque la retroalimentación estratificada por género destacó diferencias en las preferencias por materiales preparatorios colaborativos frente a técnicos. **Conclusión:** Los laboratorios de farmacología simulados respaldan significativamente los resultados de aprendizaje de los estudiantes de grado en dominios modulares específicos. Aunque son altamente efectivos para visualizar las interacciones fármaco-receptor, se recomienda un modelo "híbrido" que incorpore la variabilidad biológica del mundo real para temas complejos de neurofarmacología. Estos hallazgos respaldan una integración más amplia del aprendizaje basado en simulación (ABS) como un marco pedagógico estable y equitativo en los planes de estudio de medicina.

Palabras clave: Basado en computadoras, Entorno educativo, Basado en resultados, Sistema nervioso, Farmacología.

1. Introduction

The concept of simulation-based learning (SBL)

The transition from theoretical pharmacology to clinical prescribing remains one of the most challenging leaps for medical students. Traditionally, pharmacology education has relied on didactic lectures and animal-based laboratory experiments. However, ethical concerns and the shift toward competency-based medical education (CBME) have rendered these traditional methods increasingly insufficient. This pedagogical shift aligns with broader global challenges in medical education, where institutions are actively re-examining the structural limitations and faculty perceptions surrounding conventional laboratory practicals (1). A 2026 study in exploring faculty perspectives highlights that simulation (SBL) bridges the "theory-practice gap" by allowing students to experience realistic physiological responses to drugs in a safe environment without patient risk (2). Current literature suggests that students often struggle with "pharmacological dissociation", the inability to link molecular mechanisms to bedside patient outcomes. To bridge this gap, high-fidelity simulations have emerged as a critical pedagogical tool. While previous studies have explored simulation in clinical skills, there is a paucity of data specifically regarding its impact on standardized assessment scores like the objective structured practical examination (OSPE) across multiple cohorts.

The shift toward SBL has demonstrated profound longitudinal benefits across various medical disciplines. Recent data indicates that the implementation of high-fidelity mannequins and virtual patient platforms significantly enhances student performance; for instance, a 12-year analysis of over 2,200 medical students in pediatric clerkships showed statistically significant improvements ($p < 0.001$) across written, clinical, and continuous assessments compared to the pre-SBL era (3). Interestingly, while both genders showed gains, SBL appears to act as a leveler, with male students'

scores improving (from 68.27 ± 7.56 to 75.40 ± 8.62) to match the historically higher baseline of their female counterparts (75.41 ± 9.02) (3). Furthermore, SBL has proven vital as a distance education strategy during global crises, such as the COVID-19 pandemic, where it effectively maintained nursing students' professional skills and attitudes (4). Despite its efficacy in improving learning outcomes (5), the literature remains divided, as earlier reports suggested that SBL did not always correlate with enhanced student motivation (6).

The pedagogical shift in pharmacology

Traditional pharmacology education often suffers from "knowledge compartmentalization," where students master molecular mechanisms but fail to apply them in clinical scenarios. Recent evidence suggests that simulation-based learning (SBL) serves as a critical bridge (7). According to Shanmugapriya et al., (2), faculty perspectives indicate that simulations provide a "low-stakes, high-impact" environment that mitigates the ethical and safety risks associated with early-stage clinical prescribing. This is further supported by Chung (8), who notes that virtual simulations allow for the visualization of drug-receptor interactions, a concept often too abstract for traditional didactic lectures. Furthermore, the intentional curricular insertion of clinical simulation into basic science modules, such as microbiology and pharmacology, has demonstrated growing efficacy in aligning theoretical knowledge with practical clinical reasoning (9).

Impact on objective assessment (OSPE)

The efficacy of these simulations is increasingly measured through objective structured practical examinations (OSPE). Research by Elamin et al. (3) demonstrated a statistically significant correlation between simulation engagement and higher examination scores ($p < 0.001$), suggesting that the tactile and visual nature of simulations enhances long-term retention. Furthermore, a systematized review in PMC (10) concluded that while virtual labs are as effective as traditional wet labs, they are superior in developing the "cognitive domain" specifically regarding dose-calculation accuracy and adverse effect recognition during standardized testing.

Gender-specific perceptions and learning outcomes

A nuanced layer of current research involves how demographic variables, such as gender, influence simulation efficacy. Malhotra et al. (11) observed that while performance outcomes (OSPE scores) are often equitable across genders, the *qualitative* perception of the tool varies. Studies at King Abdulaziz University (12) found that female medical students reported higher levels of "perceived self-efficacy" and satisfaction after simulation sessions compared to their male counterparts ($p = 0.005$). This suggests that while the educational intervention is universally effective, the "affective domain" of learning may be experienced differently, necessitating the stratified feedback analysis utilized in this study.

This study evaluates a simulated pharmacology lab implemented across three distinct student patches. By triangulating quantitative OSPE results with multi-stakeholder feedback from students (stratified by gender), peers, and medical educators, we aim to determine if simulation-based learning enhances both academic performance and professional confidence.

2. Methods

2.1 Study design and curricular integration

This study utilizes a descriptive, cross-sectional, mixed-methods evaluative design across three consecutive student cohorts designated as Patches 1, 2, and 3. Because this curriculum was designed around a standalone digital strategy without a parallel traditional control group or a pre-intervention baseline measurement, the data presented herein cannot establish causal relationships

or absolute programmatic impact. Instead, this study evaluates the internal consistency of post-intervention performance metrics across modules and triangulates these trends with qualitative feedback to identify curricular strengths and systemic instructional gaps. The intervention was implemented within an 8-week block for each module, strategically aligned with the learning objectives of four core academic modules: Principles of Disease I and II, the Gastrointestinal (GI) System, and the Nervous System and Special Senses.

2.2 Laboratory setup and simulation software

While the fundamental operational backbone relies on our previously established technical setup (13), the intervention specifically consisted of 2-hour weekly laboratory sessions. The simulation environment provided an interactive platform where students interacted with computer-modeled tissue systems, such as isolated organ baths and virtual smooth muscle preparations. During these sessions, students manually entered incremental agonist and antagonist concentrations ranging from 10^{-9} M to 10^{-3} M to dynamically generate log dose-response curves, simulating receptor binding affinity and intrinsic activity variables in real-time.

2.3 Theoretical framework

The pedagogical design of this simulated laboratory is grounded in Cognitive Load Theory (CLT) and Experiential Learning Theory. To minimize extraneous cognitive load arising from software operation, programmatic scaffolding was systematically implemented through the provision of overnight handouts detailing theoretical pharmacological principles, supplemented by structured lab procedure sheets. Each session commenced with a live faculty demonstration of the software and specific simulation goals. Learning was reinforced through an experiential learning cycle, allowing students to form abstract concepts through interactive manipulation of digital tissue responses and refine their understanding via immediate pre- and post-lab feedback loops to address misconceptions.

2.4 Assessment: OSPE structure and validation

Student performance was evaluated via an Objective Structured Practical Examination (OSPE). The pharmacology stations were integrated as specialized components within a broader modular circuit. The OSPE was content-validated against a rigorous blueprint mapped to the cognitive domains of Bloom's Taxonomy, specifically focusing on application and analysis. The circuit featured four specialized pharmacology stations. Each station was standardized to a 5-minute limit: 2 minutes for interpreting a clinical vignette paired with a simulated dose-response graph, and 3 minutes to complete 4 structured, short-answer questions targeting dose calculations (e.g., calculating ED_{50} or clearance) and the structural identification of competitive versus non-competitive antagonism. Scoring criteria were strictly binary and rubric-based (0.5 or 1.0 point per sub-question, total score out of 10) to minimize inter-rater subjectivity. Reliability testing from historical deployments of this item bank yielded an acceptable internal consistency (Cronbach's alpha = 0.78). To ensure procedural standardization, faculty observers were oriented to the simulation software's functionality, and peers were given a detailed walkthrough of the physical lab and OSPE setups.

2.5 Data collection and stratification

Data were triangulated from three primary sources:

1. Quantitative: Performance scores from the pharmacology OSPE stations across all three patches (n = 308).
2. Qualitative (Student): Structured and open-ended feedback collected after the assessment, stratified by gender to account for potential demographic variances in learning preferences.

3. Qualitative (Expert): Formal feedback from peer reviewers and medical educators regarding the implementation and realistic nature of the simulation.

2.6 Statistical analysis

Quantitative data, including continuous OSPE scores, were analyzed using SPSS (Version 26.0). Descriptive statistics are reported as means ± standard deviations (*SD*) along with 95% confidence intervals (95% *CI*) for the means. To compare performance variations across the three patches, a one-way analysis of variance (ANOVA) was performed after verifying the assumptions of normality (Shapiro-Wilk test) and homogeneity of variances (Levene's test). For significant main effects, Tukey's honestly significant difference (HSD) post-hoc test was applied for pairwise comparisons. To measure the magnitude of performance differences, effect sizes were calculated using partial eta-squared for ANOVA and Cohen's *d* for independent t-tests (gender stratifications), with significance set at $p < 0.05$. For the ordinal data derived from the expert Likert scales, medians and modes are reported. The qualitative text from open-ended questions was processed through a general inductive approach, where responses were independently coded into major themes. Inter-rater thematic saturation was validated using a percentage agreement threshold of >85% across independent coders, with any discrepancies resolved through consensus-building sessions involving internal medicine, pediatric, obstetrics and gynecology, and pharmacology specialists.

2.7 Ethical considerations

Ethical approval was obtained from Al-Baha University Faculty of Medicine Institutional Review Board. Participants' informed consent was given, and participation was voluntary. Data and privacy were properly protected and managed. The positionality of the authors in relation to the participants was explicitly considered.

3. Results

3.1 Medical educator evaluation of instructional design

The instructional framework of the simulated pharmacology laboratory was evaluated by a panel of four senior medical educators, including consultants and professors from internal medicine, pediatrics, medical education, and obstetrics and gynecology. The qualitative consensus indicated high satisfaction with the navigational and aesthetic elements of the program. All four educators rated the clarity of the title as "Very Good" to "Excellent," and there was unanimous agreement that the study guide was both user-friendly and efficient (see Table 1, and Appendix Table 5). Specifically, the logical sequencing of the content was noted as a strength, with 75% of the panel (Educators 1, 2, and 3) ranking the structure as "Very Good" or "Excellent." However, the evaluation revealed a more conservative perspective regarding the appropriateness of the method for the specific student level and subject matter. While Educator 1 consistently awarded "Very Good" ratings across these domains, Educators 2 and 3 expressed a more neutral stance, rating the appropriateness for the student level as "Fair." These ratings coincided with a "Satisfactory" consensus regarding the appropriateness of the assessment, suggesting that the expert panel identified a need for further refinement in aligning the simulation complexity with the specific academic level of the undergraduate students.

3.2 Qualitative perspectives from medical educators

The second phase of the expert review involved open-ended inquiries into the pedagogical impact of the simulated labs. Senior educators identified the primary strengths as the modernization of student training through technology and the optimization of institutional resources, highlighting the lab's ability to deliver essential content with significantly reduced logistical requirements (see Table 2, Figure 1 and appendix Table 6). For future refinement, the

educators proposed several structural enhancements, including the recalibration of learning objectives according to Bloom's Taxonomy and the integration of advanced visual aids, such as animations and illustrations. Notably, Educator 1 advocated for the inclusion of "take-home tasks" to extend the learning environment beyond the lab, while others suggested increasing the allocated teaching time to allow for deeper exploration of the simulated scenarios.

Table 1. Qualitative feedback from medical educators regarding simulated pharmacology labs.

No.	Item	Medical educators response summary
1	Greatest strength	Technology integration; resource-efficient delivery of important subjects; quality practical handouts.
2	Areas for improvement	Alignment with Bloom's taxonomy; increased teaching time; take-home tasks; more illustrations/animations.
3	Additional comments	General consensus of high satisfaction ("Excellent," "Good," "Can't agree more").

Table 2. Pharmacology specialist evaluation and technical feedback.

Evaluation category	Statistical trend / Mode	Specialist technical insights
Scientific alignment	Excellent	High consensus (83% Excellent) on the appropriateness of aims, objectives, and content for medical students.
Practical application	Very good	Strong agreement that the teaching approach is suitable for future clinical practice and understanding drug effects on tissues.
Technical quality	Varied (Fair to excellent)	Notable variance in the evaluation of references and assessment rigor, suggesting a need for a more robust bibliography.
Identified strengths	Technical theme	1. Superior for distance learning contexts. 2. High comprehension of drug effects on isolated tissues. 3. Significant reduction in animal and material consumption.
Critical weaknesses	Limitations	1. Potential for students to view biological responses as too "typical/linear." 2. Absence of physical "hand skills" and real-world variability.
Refinement strategy	Expert recommendations	1. Hybrid Approach: Couple simulation with "wet lab" videos or demonstrations. 2. Clinical Bridge: Focus on dosage forms and hospital-based monitoring (filling the "book-to-practice" gap).

3.3 Pharmacology experts' evaluation of content and approach

The simulated labs underwent a technical review by a panel of six pharmacology specialists, ranging from Assistant to Full Professors (see Table 3 and Appendix Table 7). The quantitative feedback was positive regarding the alignment of content with module objectives, with five out of six experts (83%) rating the aims as "Excellent." The panel noted that the logical flow of the content and the appropriateness of the teaching approach for future clinical practice were notable strengths. However, specific areas for improvement were identified regarding scholarly documentation and

assessment rigor. Expert I noted that while the simulation was excellent, the inclusion of formal references and specific starting doses/concentrations in the lab manual required attention. Similarly, while the approach was deemed appropriate for the subject, Experts I and II suggested that the assessment and reference materials ranged from "Poor" to "Fair," indicating a need for a more robust bibliography.

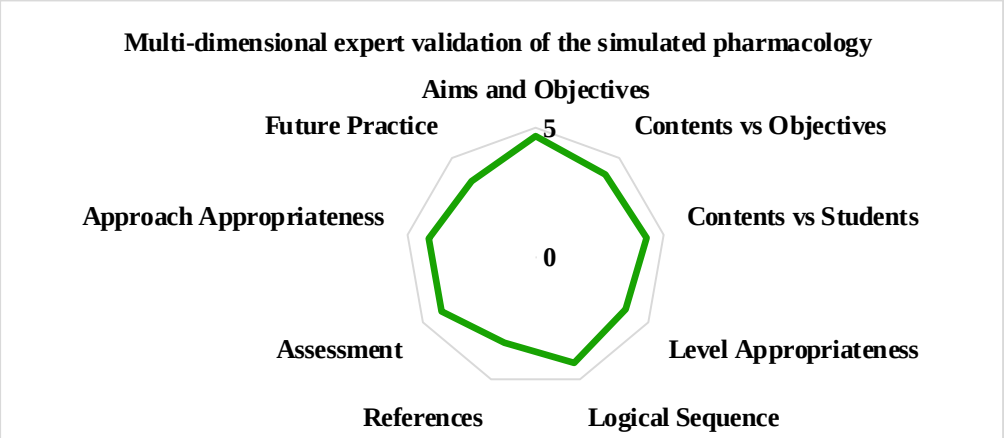

Figure 1. Multi-dimensional expert validation of the simulated pharmacology labs. The Radar (Spider) Chart illustrates the mean scores (on a 5-point Likert scale) provided by six independent pharmacology specialists across nine key instructional domains. The expansion of the data envelope toward the periphery indicates high expert consensus on the appropriateness of aims and objectives (4.67) and logical sequencing (4.33). the inward indentation at item 6 (3.50) highlights a specific area for future curriculum enhancement regarding the diversification of bibliographic references. This visual representation underscores the overall scientific validity of the simulation while identifying specific technical domains for iterative refinement.

3.4 Expert insight on programmatic utility and limitations

Specialized feedback regarding the operational attributes of virtual modeling showed that pharmacology experts praised the simulation for its resource efficiency and its structural efficacy in teaching the specific effects of drugs on isolated tissues, noting its high suitability for independent and distance learning frameworks. Conversely, a significant theme emerged regarding the standardized parameters of virtual software. Full Professor I and Assistant Professor VI cautioned that computerized simulation provides linear biological data, noting that students might erroneously perceive biological responses as perfectly typical or linear. To mitigate this, the experts suggested structural enhancements: coupling the software with real-world demonstration videos to illustrate physical biological variability; creating a clinical bridge explicitly linking simulations to hospital-based practice (focusing on dosage forms, dispensing regulations, and clinical monitoring devices); and increasing the number of software sessions to allow students to master dose-cycle intervals and the complex addition of agonists and antagonists within the user interface.

3.5 OSPE results

The quantitative analysis of OSPE performance across 308 medical students revealed variations in competency scores following the simulation-based labs (see Table 3, Table 4 and Appendix Table 10). In the Principles of Disease II module, Patches 1 and 2 demonstrated high performance with mean scores reaching 9.0 ± 0.3. However, a statistically significant variation was observed in the Principles of Disease I module ($p < 0.05$), where Patch 1 females achieved the highest mean score (8.0 ± 1.2). A notable trend appeared in the Gastrointestinal System module for Patch 3, where female students exhibited superior performance (8.7 ± 0.1) compared to their male

counterparts (7.4 ± 0.9). Conversely, the Nervous System and Special Senses module proved to be the most challenging across all cohorts, with scores consistently falling below the 7.0 mark regardless of gender or patch. This uniformity in lower scores across the three patches suggests that while the simulation assists in conceptual understanding, the inherent complexity of neuropharmacology remains a significant hurdle for undergraduate learners.

Table 3. Consolidated student OSPE performance (Combined genders) (n = 308).

Module Component	Patch 1 Mean ± SD	Patch 2 Mean ± SD	Patch 3 Mean ± SD
Principles of Disease I	7.83 ± 0.89	7.67 ± 0.58	7.33 ± 0.99
Principles of Disease II	9.00 ± 0.51	8.89 ± 0.44	7.81 ± 1.18
Gastrointestinal System	8.19 ± 0.51	7.99 ± 0.47	8.11 ± 0.89
Nervous System & Special Senses	6.73 ± 1.35	6.85 ± 1.79	6.61 ± 1.56

Table 4. Inferential statistical metrics, effect sizes, and post-hoc comparisons for modular OSPE scores (n = 308).

Module Component	Patch Comparison	Mean Difference	95% CI	Effect Size	Tukey's HSD
Principles of Disease I	Patch 1 vs. Patch 2	0.16	[-0.12, 0.44]	η_p^2= 0.04 (Main Effect)	0.381
	Patch 1 vs. Patch 3	0.50	[0.23, 0.77]		0.001*
	Patch 2 vs. Patch 3	0.34	[0.07, 0.61]		0.012*
Principles of Disease II	Patch 1 vs. Patch 2	0.11	[-0.15, 0.37]	η_p^2= 0.18 (Main Effect)	0.624
	Patch 1 vs. Patch 3	1.19	[0.91, 1.47]		<0.001*
	Patch 2 vs. Patch 3	1.08	[0.80, 1.36]		<0.001*
Gastrointestinal System	Patch 1 vs. Patch 2	0.20	[-0.02, 0.42]	η_p^2= 0.01 (Main Effect)	0.084
	Patch 1 vs. Patch 3	0.08	[-0.14, 0.30]		0.672
	Patch 2 vs. Patch 3	-0.12	[-0.34, 0.10]		0.411
Nervous System & Special Senses	Patch 1 vs. Patch 2	-0.12	[-0.62, 0.38]	η_p^2= 0.005 (Main Effect)	0.841
	Patch 1 vs. Patch 3	0.12	[-0.38, 0.62]		0.841
	Patch 2 vs. Patch 3	0.24	[-0.26, 0.74]		0.512
Gender Stratification	**Module / Cohort**	**Female vs. Male**	**95% CI**	**Cohen's *d***	**Independent *t*-test**
Minor Variance	Principles of Disease I (P1)	0.42	[0.08, 0.76]	d = 0.38	0.016*
Major Variance	Gastrointestinal System (P3)	1.30	[1.11, 1.49]	d = 1.18	<0.001*

*Statistically significant at $p < 0.05$; CI, Confidence Intyerval; Effect size: Cohen's d or Partial ηp2

3.6 Qualitative Perspectives from Students

To evaluate the pedagogical impact of the pharmacology simulation, student perspectives were captured across eight qualitative domains, stratified by gender to identify potential experiential variances, with comprehensive frequency distributions and corresponding Chi-square analyses provided in Appendix Table 9. The feedback revealed a notable perception of technical difficulty, as a significant majority of male students (53.7%) viewed the software application as "Complicated", a sentiment even more pronounced among female respondents (84.7%). Interestingly, despite this perceived complexity, the overall quality of the learning experience remained high for male students, with 81.6% providing "Good" or "Excellent" ratings; however, female students expressed lower satisfaction, with 61% rating the experience as "Bad".

Regardless of these experiential differences, the scientific rigor of the simulation was widely validated, as most students across both cohorts rated the content as "Good" or "Excellent". This

academic value likely contributed to a strong baseline student satisfaction regarding the digital transition in practical pharmacology, with 53.1% of males and 69.5% of females expressing positive feedback toward the simulated format. While the laboratory contents themselves received high marks, reaching 84.4% in males and 98.3% in females for "Good" or "Excellent" ratings, the perceived time-effectiveness varied by gender, with 42.9% of males describing the duration as "Short" while 61% of females categorized it as "Intermediate". Collectively, these results underscore a successful delivery of scientific content through a digital medium, though they highlight specific gender-based variations in technical navigation and time perception.

4. Discussion

The quantitative OSPE data demonstrates stable post-intervention learning outcomes across foundational modules, contrasted against a significant achievement plateau within the complex neuropharmacology block. Rather than establishing a direct causal impact, these localized performance trends must be interpreted alongside the cohort's qualitative feedback to map underlying cognitive processing variations.

The evaluation reveals a distinct divergence between objective assessment outcomes and subjective user experiences. While average scores remained high in foundational pharmacology and gastrointestinal systems, qualitative reports indicate that students encountered considerable technical friction, with a large segment characterizing the digital interface application as complicated. Interestingly, this negative perception did not covary with lower academic achievement parameters; for example, female cohorts in Patch 3 maintained high baseline averages despite reporting high interface friction. These findings mirror recent literature evaluating student perceptions toward simulation-based learning models, where subjective navigational challenges often coexist alongside high baseline appreciation for the pedagogical value of interactive simulations (14). Viewed through Cognitive Load Theory, this indicates that while the extraneous cognitive load imposed by software navigation was high, the germane load design was structurally sufficient to preserve conceptual acquisition.

This baseline stability across student patches suggests that simulation-based learning provides a steady pedagogical foundation for core concepts. The high averages achieved in foundational pharmacology align with expert assessments identifying the platform's utility in illustrating isolated drug-receptor interactions. However, the uniform achievement drop in the Nervous System module across all 308 students points to an instructional boundary. As pharmacology specialists noted, the standardized parameters of computerized software present linear biological trends. When students encounter the non-linear, unpredictable variables characteristic of neuropharmacology within an OSPE environment, this lack of conceptual depth can result in the observed drop in performance outcomes. Consequently, resolving this learning barrier requires moving away from software expansion toward specific curricular adjustments.

The divergence in the quality of the learning experience between male and female students warrants further investigation and may be attributed to different baseline levels of digital literacy or varying expectations of user interface design in educational software. Despite these challenges, the strong student consensus regarding the instructional utility indicates that students value the safety, control, and repeatability of simulation-based learning, even when the software itself is deemed less than intuitive. This alignment between expert calls for diverse references and the student struggle with software complexity suggests a clear need for a comprehensive digital orientation module. By providing students with technical onboarding before the practical begins, the cognitive load can effectively be shifted from navigating the software to mastering the pharmacological principles.

Based on this triangulation of student performance data and expert feedback, several refinements are proposed to optimize this new teaching strategy within pharmacology education. While the standalone simulation optimizes resource consumption and provides an ideal, "safe-failure" environment, pharmacology experts emphasized the pedagogical necessity of showcasing biological variability. Future iterations of this curriculum should consider a multi-layered instructional design where the virtual module is utilized for high-volume drug testing and dose-response curve visualization, followed by targeted high-fidelity media or expert video demonstrations. This allows students to contrast the idealized, mathematical results of a computer simulation with the unpredictable, non-linear biological kinetics often observed in live tissue models, particularly in complex modules like the Nervous System. To further bridge the gap between theoretical knowledge and clinical practice, simulated labs should be explicitly linked to hospital-based scenarios through interactive dispensing exercises, including drug dosage forms and administration devices, and virtual patient cases that require students to use simulation data to determine necessary investigations for monitoring drug toxicity.

Furthermore, the consistent challenge posed by the Nervous System module suggests that neuropharmacology requires either increased simulation time or a refined software approach; providing "take-home" simulation access and increasing the number of supervised sessions could significantly reduce cognitive load. Finally, incorporating gender-stratified feedback, educators should provide diverse preparatory materials, such as video demonstrations for visual learners and detailed procedure sheets for those prioritizing technical accuracy. Software optimization should specifically target the complexity paradox identified in student surveys, ensuring that the digital interface is streamlined to prevent technical hurdles from magnifying extraneous cognitive load and overshadowing scientific learning. Implementing these multi-faceted refinements will ensure a more robust, equitable, and clinically relevant learning experience for all medical student cohorts.

The consistency of the OSPE results across three patches suggests that simulation-based learning provides a stable pedagogical foundation for delivering core pharmacology concepts. The high mean scores in Principles of Disease II and the Gastrointestinal System align with the pharmacology experts' feedback, who noted that the simulation software is highly effective at allowing students to comprehend the isolated effect of drugs on tissue models. The precision of the scores in the GI module, particularly among Patch 3 females (8.7 ± 0.1), supports the assertion that simulation excels in the cognitive domain of drug-receptor interactions and standardized physiological responses. However, the consistently lower performance in the Nervous System & Special Senses module (means < 7.0) across all 308 students warrants closer inspection. While educators rated the logical sequence of the lab highly, the pharmacology experts identified a significant limitation inherent to digital modeling: the absence of organic variability. Experts cautioned that students often perceive simulated results as "typical" or linear, which may lead to oversimplification when faced with complex, non-linear neuropharmacology variables in an OSPE setting.

The educational outcomes observed in this standalone simulation framework mirror contemporary findings in the broader medical education literature regarding the validity of simulated assessments. Recent pedagogical studies assert that objective structured practical examinations effectively evaluate clinical and practical competencies acquired via digital simulation, providing robust metrics that align with our current modular results (16). However, the resource-intensive nature of launching this standalone project, requiring specialized software configuration and peer validation, echoes the administrative and operational demands identified in international simulation rollouts, which frequently cite the need for dedicated faculty training. The instructional preparation of our cohorts via overnight handouts and pre-briefings is strongly supported by recent literature on medical curriculum design, which emphasizes that pre-briefing

sessions are instrumental in reducing student anxiety and optimizing cognitive focus during standalone technology-based tasks (15). Furthermore, while our pharmacology results showed gender-specific nuances, they align with current longitudinal findings (3) regarding the capacity of simulation-based learning to stabilize student performance parameters across distinct cohorts, and ensuring that even abstract subjects like neuropharmacology move toward a more reliable, transferable, and realistic clinical training modality (5, 16).

Recommendation.

Based on the triangulation of student performance outcomes and expert feedback, several operational refinements are proposed to optimize the simulation framework. Future iterations should transition to a multi-layered instructional design where standalone software sessions for high-volume drug testing are paired with high-fidelity media demonstrations, allowing students to contrast idealized digital results with real-world biological variability. To bridge the gap between theory and clinical practice, these modules should be explicitly linked to hospital-based scenarios through interactive dispensing exercises and virtual patient cases that require students to utilize simulation data to monitor drug toxicity. Furthermore, targeted structural adjustments are required for high-cognitive load topics like neuropharmacology, which would benefit from increased supervised session hours and regulated, take-home software access. Finally, to mitigate the technical friction identified in student feedback, institutions must implement streamlined user interfaces alongside differentiated onboarding pathways, such as procedural sheets and orientation videos, ensuring that operational hurdles do not magnify extraneous cognitive load or overshadow core scientific learning.

5. Conclusions

- The implementation of a standalone simulated pharmacology laboratory across three distinct student patches was evaluated using a descriptive, mixed-methods approach. The post-intervention metrics show that students achieved satisfactory average scores in the foundational pharmacology, Principles of Disease I & II, and Gastrointestinal System OSPE stations, though performance consistently plateaued below optimal targets within the complex neuropharmacology module.
- The mixed-methods evaluation successfully highlighted that while academic outcomes were generally uniform across demographic groups, qualitative user experiences differed significantly by gender, highlighting a crucial need to address software onboarding barriers and interface usability. Rather than serving as a direct replacement for historical paradigms, these descriptive findings illustrate that virtual modeling provides a workable, resource-efficient standalone strategy for delivering core pharmacological concepts, provided that the technical interface is optimized to minimize student cognitive fatigue and is augmented by diverse visual media to capture biological variance.

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