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Improving grade 10 students' geometrical optics through blended predict, explain, enact, observe, and reflection inquiry-based learning

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Abstract

This study examines the impact of blended learning employing the PEEOR (Predict-Explain-Enact-Observe-Reflection) inquiry-based approach on Grade 10 students' conceptual understanding, science process skills, and motivation in geometrical optics. Although inquiry-based methods are recognized for promoting active learning, limited research has explored their integration with blended learning in science education. The study adopts a quasi-experimental quantitative design with 172 students randomly assigned to three experimental groups (blended lab, virtual lab, traditional lab) and one control group. Data were collected through pre-tests, post-tests, and a motivation questionnaire administered to the experimental groups. Findings indicate that all instructional approaches improved science process skills and conceptual understanding, with the blended learning group achieving the greatest gains. This group also demonstrated the highest motivation levels, suggesting that combining inquiry-based pedagogy with blended learning can enhance both cognitive and affective learning outcomes. The results underscore the value of blended learning frameworks in fostering deeper conceptual mastery and greater engagement in science education.

Keywords: Blended learning; inquiry-based learning; motivation; science education; student engagement

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1. INTRODUCTION

Exploring the natural world through scientific investigation has been a fundamental part of education for a long time, helping students connect with complex topics. In physics, geometrical optics stands out as an exciting area for such exploration, focusing on the rules that govern light and how it interacts with different materials. However, grasping concepts like how lenses and mirrors work, or how images are formed, can be tough for high school learners (Anderson & Thomas, 2021). Traditional teaching methods often struggle to meet diverse learning needs and fail to sufficiently motivate students.

Recent educational reforms underscore the importance of integrating science education into the learning process, with a strong emphasis on active student engagement in knowledge construction. This emphasis is particularly critical in physics, a discipline that addresses complex concepts and phenomena. Teaching physics, especially in areas such as geometric optics, presents considerable challenges due to the requirement for students to memorize and apply intricate formulas (Fitriani et al., 2022; Sasono et al., 2017). Geometric optics, which examines the interaction of light with mirrors and lenses, demands both a thorough conceptual understanding and the ability to apply knowledge in practice, as well as sustained motivation to master its core principles (Admoko et al., 2018; Ndihakubwayo et al., 2020).

Blended learning environments, which combine in-person instruction with digital resources, provide a strong foundation for inquiry-based learning (Marcellis et al., 2024). Applied to geometrical optics, the integration of traditional lessons with interactive digital tools can significantly enhance learning outcomes (McLaughlin & Farris, 2025). The PEEOR teaching strategy (Predict-Explain-Enact-Observe-Reflection) builds upon the POE (Predict-Observe-Explain) framework by adding an enactment stage, in which learners practice or demonstrate their understanding of a concept. This stage emphasizes hands-on learning, fosters connections to real-world contexts, and promotes reflection to identify areas for improvement. Such a process supports the development of metacognitive skills and learner autonomy. The present study addresses an identified gap in the literature by examining the effectiveness of PEEOR-based instruction in improving conceptual understanding and motivation in geometrical optics.

A contemporary adaptation, the Blended PEEOR model, merges structured inquiry with hands-on experimentation, enabling deeper exploration of concepts through practical engagement and reflective analysis. This approach provides a means of addressing specific instructional challenges in geometrical optics, such as the comprehension of light behavior and optical phenomena. The Blended PEEOR model seeks not only to strengthen conceptual understanding and practical skills but also to enhance learner motivation and interest. Empirical evidence supports its effectiveness: Smith and Cole (2022) reported that learners exposed to both inquiry-based and blended learning methods demonstrated greater improvement in comprehension and retention of complex physics concepts than peers in traditional classroom settings, while Pandey (2025) found that incorporating interactive digital tools in physics lessons significantly increased learner participation and motivation.

The present research investigated the impact of the Blended PEEOR inquiry-based model on Grade 10 students' knowledge, science process skills, and motivation in geometrical optics. By analyzing its effects on conceptual understanding, practical application abilities, and interest in the subject, the study aimed to identify effective strategies for delivering engaging and impactful physics instruction. The findings are of particular relevance as they demonstrate how the integration of active learning strategies with experimental inquiry can enhance comprehension, practical skill development, and engagement, thereby contributing to improved academic outcomes and heightened interest in physics.

1.1. Literature review

The scientific method involves systematic observation, hypothesis formulation, experimentation, and data analysis (Darmaji et al., 2018). Mastery of these skills is essential for conducting experiments related to light, mirrors, and optical systems in geometric optics. Effective scientific process skills enable students to design and evaluate experiments accurately, contributing to a deeper understanding of optical phenomena.

A solid grasp of optical geometry is fundamental for interpreting how light interacts with various optical components (Goldwater & Schalk, 2016; Taqwa & Taurusi, 2021). Understanding concepts such as light reflection, refraction, and the relationships between angles is critical for students. Misconceptions in these areas can significantly hinder learning (Lee & Kim, 2017; Akpan & Okon, 2019; He & Singh, 2020).

Student motivation is a key factor in learning, particularly in challenging subjects like geometric optics. Motivation can be driven by internal factors such as personal interest or external factors such as rewards and grades (Slavin, 2016). Motivated students are more likely to engage actively with the material, overcome challenges, and achieve better outcomes (Hidi & Renninger, 2006; Guo et al., 2022). Understanding and enhancing motivation can help educators design effective strategies to foster greater engagement in geometric optics.

Simulation has proven to be a valuable tool in science education, offering a bridge between theoretical knowledge and practical application (Chernikova et al., 2020; Adeyele, 2024). Blended laboratories, which integrate real experiments with virtual simulations, enhance students’ understanding by combining hands-on experience with digital learning (Dori & Belcher, 2022; Russell, 2021; Sun et al., 2025). Although blended learning generally outperforms traditional or virtual-only methods (Bernard et al., 2009; Means et al., 2013; Wong et al., 2023), there remains uncertainty about the optimal instructional strategies for physics, particularly in geometric optics (Gamage et al., 2022). This study aims to investigate how different instructional methods, including traditional experiments, virtual labs, and blended learning using the PEEOR inquiry-based approach, affect students' conceptual understanding, scientific process skills, and motivation.

1.2. Purpose of study

The primary objective of this study was to determine if there are significant differences in Grade 10 students' conceptual understanding, scientific process skills, and motivation in geometric optics when using traditional experiments, virtual labs, or a blended learning approach incorporating the PEEOR inquiry-based method. The study addressed the following research question:

RQ1- How do traditional experiments, virtual labs, and blended learning approaches incorporating the PEEOR inquiry-based method impact students' conceptual understanding, scientific process skills, and motivation in geometric optics at Woldia Secondary and preparatory Schools?

2. MATERIALS AND METHOD

This study employed a quantitative quasi-experimental design to assess the impact of a blended learning approach, incorporating virtual elements, on students' understanding, science process skills, and motivation in geometric optics. This design is suitable for educational research where random assignment is not feasible, allowing for comparisons between different instructional methods while controlling for confounding variables. Matching techniques and statistical controls were used as a pre-test to ensure comparability among the groups at baseline.

2.1. Participants

The study targeted 360 Grade 10 students from Woldia Secondary School and Woldia Preparatory School. From this population, a random sample of 172 students (4 sections) was selected to ensure adequate representation for the quasi-experimental design (Guetterman et al., 2019; Penn & Umesh, 2019). The samples were divided into four groups:

- **Blended Lab Group (n=40)**: Utilized both traditional and virtual lab methods.
- **Virtual Lab Group (n=43)**: Engaged exclusively in virtual simulations.
- **Traditional Lab Group (n=43)**: Conducted experiments using traditional lab equipment.
- **Control Group (n=46)**: Did not receive the experimental interventions.

Random sampling was performed using a random number generator to ensure the representativeness of the sample. Ethical approval was obtained from the schools, and informed consent was secured from all participants.

The study involved three experimental groups and one control group. Each group participated in six lab activities:

1. Reflection of Light from a Plane Mirror
2. Refraction of Light
3. Refraction of Light through a Prism
4. Total Internal Reflection
5. Focal Length of Convex and Concave Lenses
6. Color Addition and Subtraction

All groups followed the PEEOR (Predict-Explain-Enact-Observation-Reflection) inquiry-based instructional strategy, which integrates multimedia elements to enhance teaching. Each lab session took 42 minutes.

Blended Lab Group: Students watched videos of the experiments at home and performed the activities using traditional lab equipment for 15 minutes, followed by data collection with virtual labs for an additional 15 minutes.

Virtual Lab Group: Students watched experiment videos at home and conducted the entire lab session using virtual simulations for 30 minutes.

Traditional Lab Group: Students performed the experiments using lab equipment and materials for the full 30-minute lab session.

2.2. Data collection instrument

The study employed multiple methods to measure the research variables, such as:

Examinations: Pre- and post-test intervention exams, including multiple-choice questions to assess students' understanding of geometric optics and their scientific process skills. The exams were validated through expert reviews to ensure validity, and I used Cronbach's alpha to check reliability, which was valued at 0.76.

Motivation Questionnaire: A pre- and post-test intervention questionnaire was administered to evaluate students' motivation towards studying geometric optics. This questionnaire assessed performance objectives, perceived importance of learning physics, self-efficacy, engagement with active learning techniques (emphasizing the PEEOR approach), and stimulation of the learning environment.

Ethical considerations were addressed by obtaining necessary permissions from participating schools and ensuring informed consent from students and their guardians. Confidentiality of participant data was strictly maintained throughout the study.

2.3. Data analysis

The following sections present the results of normality tests for pre-test measures related to science process skills, conceptual understanding, self-efficacy, active learning strategies, physics learning value, performance goals, and learning environment stimulation. The accompanying tables provide the test statistics, degrees of freedom (df), and significance values for both the Kolmogorov–Smirnov and Shapiro–Wilk tests.

Table 1

Tests of Normality of science process skill, conceptual understanding, and motivation of the students

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Pre-test for science process skill	.190	113	.112	.930	113	.167
pre-conceptual understanding test	.131	113	.135	.958	113	.156
pre self-efficacy	.101	113	.145	.973	113	.124
pre-active learning strategy	.083	113	.142	.983	113	.178
pre-physics learning value	.087	113	.165	.977	113	.134
pre-performance goal	.095	113	.163	.983	113	.172
pre learning environment stimulation	.090	113	.134	.969	113	.165

a. Lilliefors Significance Correction

The results indicated that from the Shapiro-Wilk statistic (n<200) that all p-values were greater than the alpha level of .05. Thus, the data can be considered to follow a normal distribution. Therefore, the data was analyzed one way repeated ANOVA for science process skill tests and conceptual understanding tests, and MANOVA was used for the motivational subscale of physics learning of the students.

3. RESULT

Before delving into the specific results of the analysis, it's important to understand the context of the data being examined. In this case, we are analyzing the impact of different group interventions on students' science process skills using posttest data. This posttest analysis aims to determine if there are significant differences in science process skills among different groups after the interventions have been applied.

The table that follows presents the results of a test of Between-Subjects Effects for science process skills. This analysis assesses the effect of group membership on students' science process skills, including the overall impact of the intervention (intercept), differences between the groups, and the error term. The statistics provided will help us understand if the group interventions had a significant effect on enhancing students' science process skills.

Table 2

Science process skill tests of between-subjects effects

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.	Partial Eta Squared
Intercept	14067.221	1	14067.221	4168.328	.000	.971
groups	3.207	2	1.603	.475	.623	.008
Error	415.099	123	3.375			

Analysis of variance was performed to examine the effect of group membership on the dependent variable. The results (Table 2) showed a significant effect of interaction; this showed that all terms of the variance were significantly different from zero, $F(1, 123) = 4168.328$, $p < .001$, partial $\beta = .971$. A high partial eta squared value indicates that most of the change in the dependent variable is explained by the intervention. However, the main effect of group membership was not significant, $F(2, 123) = 0.475$, $p = 0.623$, partial $\beta = 0.008$. This shows that there is no significant difference between the different groups. The partial eta squared value was 0.008; This indicates that only a small portion of the variance in variance is explained by group membership. To further analyze the effectiveness of the different interventions on science process skills, it's important to review the mean scores of science process skills before and after the intervention for each group. This will help us understand how each intervention influenced the participants' skills over time.

Table 3

*Groups of participant * science process skill before(1) and after(2) intervention*

groups of participants	Science process skill	Mean	Std. Error
blended group	1	5.850	.291
	2	9.400	.274
virtual group	1	6.000	.281
	2	8.698	.265
traditional lab group	1	6.000	.281
	2	8.907	.265

The table 3 presents the mean (M) and standard error (SE) scores across the three groups of participants (blended, virtual, and traditional lab) and two science process skills (before and after). In the blended group with science process skill before intervention, the mean score is 5.85 (SE = 0.29. In the blended group with science process skill after intervention, the mean score was 9.40 (SE = 0.27). In the virtual group with science process skill before intervention, the mean score is 6.00 (SE = 0.28. In the virtual group with science process skill after intervention, the mean score is 8.70 (SE = 0.27). In the traditional lab group with science process skill before intervention, the mean score is 6.00 (SE = 0.28). In the traditional lab group with science process skill after intervention, the mean score is 8.91 (SE = 0.27).

To evaluate the impact of the interventions on students' conceptual understanding, it is important to analyze how changes in conceptual understanding vary across different groups. The following table provides detailed results from the Tests of Within-Subjects Contrasts, which examine the effects of interventions on students' conceptual understanding over time. "Linear" in this table indicates that the analysis is examining whether changes in conceptual understanding follow a straight-line trend over time and how this trend varies across different intervention groups. This approach helps in understanding if improvements in conceptual understanding are consistent and whether the interventions have differential impacts across groups.

Table 4

Conceptual understanding: Tests of within-subjects contrasts

Source	Conceptual understanding	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Conceptual understanding	Linear	366.085	1	366.085	122.469	.000	.422
Conceptual understanding * groups	Linear	120.766	3	40.255	13.467	.000	.194
Error(conceptual understanding)	Linear	502.187	168	2.989			

The linear contrast for the conceptual understanding factor was statistically significant, $F(1, 168) = 122.469$, $p < .001$, partial $\eta^2 = .422$. This indicates a significant linear trend in conceptual understanding scores across the levels of the within-subjects factor. The partial η^2 value of .422 suggests that 42.2% of the variance in conceptual understanding scores is attributable to the linear trend.

The interaction between the linear contrast of conceptual understanding and the groups factor was also statistically significant, $F(3, 168) = 13.467$, $p < .001$, partial $\eta^2 = .194$. This finding indicates that the linear trend in conceptual understanding scores varied significantly across the levels of the group factor. The partial η^2 value of .194 suggests that 19.4% of the variance in conceptual understanding scores is explained by this interaction.

Table 5

Pairwise Comparisons of conceptual understanding among groups

(I) groups of participants	(J) groups of participants	Mean Difference (I-J)	Std. Error
blended group	virtual group	2.410*	
	traditional lab group	3.015*	
	traditional teaching method groups	2.832*	
virtual group	blended group	-2.410*	
	traditional lab group	.605	
	traditional teaching method groups	.422	
traditional lab group	blended group	-3.015*	
	virtual group	-.605	
	traditional teaching method groups	-.183	
traditional teaching method groups	blended group	-2.832*	
	virtual group	-.422	
	traditional lab group	.183	

From table 5, the blended group had a significantly higher mean score compared to the virtual group (mean difference = 2.410, p < .001), the traditional lab group (mean difference = 3.015, p < .001), and the traditional teaching method groups (mean difference = 2.832, p < .001). The virtual group did not differ significantly from the traditional lab group (mean difference = 0.605, p = 0.485) or the traditional teaching method groups (mean difference = 0.422, p = 1.000). The traditional lab group did not differ significantly from the virtual group (mean difference = -0.605, p = 0.485) or the traditional teaching method groups (mean difference = -0.183, p = 1.000). The traditional teaching method groups had a significantly lower mean score compared to the blended group (mean difference = -2.832, p < .001). The traditional teaching method groups did not differ significantly from the virtual group (mean difference = -0.422, p = 1.000) or the traditional lab group (mean difference = 0.183, p = 1.00).

Table 6

Multivariate Tests[a] for motivation of the student in learning

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
Intercept	Pillai's Trace	.987	754.973[b]	10.000	101.000	.000	.987
	Wilks' Lambda	.013	754.973[b]	10.000	101.000	.000	.987
	Hotelling's Trace	74.750	754.973[b]	10.000	101.000	.000	.987
	Roy's Largest Root	74.750	754.973[b]	10.000	101.000	.000	.987
groups	Pillai's Trace	.574	4.103	20.000	204.000	.000	.287
	Wilks' Lambda	.452	4.927[b]	20.000	202.000	.000	.328
	Hotelling's Trace	1.157	5.786	20.000	200.000	.000	.367
	Roy's Largest Root	1.106	11.283[c]	10.000	102.000	.000	.525

A multivariate analysis of variance (MANOVA) was conducted to examine the effect of group type (blended, virtual, and traditional lab) on a combination of dependent variables: self-efficacy, PEEOR learning strategy, physics learning value, performance goals, and learning environment stimulation.

The results (Table 6) indicated a significant multivariate effect for the intercept across all four multivariate criteria: Wilks' Lambda: Λ=0.013, (10,101)= 754.973, p<.001 2= 0.987. The results also revealed a significant multivariate effect of the group type across all four multivariate criteria: Wilks' Lambda: Λ=0.452, (10,202)= 4.927, p<.001 2= 0.328

These results suggest that there are statistically significant differences between the blended, virtual, and traditional lab groups when considering the combined dependent variables. The partial eta squared values indicate that the group type explains a substantial proportion of the variance in the combined dependent variables.

Figure 1

Pairwise Comparisons of the student motivation scale among different groups

Level	subscale	self-efficacy		PEEOR inquiry based Approach model		physics learning value		performance goal		learning environment stimulation	
		M.d	sig	M.d	sig	M .d	sig	M.d	sig	M.d	Sig
Blended -virtual	pre	.076	1.000	.011	1.000	-.065	1.000	.005	1.000	-.009	1.000
-traditional		.175	.997	.277	.149	-. 071	1.000	-.058	1.000	.121	1.000
Virtual - blended	pre	-.076	1.000	-.011	1.000	.065	1.000	-.005	1.000	.009	1.000
-traditional		.100	1.000	.266	.177	-.006	1.000	-.064	1.000	.130	1.000
Traditional – blended	pre	-.175	.997	-.277	.149	.071	1.000	.058	1.000	-.121	1.000
-virtual		-.100	1.000	-.266	.177	0.06	1.000	.064	1.000	-.130	1.000
Blended -virtual	pos	.562*	.002	.422*	.005	.481*	.006	.622*	.000	.468*	.033
-traditional		.726*	.000	.643*	.000	.522*	.002	.550*	.001	.617*	.002
Virtual - blended	post	-.562*	.002	-.422*	.005	-.481*	.006	-.622*	.000	-.468*	.033
-traditional		.164	.905	.221	.272	.041	1.000	-.071	1.000	.148	1.000
Traditional – blended	post	-.726*	.905	-.643	.000	-.522	.002	-.550*	.001	-.617*	.002
-virtual		-.164	.000	-.221	.272	-.041	1.000	.071	1.000	-.148	1.000

Posttest comparisons indicated statistically significant differences between the blended group and the other groups (virtual laboratory and traditional laboratory) across all subscales (Figure 1). Relative to the virtual laboratory group, the blended group demonstrated higher scores in self-efficacy (M.D = 0.562, p = .002), PEEOR (M.D = 0.422, p = .005), performance goals (M.D = 0.481, p = .006), physics learning value (M.D = 0.622, p < .001), and learning goal orientation (M.D = 0.468, p = .033). Similarly, when compared to the traditional laboratory group, the blended group achieved higher scores in self-efficacy (M.D = 0.726, p < .001), PEEOR (M.D = 0.643, p < .001), performance goals (M.D = 0.522, p = .002), physics learning value (M.D = 0.550, p = .001), and learning goal orientation (M.D = 0.617, p = .002).

No statistically significant differences were observed between the posttest subscale scores of the virtual laboratory group and the traditional laboratory group, indicating that both groups were similarly motivated to learn physics following the intervention. These results suggest that blended learning may be more effective than either virtual or traditional laboratory instruction in enhancing motivation to learn physics.

4. DISCUSSION

The current research results indicated that science process skills differed significantly across learning environments. Participants in both traditional and virtual laboratories demonstrated significant improvements in science process skills, with scores increasing from 5.85 to 9.40. These findings align with previous studies by Cavanaugh et al. (2004) and Bayraktar and Geban (2017), who observed that integrating multiple learning environments can enhance science abilities. Cavanaugh et al. (2004) highlighted that combined instructional methods leverage the strengths of each approach, thereby contributing to a deeper understanding of science concepts. Similarly, Bayraktar and Geban (2017) noted that blended learning environments support diverse learning styles and increase student engagement, resulting in improved performance.

Bernard et al. (2009) indicated that the effectiveness of blended learning can vary depending on context. They suggested that blended environments do not always produce optimal outcomes, with success dependent on situational factors. The current study noted significant gains for participants in the combined traditional/virtual lab condition, suggesting that blended approaches may be particularly effective in certain contexts. Bernard et al. (2009) also found that virtual laboratories can be as effective as traditional labs in developing science skills. Consistent with this, the virtual lab group in the present study demonstrated a notable increase in science process skills, with scores rising from 6.00 to 8.70, indicating that virtual laboratories can serve as a viable alternative to traditional methods when properly designed and implemented. Xu and Jaggars (2014), however, cautioned that virtual labs may not be equally effective for all students, reflecting variability in outcomes and underscoring the importance of considering individual learning preferences.

Students engaged exclusively in traditional lab activities also showed significant improvement, with scores increasing from 6.00 to 8.91. This finding reinforces Hofstein and Lunetta's (2004) argument regarding the essential role of hands-on laboratory work in effective science education. Nonetheless, Hofstein and Mamlok-Naaman (2011) emphasized that traditional labs alone may not always suffice for enhancing learning, highlighting the need to integrate complementary instructional methods. Overall, the findings suggest that combining traditional and virtual learning environments significantly enhances science process skills, consistent with prior research on the benefits of blended learning, while also acknowledging contextual and individual variability.

The blended learning environment emerged as particularly effective. Participants in the blended group improved their performance, with mean scores increasing from 8.875 to 12.875, demonstrating the advantages of integrating traditional and digital instructional methods. These results corroborate the findings of Alammary et al. (2014), who reported that blended learning enhances conceptual knowledge acquisition by providing a richer learning experience through the combination of face-to-face and virtual elements. Bernard et al. (2009) similarly noted that virtual laboratories can improve conceptual understanding. In this study, the virtual group's mean conceptual score increased from 7.465 to 9.465, confirming the effectiveness of virtual lab settings. The traditional lab group also contributed to conceptual development, with mean scores rising from 6.581 to 9.140, supporting Hofstein and Mamlok-Naaman's (2011) assertion regarding the importance of hands-on laboratory work. The findings indicate that traditional approaches alone are insufficient for maximizing conceptual understanding and highlight the benefits of a blended approach. Overall, blended learning environments, combining traditional and virtual elements, substantially enhanced students' conceptual understanding, consistent with existing literature (Selcuk, 2018).

Regarding student motivation, the blended learning environment produced significant improvements in motivation toward studying physics. These results align with Means et al. (2013), who found that students in blended learning models, combining face-to-face and virtual components, demonstrated higher engagement and motivation compared to those in exclusively traditional or virtual settings. In this study, the blended lab group consistently exhibited the highest levels of motivation. While virtual and traditional labs also contributed to motivation, their effects were less pronounced. Xu and Jaggars (2014) noted that virtual labs may not sustain motivation as effectively as blended or traditional approaches, a finding reflected in the present study. Boelens et al. (2017) emphasized that blended learning enhances both motivation and self-regulation by providing flexible and varied learning experiences that promote student participation and responsibility. Domin (2008) suggested that traditional labs may not maximize motivation if activities become overly procedural; however, the current study demonstrated that traditional labs could still foster motivation when interactive elements are incorporated.

In conclusion, the present findings indicate that blended learning environments are highly effective in enhancing students' motivation. Traditional and virtual labs also contribute to motivation, but blended learning offers the most substantial gains, supporting the broader literature on the advantages of integrating multiple instructional methods.

5. CONCLUSION

The current research demonstrates that integrating traditional and virtual laboratory experiences significantly enhances students' science process skills. Participants in the blended learning group showed a substantial increase in mean scores from 5.85 to 9.40, highlighting the effectiveness of combining different instructional methods to foster a deeper understanding of scientific processes. This finding underscores the value of blended approaches in promoting practical scientific competencies.

The study also indicates that students achieve greater gains in conceptual understanding within a blended learning environment. The average score for the blended group increased markedly from M = 8.875 to M = 12.875. Virtual labs alone also contributed to conceptual growth, with scores rising from M = 7.465 to M = 9.465, consistent with the findings of Bernard et al. (2009). While traditional labs improved understanding from M = 6.581 to M = 9.140, their effect was less pronounced compared to blended and virtual approaches. This suggests that traditional methods, although essential, may be more effective when combined with other instructional strategies.

In terms of student motivation, the blended learning environment produced the highest improvements. Although motivation increased in traditional lab settings, from M = 6.581 to M = 9.140, the blended approach elicited even greater engagement and enthusiasm. These findings indicate that integrating traditional and virtual components maximizes motivational outcomes in physics learning.

Overall, the study concludes that blended learning environments provide the most substantial benefits across science process skills, conceptual understanding, and student motivation. While traditional and virtual labs individually offer unique advantages, their combination in a blended learning approach produces the highest educational gains. These results reinforce the importance of integrating multiple instructional strategies to optimize learning and engagement. Educators should therefore strive to develop integrated teaching methods that leverage the strengths of both traditional and virtual modalities.

To improve students' science process skills, educators should integrate both traditional and virtual laboratories into their teaching. The findings of this study indicate that a blended approach, combining hands-on and virtual activities, significantly enhances students' abilities in scientific processes by leveraging the strengths of each method. However, the effectiveness of blended learning can vary depending on the context and available resources. Therefore, schools and educators should carefully assess the specific needs of their students and the learning environment when designing interventions. Continuous evaluation and adaptation of teaching strategies are crucial to ensure that these approaches remain effective over time.

To strengthen students' conceptual understanding, adopting a blended learning environment that combines face-to-face instruction with virtual components is recommended. Virtual labs provide interactive opportunities for students to explore complex concepts and reinforce their understanding, making them an ideal complement to traditional laboratory experiences. Traditional labs, while still valuable, can be further enhanced by incorporating more interactive, inquiry-based activities that integrate with other modes of instruction. By thoughtfully designing both traditional and virtual components, educators can maximize the conceptual learning gains of their students.

Enhancing student motivation also requires careful integration of blended learning strategies. Learning environments that combine traditional and virtual approaches have been shown to foster higher levels of engagement and enthusiasm. Virtual labs, when designed with interactive and engaging features, can sustain motivation and encourage active participation. Similarly, traditional labs should be made more dynamic, moving beyond routine procedures to include problem-solving and inquiry-based activities that capture students' interest. Educators should also continuously evaluate how different teaching methods affect student motivation and adjust their approaches based on feedback and observed outcomes. This ongoing assessment helps create a learning environment that remains engaging and motivating for all students.

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