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Integrating Gamified Retrieval Practice and Online Collaborative Learning in Laser Physics

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Abstract

Physics concepts can be difficult for first-year engineering students to connect with practical applications, highlighting the need for blended learning designs that combine conceptual reinforcement with collaborative inquiry. This study explored CBRL–LASERCON, a two-phase framework integrating offline crossword-based retrieval practice with online convention-based collaborative learning in laser physics. A mixed-methods, single-group pre–post design involved 110 first-year mechanical engineering students. Assessment scores were compared descriptively and inferentially, while student feedback and reflections were examined to characterize learning experiences. Post-intervention assessment scores were higher than earlier scores, with a statistically significant but modest difference. Students generally reported positive experiences, particularly regarding engagement and opportunities for critical thinking, communication, and collaboration. The findings suggest that sequencing gamified retrieval activities before online presentations, discussions, and peer questioning may provide a useful structure for active learning in engineering physics. However, the absence of a control group and the use of non-equivalent pre- and post-intervention assessments prevent causal attribution or firm conclusions about learning gains. Further controlled research using equivalent assessments and delayed follow-up measures is needed to evaluate learning outcomes and retention.

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INTRODUCTION

Physics in engineering education has historically been recognized for providing the intellectual backbone of engineering curriculum through the enhancement of analytical reasoning, scientific investigation, and mathematical and problem-solving approaches required of technical fields of engineering. Typically, first-year engineering students perceive physics courses as abstract, complex, mathematically intensive and difficult conceptually (Freeman et al., 2014; Nauryzbayeva et al., 2025), particularly intricate subjects such as laser physics, physics of semiconductors, quantum mechanics, physics of wave optic and electromagnetic etc. Traditional lecture-based teaching often emphasizes passive content delivery and rote learning rather than providing for meaningful engagement with concepts, inquiry-based learning, and interdisciplinary applications (Prince, 2004). Consequently,

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engineering student motivation and engagement can be lower than it might be, leading to poor retention of concepts.

Contemporary STEM education active learning strategies increasingly prioritize strategies that enhance concept understanding, learner engagement, collaboration, and higher-order thinking (Theobald et al., 2020). (Freeman et al., 2014) emphasized active learning pedagogies that improve academic performance, scientific communication, and conceptual mastery by advancing students to engage actively in discussions, problem solving, and collaborative inquiry. Similarly, blended learning environments that integrate online and offline instructional experiences offer flexible participation, peer interaction, and retrieval-based reinforcement opportunities (Hrastinski, 2019; Müller et al., 2023). Research indicates that blended learning significantly enhances learner autonomy, engagement, and concept retention when instructional design emphasizes interaction over passive content consumption (De Bruijn-Smolders & Prinsen, 2024; Wiggins et al., 2017)

Consistent with the constructivist-centered and interactive pedagogical models described above, gamification has proven itself to be an effective pedagogy in engineering and science instruction, because challenge-centered environments enhance motivation, participation, and cognition of learners (Adinda & Mohib, 2020; Zhao & Cao, 2023). Psychologically engaging learning experiences that require problem-solving skills were established through games with puzzles, points, badges, time constraints, and levelled difficulties (Coelho et al., 2026; Sailer & Homner, 2020). Research meta-analyses have confirmed that gamification positively influences concept learning, learner satisfaction, and problem-solving skills in the STEM field (Huang et al., 2020). Retrieval-based learning, on the other hand, improves long-term memory through enhancing memory consolidation and promoting knowledge transfer through frequent acts of cognitive retrieval (Larsen, 2018; McDermott, 2021)

Collaborative learning pedagogies are equally vital in engineering education as professional practice demands teamwork, communication, interdisciplinary interaction, and collective problem solving (McQuade et al., 2020; Van Helden et al., 2023). Conventional-based learning (CBL) exemplifies a collaborative pedagogy wherein students engage in conference-style discussions, committee interactions, analytical questioning, and application-focused presentations. This approach aligns with constructivist learning theory, which posits that knowledge is actively constructed through dialogue, participation, and social interaction (Chand, 2023; Kieu Oanh & Hong Nhung, 2022; Mishra, 2023). Therefore, the use of collaborative inquiry environments contributes to developing critical thinking, scientific communication, and conceptual understanding (Irwanto, 2023; Priastuti et al., 2020).

The combination of gamified learning, reinforcement via retrieval, and collaborative inquiry (Lu et al., 2021; Van Helden et al., 2023) creates a theoretical basis for the Crossword-Based Reinforcement Learning (CBRL) pedagogical framework, aimed at improving learning, conceptual understanding, and long-term retention. In a crossword activity, students practice scientific vocabulary recognition, conceptual relationship formation, and critical reasoning while increasing motivation and reducing the fear and frustration of complex STEM concepts. Such techniques for reinforcement are important in engineering physics, where students often need to repeatedly retrieve and use scientific concepts in a variety of engineering situations.

Despite extensive work on active learning, blended learning, gamification, and online labs in engineering education, prior studies validate individual components in isolation and rely on mechanism-oriented blended models that do not specify how online and offline phases should interact to support physics conceptual reasoning and long-term retention (Van den Beemt et al., 2023; Wiggins et al., 2017) Existing inquiry frameworks for virtual and remote labs foreground online collaborative investigation but omit designed, offline retrieval-based reinforcement**,** while gamification studies focus on short-term engagement without testing whether specific game elements drive durable retrieval-based learning gains (Cigdem et al., 2024). Meanwhile, the body of research on active learning and blended courses in engineering has consistently noted conceptually vague definitions, non-discipline-specific classifications, challenges with student self-regulation, and the scarcity of studies that use appropriate and validated measures of retention and transfer, leaving educators lacking a clear, outcome-centered design framework for coordinating offline practice with online inquiry for complex, conceptually intensive disciplines like engineering physics (Sala et al., 2024)

Although previous studies have examined collaborative learning, gamification, retrieval practice, and blended learning approaches, these strategies have largely been investigated separately or in different combinations, with comparatively limited attention to their purposeful integration within Engineering Physics education. In the present work, the authors propose a blended pedagogical framework for Laser Physics as a case study that combines online Convention-Based Learning (LASERCON) with offline Crossword-Based Reinforcement Learning (CBRL). The proposed framework synergizes collaborative inquiry, gamified learning, retrieval practice, and blended learning principles to promote conceptual understanding and student engagement in Engineering Physics.

METHOD

Research Design and Instructional Framework

The research employed a mixed-method, single-group pre and post-comparative design (Moon et al., 2024) to examine the efficiency of a blended instructional model that combined offline gamified reinforcement learning with an online Convention-Based Learning environment. The intent of this design was to explore changes in students' performance and participation within the same cohort before and after the blended intervention. Because no parallel control group was included, the study provides associational, design-based evidence rather than strong causal claims about the impact of the intervention (Tejeswini et al., 2024).

The intervention was implemented in two sequential phases during regular instructional hours. The first phase involved offline Crossword-Based Reinforcement Learning (CBRL), followed by the second phase involving the online Convention-Based Learning environment, LASERCON 2025. The CBRL phase comprised 2 sessions of approximately 1 hour each, conducted on alternate weeks. The LASERCON phase comprised 2 hours of online sessions of approximately 30 minutes each. Thus, the two components were implemented sequentially rather than as separate experimental groups.

The two-phase instructional model began with offline reinforcement of key concepts through gamified crossword activities generated using freely available crossword-creation websites. These crosswords targeted term recognition, conceptual association, and retrieval practice (Torres et al., 2022). Students worked individually and in groups of 3–4 while solving crosswords, with the aim of promoting active recall, peer explanation, discussion of concepts, and collaborative learning. In this phase, instructors designed clues for key concepts/keywords at easy, moderate, and difficult levels; these clues and their corresponding answers served as input for the crossword-generation tools.

During the CBRL sessions, the instructor introduced or briefly reviewed the relevant laser-physics concepts, provided the crossword activity, monitored individual and group participation, encouraged peer explanation and discussion, and clarified misconceptions following completion of the activity. Group allocation was based on pre-existing classroom groups, with 3–4 students per group. In CBRL, we retained the pre-defined classroom groups to ensure continuity of peer interaction, facilitate equitable participation, and minimize disruption to the regular classroom setting while supporting collaborative learning and peer-based knowledge construction.

The second phase involved an online Convention-Based Learning environment, termed LASERCON 2025, in which students engaged in collaborative presentations, committee-style debates, peer questioning, voting sessions, and reflective discussions supported by learning technologies (Ahshan, 2021) listed in Table 1. This phase emphasized inquiry, argumentation, and collective knowledge building around laser-physics topics.

During LASERCON 2025, students were organized into 5 groups and participated in a structured sequence of collaborative presentations → committee-style discussions/debates → peer questioning → voting → reflection. The instructor acted primarily as a facilitator by organizing the activities, providing topic-related guidance, monitoring group discussions, encouraging questioning and argumentation, clarifying conceptual issues when required, and facilitating reflection at the end of the activities. To support the online collaborative activities in LASERCON 2025, several digital tools were used for videoconferencing, collaborative presentations, interactive polling, and resource sharing.

Table 1. Various Digital Resources Adopted for Facilitating Collaborative Work

Digital Tool	Purpose
Microsoft Teams	Video conferencing and breakout discussions
Google Slides	Collaborative presentations
Mentimeter/Kahoot	Interactive polls and quizzes
Google Classroom	Resource sharing and discussions

The combined framework therefore enabled examination of students' academic performance, participation, and learning experiences following the sequential implementation of offline retrieval-based reinforcement and online collaborative inquiry. However, because the pre- and post-intervention academic assessments were not identical or psychometrically equivalent instruments and no control group was included, the observed differences are interpreted as changes in assessment performance over time rather than as direct measures of learning gain or definitive evidence of the causal effectiveness of the blended framework.

Participants

The studies involved first-year Mechanical Engineering students enrolled in an undergraduate Engineering Physics course. Students were recruited through convenience sampling based on their enrolment in the course and availability during the instructional intervention. Their demographic and educational characteristics, along with the rationale for participant selection, are summarized in Table 2.

This particular class was considered suitable because both theoretical and practical sessions were organized for the same group of students, facilitating the systematic implementation of offline gamified reinforcement tasks and online Convention-Based Learning activities during regular teaching hours. All students had previously studied fundamental physics at the higher secondary level but had no prior experience with either gamified reinforcement learning or cooperative, convention-based pedagogies.

Table 2. Participant Characteristics and Study Context

Parameter	Description
Participants	110 Students
Educational Level	First-year undergraduate
Stream	Mechanical Engineering
Course	Engineering Physics
Sampling Method	Convenience sampling

Data Collection, Instruments, Evaluation, and Analysis

Quantitative Performance Data

Quantitative data were collected primarily through a mid-term examination administered after completion of the offline gamified reinforcement and the online Convention-Based Learning modules. These post-intervention mid-term scores were benchmarked against earlier internal assessment scores obtained prior to the implementation of the blended approach for the same cohort of students.

The pre-intervention assessment was an earlier Internal Continuous Assessment (ICA), whereas the post-intervention assessment was the mid-term examination on the same topic where conceptual evaluation is done at all cognitive level is done. The ICA covered the full laser chapter with conceptual as well as numerical questions in the MCQ, while the mid-term examination focused on the full chapter of laser in the form of numerical and theory at a slightly higher cognitive level. The ICA consisted of 10 MCQ questions, with a maximum raw score of 5 marks. The mid-term examination consisted of 5 descriptive theory and numerical questions, with a maximum raw score of 20 marks. For reporting and paired comparison, the two raw scores were expressed on a common 0–10 scale (ICA score/5 × 10; mid-term score/20 × 10). The ICA was administered approximately 5 days before the intervention, whereas the mid-term examination was conducted approximately 15 days after completion of the intervention.

Both the internal assessment and the mid-term evaluated conceptual knowledge, analytical capability, solution interpretation, practical application, and overall comprehension. The pre-intervention assessment was an earlier Internal Continuous Assessment (ICA), whereas the post-intervention assessment was a mid-term examination covering the same laser-physics topic, with conceptual understanding evaluated across different cognitive levels. The ICA covered the complete laser chapter and included both conceptual and numerical questions presented in a multiple-choice format. It consisted of 10 MCQ items, with a maximum raw score of 5 marks. In contrast, the mid-term examination also covered the complete laser chapter but assessed conceptual understanding and numerical problem-solving at a relatively higher cognitive level through five descriptive questions comprising both theoretical and numerical components, with a maximum raw score of 20 marks. For analysis, the pre-intervention ICA and post-intervention mid-term raw marks were converted to scores out of 10 using their respective maximum possible marks. The ICA was administered approximately five days before the intervention, whereas the mid-term examination was conducted approximately 15 days after completion of the intervention, covering relevant engineering-physics concepts, with a specific emphasis on laser-physics topics in the mid-term.

Although both assessments addressed overlapping learning outcomes related to conceptual understanding and application of Engineering Physics, they were not designed as parallel or equivalent forms of the same test. Differences in topic coverage, question composition, difficulty, and timing may therefore have contributed to differences in observed scores. Accordingly, the comparison was used to examine an exploratory change in assessment performance within the same cohort rather than to estimate a standardized learning gain. Comparing these pre-intervention internal assessment scores with the post-intervention mid-term scores enabled examination of changes in student performance over time.

Instruments for Participation

As listed in Table 3, learners' involvement and participation, as well as their interaction, communication, teamwork, and higher-order skills, were assessed using a combination of structured feedback questionnaires, teacher observation sheets, and written reflection forms during both the offline and online learning phases.

The student questionnaire comprised 10 items assessing perceived engagement, collaboration, confidence, conceptual understanding, communication, and perceived learning experiences. Responses were recorded on a five-point Likert scale ranging from 1 = strongly disagree to 5 = strongly agree. The observation sheet was used to record indicators related to participation, interaction, communication, collaboration, questioning, and engagement during the instructional activities. Written reflection forms provided students with an opportunity to describe their learning experiences and perceptions of the CBRL and LASERCON activities.

Table 3. Student Performance and Participation were Evaluated using Rubric-based Criteria

Evaluation Criteria	Assessment Focus
Conceptual Understanding	Clarity and application of laser physics concepts
Collaboration	Participation in group discussions and activities
Critical Thinking	Analytical questioning and reasoning
Communication Skills	Presentation and discussion quality
Engagement	Participation during offline/virtual sessions

The questionnaire was designed to assess students' perceived engagement, collaboration, confidence, and learning gains. Both the items and the rubric criteria were drafted based on prior research on active and collaborative learning in engineering education and were tailored to the laser-physics context (Hussain et al., 2026; Xu et al., 2024). Draft questionnaire items and rubric descriptors were examined by faculty members with expertise in engineering pedagogy to evaluate content relevance and clarity, and were subsequently refined based on their feedback. The principal aim of this study was to design and assess the feasibility of a blended instructional framework. Accordingly, the questionnaire and rubric should be viewed as exploratory, context-specific instruments.

The performance rubric targeted five outcomes: conceptual understanding, communication, collaboration, critical thinking, and engagement, which are consistently highlighted in engineering education assessment frameworks (Chen et al., 2022; Zhang & Tse, 2025). The descriptors were independently reviewed by three engineering faculty members to establish content validity by judging whether each descriptor appropriately represented its intended outcome (Reynders et al., 2020). This expert review was used as preliminary evidence of content relevance and alignment; however, formal construct validity, internal-consistency reliability, and inter-rater reliability were not established in the present study.

Minor modifications were made following expert feedback to enhance descriptor clarity before classroom implementation, in line with iterative approaches to rubric development. A common rubric was used to evaluate students' performance during their respective offline and online activities rather than independently scoring the same student work. This review provides preliminary evidence of content alignment but does not yet address broader forms of validity, such as interrater reliability or construct validity; further studies are needed in the future.

Data Analysis

Data analysis focused on pre-intervention ICA and post-intervention mid-term scores expressed on a common 0–10 scale, together with questionnaire ratings. Descriptive statistics, including means, standard deviations, medians, and percentages, were calculated for the ICA scores and each questionnaire item in order to summarize academic performance and student perceptions (Haryati et al., 2025). To examine changes in academic performance, pre-intervention ICA and post-intervention mid-term scores for the same students were compared using a paired-samples t test when the distribution of the paired difference scores satisfied the normality assumption. When the normality assumption was not satisfied, the Wilcoxon signed-rank test was used as the non-parametric alternative. For this assessment comparison, Cohen's d for paired samples was calculated to quantify the magnitude of the observed difference. Questionnaire responses were collected using a 5-point Likert scale and were summarized using medians, means, standard deviations, and response percentages (Zumrawi & Macfadyen, 2023). The questionnaire findings were interpreted primarily as descriptive evidence of a student perception of conceptual understanding, collaboration, communication, critical thinking, and engagement in the crossword-based reinforcement and online LASERCON activities. Because the questionnaire data did not include comparable pre-intervention and post-intervention ratings, no paired inferential test was applied to the questionnaire responses.

RESULTS AND DISCUSSIONS

Successful engineering learning requires instructional approaches that support not only conceptual learning but also opportunities for retrieval, application, communication, and collaboration. With these needs in mind, a blended instructional model was implemented using Crossword-Based Reinforcement Learning (CBRL) and LASERCON Convention-Based Learning (CBL) for first-year Mechanical Engineering students studying laser physics within the Engineering Physics course.

Blended Pedagogical Framework

The blended pedagogical framework combining CBRL and LASERCON is illustrated in Figure 1. The framework draws on retrieval practice, constructivist learning, and collaborative inquiry and was designed to provide a progression from conceptual acquisition and reinforcement to collaborative interpretation and application.

The framework followed two sequential phases. In the first phase, students engaged in offline crossword-based reinforcement activities following concept-cluster learning. The activities required students to retrieve and repeatedly practice key concepts through structured clues, thereby supporting conceptual consolidation and familiarity with scientific terminology and principles. This phase was intended to establish conceptual readiness for the subsequent learning activities. The second phase involved LASERCON Convention-Based Learning, an online collaborative learning environment in which students applied the reinforced concepts to engineering-related problems. Students participated in committee discussions, presentations, questioning, and application-

oriented tasks. The emphasis consequently shifted from retrieval and reinforcement towards interpretation, communication, collaboration, and application. Through peer interaction, students had opportunities to articulate, justify, and develop their understanding. Thus, the framework provided a structured progression from individual retrieval and reinforcement to collaborative interpretation and application.

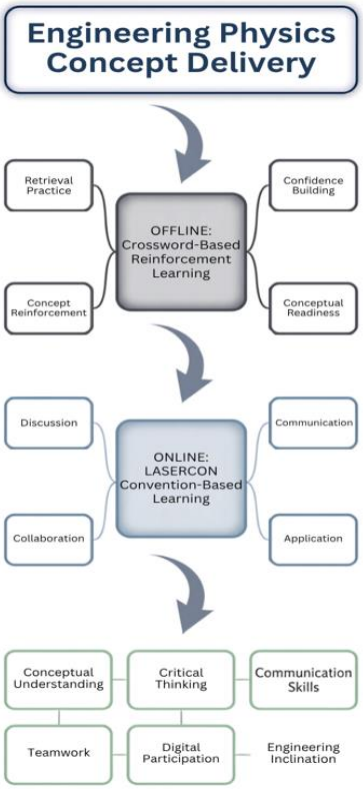


Figure1. Two-level Framework Design for Crossword-Based Reinforcement Learning (CBRL) and Convention-Based Learning (CBL)

Student Characteristics and Need for Pedagogical Intervention

Initial classroom observations, one-to-one discussions during mentoring sessions, and classroom participation indicated varying levels of preparedness and learner involvement. Based on these observations and mentoring interactions, approximately 10%, 20%, and 70% of students were broadly characterised as self-motivated, interested, and demotivated, respectively (Figure 2). This classification was observational rather than based on a validated motivation or engagement instrument. The categorisation considered students' observed classroom behaviour, participation, responses during initial activities, and interactions during mentoring sessions.

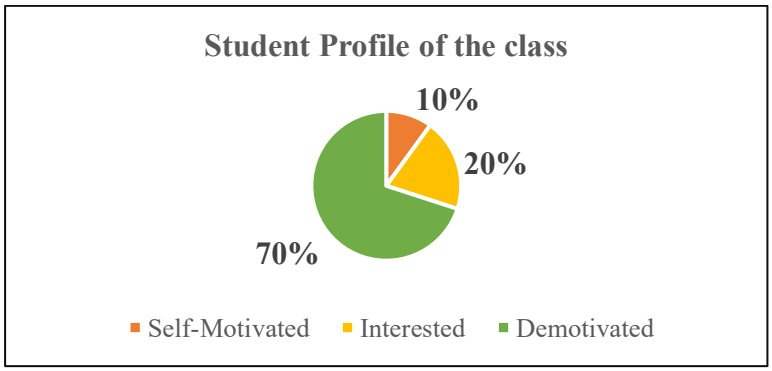


Figure 2. Students' Distribution Based on Varying Degrees of Preparedness and Learner Involvement in the Class

Approximately 10% of students demonstrated strong self-motivation and active interest in their chosen branch, while approximately 20% showed interest in pursuing engineering irrespective of their specific branch. The remaining 70% displayed comparatively lower initial involvement. Informal discussions with these students indicated factors including parental or peer influence, non-availability of their preferred branch, or alternative career interests. These observations indicated heterogeneity in students' initial engagement and highlighted the need for structured conceptual reinforcement and active learning opportunities in the Engineering Physics classroom. This observation is consistent with the challenges reported in first-year engineering education, where students may require additional conceptual reinforcement and engagement-oriented learning activities (Nelavai & Ramesh, 2020). The abstract nature of many Engineering Physics concepts may further make it difficult for students to connect theoretical principles with engineering applications (Hake, 1998).

Figure 3 clearly shows that students were more actively involved in learning and showed increased participation after implementation of the blended pedagogy. The participation level increased from 50% during conventional lecture learning to 88% after the crossword reinforcement, and engagement level rose to 92% after the online collaborative learning. Both these values indicate that the intervention provided a more active and participative learning experience than traditional classroom learning.

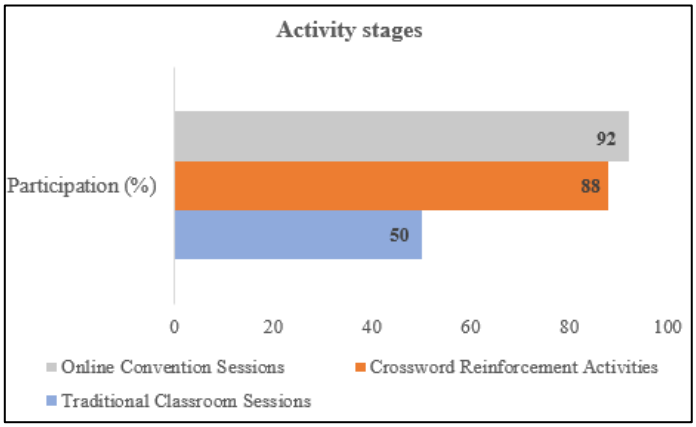


Figure 3. Students' Participation Comparison of Traditional vs Pedagogical Intervention

In the typical lecture sessions, students remain quiet throughout, and it is noticed that most of the students remain non-participatory. The use of crossword puzzles helped to overcome this by requiring students to infer answers from clues, retrieve scientific information, collaborate with fellow students, and communicate in group work. Even those students who normally would hesitate to answer questions during a lecture started to feel encouraged to provide answers while attempting to solve the crossword puzzle using scientific concepts. This activity seemed to invoke curiosity and a sense of accomplishment for them as they tried to complete one clue after another and connect them with their existing scientific knowledge. This crossword activity had the psychological impact of active participation, confidence in recollection of scientific terms, and less fear or anxiety about answering questions in an academic setting. Due to repeated recall of the terms coherence, stimulated emission, and population inversion, the scientific concepts became firm and strong in the learner's mind (Corral & Carpenter, 2025; Larsen, 2018). This matches with reports about the success of game-based learning environments in increasing student motivation, participation, and engagement in STEM learning (Gui et al., 2023; Wang et al., 2022; Zhao et al., 2022).

Impact of Online Convention-Based Learning, Combined with Offline Gamified Reinforcement Learning

The online collaboration activity, on the other hand, helped in strengthening the concepts learned in the crossword activity further and applying them to the real-world situation (Angeioplastis et al., 2025; Strielkowski et al., 2025). By that time, students had reinforced scientific concepts and then started to discuss the various applications of lasers in different fields. Students

participated more and more enthusiastically in discussions. The interaction was very fruitful, with students debating over the various issues and asking pertinent questions. Students felt very free and confident in the virtual classroom in presenting their thoughts and interacting with the students from the online learning platform. Psychologically, it made students feel they were part of a team, owning their learning, and felt connected through this activity. They also felt more confident in their own abilities because they were using the already learned information and applying it to concrete situations and getting feedback from others. Digital devices, instead of creating a distraction, helped in the construction of knowledge through collaboration.

Another interesting observation was that both activities aided in different aspects of learning; the crossword activities enhanced recall, concept reinforcement, and confidence, while the online collaborative activity stimulated higher-order concepts such as application, interpretation, and discussion (Hamzah et al., 2024). This sequence is probably what made it so successful because the students already had concrete scientific concepts before joining the online collaborative session, which made them feel more confident while exchanging ideas with their peers. This may be another reason for the enhanced student participation and engagement.

Mid-Term Performance Analysis

The blended pedagogy was implemented during regular classes to examine changes in the students' academic performance following the combination of offline crossword-based reinforcement and online CBL through LASERCON. Accordingly, pre-intervention and post-intervention paired assessment scores of a total of 110 students (both expressed out of 10) were included in the analysis. As observed in Table 4. The mean ± standard deviation (SD) was 5.44 ± 2.89 before intervention and 6.35 ± 2.26 after intervention on the common 0–10 scale, representing a mean paired difference of 0.90 points (based on unrounded values). The distribution of the paired difference scores was examined using the Shapiro-Wilk test. The result did not indicate a significant departure from normality (W = 0.990, p = 0.575). Therefore, a paired sample t-test was used as the primary statistical analysis.

Table 4. Descriptive and Inferential Statistics of Pre-Intervention ICA and Post-Intervention Mid-Term Scores (0–10 scale)

Statistical Parameter	Formula	Result
Number of students	n=number of paired observations	110
Pre-intervention ICA (0–10), mean ± SD	$\bar{X} = \frac{\sum X_i}{n}$ Raw mid-term / 20 × 10	5.44 ± 2.89
Post-intervention mid-term (0–10), mean ± SD		6.35 ± 2.26
Mean paired difference (0–10 points)	$d_i = X_{post,i} - X_{pre,i}$ $\bar{d} = \frac{\sum d_i}{n}$	0.90
SD of paired differences (0–10 points)	$SD_d = \sqrt{\frac{\sum(d_i - \bar{d})^2}{n-1}}$	2.46
95% CI of mean paired difference (0–10 points)	$CI_{95\%} = \bar{d} \pm t_{0.975,n-1}\left(\frac{SD_d}{\sqrt{n}}\right)$	0.44 to 1.37
Shapiro-Wilk test	$W = \frac{(\sum a_i X_{(i)})^2}{\sum(X_i - \bar{X})^2}$	W=0.990
Shapiro-Wilk p-value	$p = P(W \leq W_{observed} \mid H_0)$	0.575
Paired samples *t* test	$t = \frac{\bar{d}}{SD_d/\sqrt{n}}$	t (109)=3.856
p value	two-tailed p-value of the paired samples t-test	< 0.001
Cohen's d	$d_z = \frac{\bar{d}}{SD_d}$	0.37
Wilcoxon signed-rank test	$W = \min(W^+, W^-)$	W=1503.0
Wilcoxon *p*-value	Two-sided probability associated with the observed Wilcoxon statistic	< 0.001

The paired t-test indicated a statistically significant increase in scores on the common 0–10 reporting scale from the pre-intervention assessment to the post-intervention assessment, $t(109) = 3.856$, $p < 0.001$. The 95% confidence interval for the mean improvement ranged from 0.44 to 1.37 marks. The corresponding paired size was Cohen's $d = 0.37$, indicating a small to moderate magnitude of change. As a sensitivity analysis, the Wilcoxon signed-rank test was also conducted and produced a consistent statistically significant result ($W = 1503.0$, $p < 0.001$). At the individual student level, 65 students (59.1%) showed an increase in their standardized assessment score, while 35 students (31.8%) showed a decrease and 10 students (9.1%) showed no change.

These findings indicate an overall improvement in academic performance within the participating cohort following implementation of the blended pedagogical approach (Bond et al., 2020; Theobald et al., 2020). The reduction in the standard deviation from 2.89 in the pre-intervention assessment to 2.26 in the post-intervention assessment also suggests that the distribution of student performance became somewhat less variable after intervention. However, the study followed a single-group design without a parallel control group. Therefore, the observed improvement represents a change within the participating cohort and should not be interpreted as definitive evidence that the blended framework alone caused the improvement.

The possible explanation for this change is the complementary sequence of the two pedagogical activities (Bou Saad et al., 2025; Carpenter, 2020). The reinforcement through crossword puzzles provided students with repeated retrieval of important concepts and terminology, allowing them to practice difficult topics through an interactive learning activity. Repeated retrieval and practice may support conceptual recall and provide students an opportunity to revisit concepts that may otherwise be difficult to retain through conventional instruction alone. The collaborative nature of the crosswords activity also provided an opportunity for peer discussion and explanation while solving the clues.

The subsequent online CBL activity, LASERCON, extended the learning process beyond concept retrieval towards discussion, application, questioning, presentation, and interpretation of laser physics concepts (Nungu et al., 2023; Zabolotna et al., 2025). Students were allowed to discuss laser applications in engineering, medical, and industrial contexts and to communicate their understanding with peers. This progression from retrieval - reinforcement - collaborative application is consistent with the intended design of the blended framework. Research on active, collaborative, and blended learning has similarly reported potential benefits for student engagement, participation, and learning experiences in STEM education (De Bruijn-Smolders & Prinsen, 2024; Hrastinski, 2019; Sandrone et al., 2021).

The questionnaire findings provide additional descriptive evidence regarding students' perceptions of these learning activities (Table 5). A total of 110 students responded to a 10-item questionnaire using a five-point Likert scale. The overall questionnaire mean was 3.98 out of 5, indicating positive students' perceptions of the blended learning activities. Among the five assessed dimensions, engagement received the highest mean rating (4.37), followed by critical thinking (4.03), conceptual understanding (3.94), collaboration (3.94), and communication (3.62).

Table 5. Questionnaire Score for Learning Dimension

Learning Dimension	Questionnaire items	Mean Score
Conceptual understanding	Q1, Q6	3.94
Collaboration	Q2, Q7	3.94
Communication	Q3, Q8	3.62
Critical thinking	Q4, Q9	4.03
Engagement	Q5, Q10	4.37
Overall mean Score		3.98

The crossword-based reinforcement component received an overall mean rating of 4.16 out of 5, whereas the online LASERCON component received a mean rating of 3.80 out of 5. The higher rating for the crossword component indicates that students reported a particularly positive perception of the reinforcement activity. However, this comparison should be interpreted as a difference in student perceptions of the two instructional components, rather than evidence that one

component was more effective than the other. The questionnaire was not administered as a comparable pre-intervention and post-intervention measure, and therefore no paired inferential test was applied to these questionnaire responses.

Among the individual questionnaire dimensions, engagement showed the strongest overall perception, with a mean of 4.37. This finding is consistent with the intended role of gamified reinforcement and collaborative learning in encouraging active participation. Critical thinking also received a relatively high mean rating of 4.03, suggesting that students perceived the activities as providing opportunities to connect concepts, analyse questions, and justify their responses. Conceptual understanding and collaboration both received a mean rating of 3.94, indicating generally positive perceptions in these areas. Communication received the lowest mean rating of 3.62. In particular, the online communication item showed greater variation in responses than the other questionnaire items, suggesting that the online component may have provided different levels of opportunity or confidence for students to communicate their ideas.

From a pedagogical perspective, the findings suggest that the combined sequence of retrieval-based reinforcement followed by collaborative application may provide a useful learning structure for engineering physics. The crossword activities offered students opportunities to retrieve and reinforce fundamental concepts, while LASERCON provided opportunities for discussion, questioning, presentation, and application of those concepts. The change in scores on the common assessment reporting scale, together with the generally positive questionnaire responses, suggests that the framework was associated with both improved academic performance and favourable student perceptions within this cohort.

Nevertheless, these findings should be interpreted cautiously. The statistically significant increase in scores on the common 0–10 scale demonstrates a measurable change between the two assessments, but the absence of a control group means that alternative explanations such as normal academic progression, differences between assessments, previous learning, or other classroom experiences cannot be ruled out (Chang & Hung, 2014; Hammert et al., 2024). Similarly, the questionnaire results represent students' perceptions and should not be treated as direct evidence of learning effectiveness. The present findings therefore provide preliminary, associational evidence supporting the feasibility and potential value of the blended pedagogical framework rather than definitive causal evidence of its effectiveness.

LIMITATIONS

This study has the following limitations: participants were selected through convenience sampling from a single cohort of first-year Mechanical Engineering students from one single institution; therefore, these findings cannot be generalized. The single-group pre- and post-interventions were conducted; therefore, the improvements should be considered as preliminary associational evidence. These interventions were conducted over short, single semesters and only focused on laser physics; long-term retention was not assessed through a delayed post-test. Additionally, the questionnaire and rubric were exploratory, context-specific instruments. Although their content was reviewed by faculty members, formal construct validation, reliability estimates, and interrater reliability were not established. Further studies should therefore use larger and more diverse samples, controlled comparative designs, longer intervention periods, delayed retention measures, and formally validated instruments to provide stronger evidence regarding the effectiveness and generalizability of the proposed framework.

CONCLUSION

The present study contributes to engineering physics education by illustrating how the CBRL–LASERCON framework can integrate offline concept retrieval and reinforcement with online collaborative learning to support the teaching of laser physics. The observed improvement in students' performance, together with their generally positive perceptions of engagement and critical thinking, provides preliminary associative evidence supporting the potential value of this integrated instructional approach. Importantly, given the single-group, non-controlled design, these findings should not be interpreted as definitive evidence of intervention effectiveness. The study nevertheless offers a pedagogical framework for structuring sequential retrieval, collaborative discussion, and

conceptual application within engineering physics instruction. Future research should employ controlled and preferably multi-group designs, larger and more diverse student populations, equivalent and validated assessment instruments, and delayed post-intervention assessments to determine whether the observed learning gains are attributable to the framework and sustained over time. Such investigations would provide stronger evidence regarding the effectiveness, generalizability, and long-term educational value of CBRL–LASERCON.

AUTHOR CONTRIBUTIONS

NCD and AH conceptualized and designed the study. NCD developed the offline Crossword-Based Reinforcement Learning (CBRL) pedagogy and led its classroom implementation, while AH developed and implemented the online LASERCON component. NCD and AH conducted the fieldwork, data collection, and initial data analysis. AS contributed to the research methodology, validation, interpretation of the findings, and critical revision of the manuscript. VRP contributed to the development of the instructional framework, interpretation of the results, and review of the manuscript. SM contributed to data interpretation, methodological review, and critical revision of the manuscript. KS contributed to the validation of the pedagogical framework, interpretation of the findings, and review and editing of the manuscript. All authors contributed to the preparation of the manuscript, reviewed and approved the final version, and agreed to be accountable for the work.

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