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ORIGINAL ARTICLE

The Influence of Technology-enhanced Brain-based Learning on the Science Understanding and Performance of First-year Undergraduate Engineering Students

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ABSTRACT

This study examines the impact of technology-enhanced, brain-based learning (BBL) on the science understanding and performance of disadvantaged students in South Africa. The research employed an experimental design, involving 18 students in the control group and 23 in the experimental group. These students were assessed at a University of Technology in South Africa over six consecutive sessions, focusing on a challenging physics concept, fluid mechanics, which is not covered in the school syllabus. The teaching intervention incorporated BBL strategies supported by technology, integrating current neuroscientific insights with evidence-based pedagogical approaches in the classroom. A science achievement test was administered before and after the intervention, along with a structured Likert-scale questionnaire. The findings suggest that the intervention positively influenced science understanding and performance. Participant feedback indicated that 91.3% felt optimistic that the intervention helped them better grasp science concepts. The statistical analysis shows that the experimental group exhibited greater improvement in science scores than the control group, although the difference was not statistically significant.

KEY WORDS: Brain-based learning, science performance, technology

INTRODUCTION

It is widely accepted that a country's economic growth and scientific achievements are positively correlated (Mullis et al., 2020). Unfortunately, poor facilities and ineffective teachers have frequently been blamed for low academic achievement in science teaching in South Africa, and the legacy of the apartheid government is still evident in educational disparities many years later (Council for Higher Education, 2015). Statistics from the South African Department of Higher Education and Training (Department of Higher Education and Training, 2023) show that only 29% of 2019 graduates were from science, technology, engineering, and mathematics (STEM) fields. According to the Organization for Economic Co-operation and Development (OECD), only 7% of adults in South Africa have a tertiary education, well below the OECD average of 38% and the lowest among OECD partner countries (Organization for Economic Co-operation and Development, 2021). The cost of failing to address poor performance in science education is substantial for countries like South Africa.

Universities of technology in South Africa are committed to providing access to higher education for students from disadvantaged backgrounds. The National Student Financial Aid Scheme (NSFAS) bursaries support this objective. These bursaries specifically target students from low-income and working-class families, as they are limited to those with a combined household income of less than R350 000 per year. These universities aim to assist students from lower socioeconomic and educational backgrounds through extended programs. Viljoen (2015) compared students' performance at one of the universities of technology between a conventional 3-year national diploma program and a 3½ year extended program over 5 years. The study demonstrated that the extended program helps previously disadvantaged students catch up and remain aligned with the mainstream program from the 2nd year onwards. The university admits engineering students who meet the minimum entry requirements of approximately 40–50% in Mathematics and 30–40% in Physical Science. Another approach to addressing these challenges involves exploring instructional methods beyond traditional teaching. This is where the focus of this research lies.

This study investigates explicitly chosen alternative pedagogies rooted in brain-based learning (BBL) principles. Kaur (2023) proposes that BBL, as a teaching method, should inform educational practices by integrating insights from brain science to create more effective and engaging learning experiences. Brain-based principles are educational strategies grounded in neuroscience that highlight how the brain naturally learns and processes information. These principles improve learning by aligning teaching methods with the brain's cognitive functions. By adapting instructional strategies to the brain's natural learning processes, BBL can foster more effective and impactful learning experiences (Caine et al., 2005; Schachl, 2013).

BBL is a highly effective educational approach for disadvantaged students with lower academic performance, as it aligns pedagogy with the brain's natural learning processes (Funa et al., 2024). High levels of stress and trauma – common among disadvantaged students with lower academic performance – have been shown to impair memory, attention, and emotional regulation (Jensen, 2009). According to Jensen (2009), BBL aims to mitigate these effects by creating emotionally safe environments, using positive reinforcement, and fostering strong relational connections. By incorporating movement, visuals, music, and hands-on activities, BBL enhances engagement and retention through embodied cognition and multisensory stimulation (Rahman and Ajineh, 2025). Predictable routines and mindfulness practices help reduce stress and cognitive load, thereby improving executive function and academic outcomes (Meier et al., 2020; Whitfield et al., 2022). Given its emphasis on inclusion, emotional engagement, and active learning, BBL is a suitable and highly beneficial approach in university teaching, particularly for reducing equity gaps in higher education. In addition, prior research by Di Pietro and Muñoz (2025), Dietrichson et al. (2017), and Devlin et al. (2012) has demonstrated that technology can effectively support the learning needs of students from disadvantaged backgrounds.

The main research question for this study is:

What is the impact of adopting technology-enhanced, BBL on the science understanding and performance of 1st-year undergraduate engineering students from disadvantaged backgrounds in South Africa?

The following research questions were employed to address the main research question:

1. What are the views of the students on the contribution of technology and BBL to science understanding?
2. What impact does the implementation of technology and BBL have on science performance?

LITERATURE REVIEW

As the introduction has shown, certain attributes positively affect learning. The following sections will examine the role of technology in the science classroom and the use of BBL as a teaching method.

Technology-enhanced Learning

Research into technology-enhanced learning consistently shows that technology can improve student engagement and achievement, particularly for students from disadvantaged backgrounds, when embedded within sound pedagogical practices rather than used in isolation. Across qualitative, quantitative, and meta-analytic studies, a recurring theme is that technology is most effective when it supports interaction, personalization, and active learning (Sailer et al., 2024).

Studies focusing on equity highlight technology's potential to narrow achievement gaps. Devlin et al. (2012) found that successful students from low socioeconomic backgrounds benefited from interactive digital resources, personalized support, and high academic expectations. These findings align with systematic and meta-analytic evidence showing that technology-assisted interventions yield moderate but meaningful gains, particularly when adaptable and supported by teacher professional development (Dietrichson et al., 2017; Di Pietro and Muñoz, 2025). Similarly, large-scale reviews emphasize that positive outcomes are strongest in STEM contexts and when institutional support structures are in place (OECD, 2015; Zheng et al., 2016).

However, the literature also cautions against simplistic assumptions about technology use. Cheung and Slavin (2013) and Pane et al. (2015) show that technology alone does not improve learning outcomes; rather, its effectiveness depends on how well it is integrated with active teaching strategies. This conclusion is reinforced by reviews of classroom applications, which show that tools such as student response systems, game-based platforms, and virtual reality environments enhance motivation and engagement only when aligned with instructional goals (Lai and Bower, 2019; Makransky et al., 2020; Mader and Bry, 2019; Rahmahani et al., 2020; Swai, 2025). These studies suggest that technology works best as a catalyst for learning – amplifying pedagogical approaches that are already learner-centered and cognitively informed.

This insight provides a conceptual bridge to BBL, which offers a theoretical framework for understanding why these pedagogical conditions are effective.

BBL

BBL draws on insights from neuroscience, psychology, and education to inform instructional practices that align with how the brain naturally learns. Foundational work in mind, brain, and education underscores that multisensory engagement, emotional relevance, social interaction, and active meaning-making are central to effective learning (Caine et al., 2005; Tokuhama-Espinosa, 2017; Thomas et al., 2019).

Empirical studies in science education largely support the effectiveness of BBL approaches. Experimental research comparing BBL with traditional instruction consistently reports higher achievement among students exposed to brain-based strategies, particularly in physics and general science contexts (Saleh and Subramaniam, 2018; Achor and Gbadamosi, 2020). These findings are echoed across multiple secondary-school studies, suggesting that BBL principles can positively influence conceptual understanding and academic performance (Lagoudakis et al., 2022; Ozden and Gultekin, 2008).

At the same time, the literature reveals important gaps and limitations. Bada and Jita's (2022) systematic review indicates that most BBL research is concentrated at the primary and secondary school levels, with relatively limited application in higher education and across certain science disciplines.

Although this distribution reflects historical research trends rather than theoretical constraints, it highlights the need for further investigation into how BBL principles translate into undergraduate science learning environments. Notably, many studies emphasize core BBL principles – such as multisensory learning and emotional engagement – without fully theorizing how these principles can be systematically supported through instructional design.

This gap highlights the potential value of technology as a mediating tool that can operationalize BBL principles more consistently and at scale. By synthesizing these two bodies of literature, it becomes evident that technology-enhanced learning and BBL are complementary rather than independent approaches. Technology provides the tools and environments that support multisensory, interactive, and learner-centered experiences, while BBL offers the theoretical rationale for why these experiences enhance learning. This study directly addresses the identified gaps by integrating technology-enhanced strategies with BBL principles in an undergraduate science context, particularly for disadvantaged 1st-year students.

Theoretical Framework

This study is guided by a BBL theoretical framework synthesized from the work of Tokuhama-Espinosa (2017), Caine et al. (2005), and Schachl (2013). Fourteen brain-based principles were identified and conceptually organized into three overarching elements – relaxed alertness, orchestrated immersion, and active processing – as proposed by Caine et al. (2005). Rather than presenting neuroscience concepts in isolation, these elements are used as analytical constructs that inform both the design of the intervention and the interpretation of learning processes observed during the study.

Relaxed alertness refers to an optimal learning condition characterised by low threat and high challenge. Within this framework, it is not treated merely as a classroom atmosphere but as an indicator of learners' emotional regulation, perceived safety, motivation, and readiness to engage cognitively. Practices such as mindfulness, structured breaks, and explicit attention to stress reduction are therefore interpreted analytically as mechanisms supporting emotional stability and sustained attention, rather than solely as wellbeing interventions.

Orchestrated immersion describes the deliberate design of learning environments that promote deep engagement with meaningful content through rich, multimodal experiences. Analytically, this element examines the extent to which learning activities expose students to patterns, connections, and authentic disciplinary practices. Multisensory learning, for example, is conceptualized as evidence of enhanced cognitive encoding and integration, rather than as the simple use of multiple media. Instructional strategies involving visuals, movement, audio input, and interactive technologies are thus interpreted as manifestations of immersive learning conditions that support conceptual understanding.

Active processing focuses on how learners consolidate, reflect on, and apply new knowledge. Within the analytical framework, this element guides the interpretation of students' opportunities to rehearse concepts, receive feedback, make connections to prior knowledge, and engage in metacognitive reflection. Principles such as repetition, feedback, attention regulation, and memory are therefore examined as indicators of how learning is internalized and transferred, rather than as isolated teaching techniques.

Specific brain-based principles, including neuroplasticity, mindfulness, and physical movement, are framed analytically as mechanisms that influence learners' beliefs about learning, effort, and adaptability. For instance, explicit attention to neuroplasticity is interpreted as shaping students' mindsets and responses to challenge, while movement-based activities and mindfulness practices are analyzed for their role in supporting attention, emotional regulation, and cognitive readiness (Medina, 2011). In this way, neuroscience-informed practices are not positioned as ends in themselves but as observable expressions of deeper learning processes.

Importantly, the framework is operationalized analytically by using the three BBL elements. Classroom observations, student reflections, and learning artefacts are examined to identify evidence of relaxed alertness, orchestrated immersion, and active processing during the intervention (Caine et al., 2005). This approach allows the study to move beyond describing instructional strategies and towards analyzing how learning unfolds cognitively and affectively within a technology-enhanced, BBL environment.

Existing BBL studies in science education largely focus on primary and secondary school contexts and rarely include disadvantaged or undergraduate learners (Bada and Jita, 2022). Moreover, many interventions emphasize selected BBL principles without explicitly addressing how knowledge of brain functioning is communicated to students or how such principles are systematically integrated with technology. These limitations informed the present study, which applies the BBL framework in an undergraduate science context and uses it analytically to examine learning processes among disadvantaged 1st-year students.

The Teaching Intervention

The teaching intervention was delivered to the experimental group, while the control group received instruction in fluid mechanics via conventional lecture-based methods.

Experimental group

The research intervention was designed following a comprehensive review of the relevant literature. BBL elements, principles, and activities were systematically integrated with educational technology to support the teaching of fluid mechanics concepts, including density. In accordance with Morgan et al. (2022), a range of classroom technologies was employed to enhance conceptual understanding and learner engagement. These included video and audio systems to support multimodal explanation and content capture, digital white boarding tools, online discussion platforms, polling tools, and structured group activities. Collectively, these tools were used to support active engagement, multisensory learning, and interaction opportunities aligned with BBL principles.

Control group

Participants in the control group were not exposed to the intervention. Instruction in fluid mechanics was delivered using traditional lecture-based methods, with the lecturer serving as the primary source of information. No BBL strategies, educational technology, or multisensory approaches were incorporated. Teaching followed the prescribed textbook, standardized pacing, and conventional summative assessment practices. Learners completed a range of tasks, worksheets, and questions to reinforce their understanding of the content. To ensure comparability between groups, participants in the control group completed the same pre- and post-tests in science as those in the experimental group, enabling measurement of performance differences attributable to the intervention.

METHODOLOGY

This study adopted an experimental research design involving a specific cohort of 1st-year disadvantaged engineering students enrolled in an extended engineering science program at a single institution. Within this defined context, an experimental design was used to examine the causal effect of a technology-enhanced BBL intervention on students' understanding of fluid mechanics.

The experimental design allowed for a systematic comparison between an experimental group and a control group and serves as the primary methodological strategy for testing cause-and-effect relationships.

The study population comprised 1st-year disadvantaged engineering students enrolled in the extended engineering science course, all of whom had an average academic performance below 60%. As the intervention content is not part of the Grade 12 curriculum, a conceptually demanding topic – fluid mechanics – was selected as the focus.

Random assignment was used to allocate students to either the control or experimental group. The Rand between function in Microsoft Excel was applied to generate random values following a uniform distribution on the interval (0, 1). Students assigned a value of 0 formed the control group, while those assigned a value of 1 formed the experimental group. Of the 90 students who initially provided informed consent, 41 completed all research activities, including attendance at all six intervention sessions. The final sample comprised 18 students in the control group and 23 students in the experimental group.

The experimental group received a technology-enhanced BBL intervention over six consecutive Saturdays, while the control group was taught the same fluid mechanics content using conventional lecture-based teaching methods. An example of how the intervention was planned and applied is provided in the Appendix.

A pilot study was conducted to evaluate the quality, clarity, and practicality of the research instruments. The pilot involved 33 1st-year engineering students who followed the same syllabus and were situated in comparable academic and socioeconomic contexts. Approval for the data-collection instruments was obtained from the subject head before implementation.

The study followed a pre-test–post-test design. Quantitative data were collected to investigate the effect of the teaching intervention on students' conceptual understanding of fluid mechanics and their academic performance. Two instruments were used. First, a written science achievement test covering all aspects of fluid mechanics was administered as both a pre-test and a post-test. The post-test was comparable in structure and cognitive demand to the pre-test, but not identical, to minimise test–retest effects. Multiple-choice questions were deliberately excluded to reduce the likelihood of guessing and to better assess conceptual understanding and logical reasoning.

Second, a structured Likert-scale questionnaire was administered to students in the experimental group to collect feedback on their learning experiences and perceptions of the intervention. The questionnaire achieved a Cronbach's alpha coefficient of 0.88, indicating excellent internal consistency and reliability (Bhattacherjee, 2012).

To enhance internal validity, the same lecturer taught both the experimental and control groups, thereby controlling for instructor-related variables such as teaching style, expertise, and expectations. Additional measures were taken to support reliability and procedural consistency. The subject head and a former student observed sessions in both groups to verify consistency in content coverage and to ensure that no conflict of interest influenced the implementation of the intervention.

FINDINGS

As outlined below, both descriptive and inferential quantitative statistical methods were used to analyze the data. In addition

Table 1: The experiment implementation plan

Group	Pre-intervention tests	Intervention	Post-intervention tests	Structured feedback
Experimental	Pre-test on science knowledge	Technology-enhanced BBL techniques	Post-test on science knowledge	Structured questions to compare pre-and post-interventions (Likert scale)
Control		Conventional teaching methods		N/A

BBL: Brain-based learning

to statistical significance, emphasis is placed on performance trends, the direction and magnitude of change, and the educational relevance of the findings.

The gender distribution of participants in the control and experimental groups was approximately balanced (Table 2), suggesting that gender-related bias is unlikely to have influenced the outcomes.

All participants were recipients of NSFAS bursaries, indicating that the sample represents students from socioeconomically disadvantaged backgrounds, a key target group for universities of technology in South Africa. This contextual factor strengthens the educational relevance of the study, as the findings speak directly to equity-oriented teaching interventions.

Pre-test comparisons using the Mann–Whitney U test (Table 3) indicated no statistically significant difference between the experimental and control groups before the intervention. More importantly, the similar central tendencies and score distributions suggest that both groups entered the study at a comparable level of conceptual understanding. This baseline equivalence supports meaningful interpretation of post-intervention trends. The results are listed in Table 3.

Descriptive statistics (Table 4) reveal a clear upward trend in post-test scores for both groups, indicating that learning occurred over the 6 weeks regardless of instructional approach. However, the magnitude of improvement was consistently greater in the experimental group, as evidenced by higher post-test medians and larger relative gains. These patterns indicate a positive directional effect of the technology-enhanced BBL intervention. An exceptionally high score in the control group was identified as an outlier and removed before inferential analysis to prevent distortion of central tendency measures. This decision improved the interpretability of trends across groups.

Table 2: Percentage of male-to-female participants in the control and experimental groups

Participant group	Male participants		Female participants		Total	
	n	%	n	%	N	%
Experimental group	10	43	13	57	23	56
Control group	12	67	6	33	18	44
Total	22	54	19	46	41	100

Table 3: Mann–Whitney U test results for pre-test comparisons

Achievement test	$\text{Median}_{\text{exp}}$	$\text{Median}_{\text{cont}}$	n_{exp}	n_{cont}	U	p-value
Pre-test	15	15	23	17	172.5	0.536

The Wilcoxon signed-rank test results (Table 5) showed statistically significant improvements from pre-test to post-test in both the experimental group ($p < 0.001$) and the control group ($p = 0.001$). From an educational perspective, this finding indicates that exposure to structured instruction in fluid mechanics – regardless of method – supports conceptual development.

However, the direction and strength of change differed meaningfully between groups. The experimental group demonstrated a larger and more consistent upward shift in scores, suggesting that the integration of technology and BBL principles enhanced learning beyond normal instructional gains. This pattern aligns with the study's theoretical premise that multisensory and cognitively aligned teaching strategies support deeper understanding.

Although the one-sided Mann–Whitney U test on relative change (Table 6) did not reach conventional statistical significance at the 0.05 level ($p = 0.114$), the direction of the effect favored the experimental group. The observed trend suggests that students exposed to the technology-enhanced BBL intervention experienced greater proportional improvement than those taught using traditional methods.

From an educational standpoint, this result is noteworthy. The p-value approaching 0.10, together with a small sample size, suggests that the lack of statistical significance may reflect limited statistical power rather than the absence of an educationally meaningful effect. In applied educational research, particularly in constrained institutional contexts, such trends provide valuable evidence to inform pedagogical decision-making and to justify further investigation with larger cohorts.

The structured feedback collected from participants in the experimental group through a Likert-scale questionnaire

Table 4: Descriptive statistics for the science achievement test

Participant group	Mean (%)	Standard deviation	Minimum (%)	Median (%)	Maximum (%)
Experimental group					
Pre-test	15.870	8.925	3	15	40
Post-test	36.740	11.482	15	33	58
Difference	20.869	2.557	12	18	18
Control group					
Pre-test	18.882	11.597	5	15	50
Post-test	37.353	16.613	10	38	65
Difference	18.471	5.016	5	23	15

provided further insight into the practical and experiential value of the intervention. The theoretical framework- provided- guided the formulation of the questions as depicted in Figure 1.

Relaxed alertness was established through stress-reduction techniques, including deep breathing exercises (83% satisfaction) that activate the parasympathetic nervous system, mind-move activities (83% satisfaction) that increased cerebral blood flow while preventing cognitive overload, and game-based learning via Kahoot! (96% enjoyment) that created psychological safety by removing fear of failure while maintaining intellectual challenge. Instruction on brain function (78% understanding) further empowered students through metacognitive awareness.

Orchestrated immersion was achieved through video-based instruction (74% helpfulness), engaging multiple sensory modalities, technology integration (91% effectiveness), providing varied interactive representations of content, and BBL-enhanced science instruction (87% effectiveness), creating a meta-contextual framework where students perceived themselves as learners within the content.

Active processing occurred through Kahoot!'s requirement for immediate knowledge retrieval and application with instant feedback (96% enjoyment), learning management systems enabling asynchronous consolidation (52% Schoology usage), and mind-move exercises allowing background information processing. Students' strong desire for continuation (96%) indicated meaningful consolidation and schema formation.

Mean scores for positively framed items ranged from 3.3 to 4.9, with an overall mean of 4.3 out of 5, indicating strong learner endorsement. Notably, 91% of participants reported improved confidence and understanding of science concepts and expressed a desire for similar instructional approaches in the future (Figure 1).

The intervention demonstrated exceptionally high acceptance rates (91–96%) for overall effectiveness and student desire for continuation, suggesting strong affective and motivational benefits critical for disadvantaged student populations. While statistical significance was not uniformly achieved, the consistent positive trends and high learner acceptance demonstrate pedagogical meaningfulness, particularly as affective outcomes – positive attitudes, self-efficacy, and intrinsic motivation – are strong predictors of academic persistence for disadvantaged students in STEM disciplines. The summary of the findings is shown in Table 7.

Table 5: Wilcoxon test results for science achievement tests within the experimental and control groups

Participant group	Median_{pre}	Median_{post}	n_{pre}	n_{post}	V	p-value
Experimental	15	33	23	23	38	<0.001
Control	15	38	17	17	52	0.001

Table 6: Mann–Whitney U test results for the relative changes between the groups

Change	Median_{exp}	Median_{cont}	n_{exp}	n_{cont}	U	p-value
Relative change	1.222	1.111	23	17	240	0.114

DISCUSSION

Findings from the science achievement test indicate that the chosen topic, fluid mechanics, posed significant challenges, as students struggled to fully understand the concepts. Providing additional time for review could help strengthen their understanding of these concepts. As a result, the post-test averages for both the control and experimental groups remained low. Nevertheless, the experimental group showed greater relative improvement (2.32 times their pre-test score) compared to the control group (1.98 times their pre-test score). Statistical analysis, however, suggested that this difference was not statistically significant (p = 0.114) at the 0.05 significance level, although it approached significance at 0.1.

Participants in the experimental group responded positively to the intervention and expressed a clear interest in taking part in similar courses in the future. As shown in Figure 1, the use of technology within the intervention was generally viewed favorably. Schoology was utilized to provide supplementary materials beyond classroom instruction; however, perceptions of this platform were less favorable (52%). Limited engagement with these resources may partly explain the lack of statistical significance in the relative improvement. Participants rated the use of BBL very positively, with 91% indicating that technology and BBL had an extremely positive impact on their understanding of science.

The findings of this study support previous research by Di Pietro and Muñoz (2025), Dietrichson et al. (2017), and Devlin et al. (2012), which have demonstrated that technology can be effectively used to meet the learning needs of students from

Table 7: Summary of findings

S. No.	Research question	Finding
1.	What is the effect of technology and brain-based learning on science understanding?	Feedback from the experimental group indicated that 91% of participants were optimistic that the intervention improved their understanding of science and expressed a desire for more similar classes in the future [Figure 1]
2.	What is the effect of implementing technology and brain-based learning on science performance?	Although the experimental group demonstrated higher gains than the control group on the post-achievement test, a Mann–Whitney U test revealed that this difference was not statistically significant (α=0.05; *P*=0.114), approaching significance at α=0.10 [Table 5]

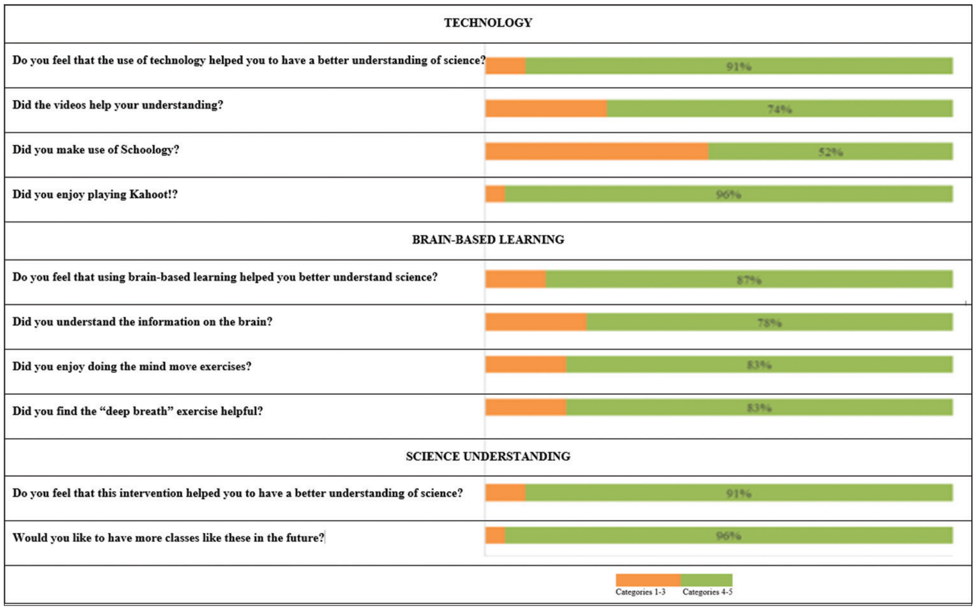

Figure 1: Illustration of the intervention's effect on science understanding within the experimental group

disadvantaged backgrounds, as noted in the literature review. Achor and Gbadamosi (2020), Lagoudakis et al. (2022), Ozden and Gultekin (2008), and Saleh and Subramaniam (2018) have documented the positive effects of BBL and multisensory approaches on science performance. None of the studies explicitly focused on disadvantaged learners; instead, their samples mainly comprised students in years 5–7 within school settings, with a disciplinary focus on physics, science, or biology. Two of the four studies acknowledged technology but did not explicitly utilize it. While all the studies were based on BBL, they engaged with only a few of the fourteen principles used in this study. Moreover, none of the interventions included instruction on how the brain functions.

In this context, the current study advocates for the complete integration of technology and BBL in the education of disadvantaged university students. The results emphasize the intervention's positive influence on science understanding and performance, consistent with existing literature on effective methods to improve science achievement. Therefore, the study offers evidence that addresses the main research question.

CONCLUSION

This study explored the effect of a technology-enhanced, BBL intervention on the science understanding and performance of 1st-year undergraduate engineering students from disadvantaged backgrounds. The results show that both the experimental and control groups experienced statistically significant improvements from pre-test to post-test. Although the difference did not reach statistical significance at the 0.05 level, the experimental group demonstrated a greater relative increase in science performance. Student feedback strongly indicated that integrating technology and BBL strategies enhanced their understanding of science, with 91% expressing optimism about its effectiveness and a desire for similar interventions in future courses.

The results, therefore, support the growing body of evidence suggesting that combining technology with BBL principles – such as neuroplasticity, multisensory engagement, mindfulness, feedback cycles, and active processing – can foster greater engagement and deeper conceptual understanding. Although performance gains were modest, the intervention proved successful in improving students' perceived learning, motivation, and confidence, which are critical foundations for success in STEM disciplines. The study thus contributes to the underexplored field of BBL in higher education, particularly within disadvantaged university populations, and highlights the value of integrating neuroscience-informed pedagogy with instructional technologies in undergraduate science teaching.

This study highlights the potential of BBL and technology-supported pedagogies to enhance engagement, reduce stress, and address equity gaps.

LIMITATIONS

Several limitations should be considered when interpreting the study's findings.

The sample sizes for both the experimental (n = 23) and control (n = 17) groups were small. The limited number of participants diminishes statistical power and restricts the extent to which firm conclusions can be drawn. Consequently, the study should be regarded as a preliminary investigation, offering exploratory rather than definitive evidence for the effects of technology-enhanced BBL.

Although the groups were randomly allocated, the gender distribution differed significantly between them, with a higher proportion of females in the experimental group and a higher proportion of males in the control group. If gender differences influence learning preferences, technology use, or responses to BBL strategies, interventions, the potential confounding effect of gender cannot be dismissed.

The intervention was carried out at a single institution over a relatively short period. This limits the external validity of the findings and their applicability to other higher education environments or STEM disciplines.

Similarly, the exclusive focus on a single topic – fluid mechanics – may limit the generalisability of the observed effects to other areas of scientific learning.

FUTURE RESEARCH

The following recommendations may be considered for future research:

Expanding the study to include multiple universities, increasing the sample size, extending the intervention duration, and incorporating longitudinal measures would yield more robust evidence and enhance external validity.

Additional studies at the tertiary level and in other subject areas may also be considered.

Given the gender imbalance observed in this study, future trials should aim for a more balanced gender representation across groups or explicitly include gender as a variable in the analysis.

Including interviews, focus groups, or classroom observations would provide deeper insights into students' experiences, learning methods, and diverse responses across subgroups. Collecting feedback from control groups would support more meaningful comparisons of perceptions and engagement.

In addition, future studies could adopt a comparative or factorial design to disentangle the individual and combined effects of instructional approaches. For example, separate groups could receive technology-only instruction, BBL-only instruction, and a combined technology-enhanced BBL intervention, allowing researchers to examine the relative contribution of each component to learning outcomes. Such designs would provide clearer insight into whether observed effects are attributable primarily to technology use, brain-based pedagogical principles, or their interaction.

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APPENDIX

Example of an application of the intervention

WEEK 2 (Density)

Brain-based learning element	**Brain-based learning principles**	**Technology**	**Brain-based learning application**
Orchestrated immersion	7. Patterns give meaning 8. Multisensory approach	Web 2.0: YouTube Mobile device: Laptop and data projector	Show a video on the influence that threats have on the brain.
Orchestrated immersion	8. Multisensory approach	Mobile device: Laptop and data projector, whiteboard Animation: PNET simulations Social media: WhatsApp	Demonstrate a practical experiment: Work in groups while the others solve their problems on density. So, how can I measure the mass of water in my swimming pool? Can I put it on a scale?
Active processing	10. Neuroplasticity 11. Feedback and repetition 12. Memory 13. Attention 14. Prior knowledge	Mobile device: Laptop and data projector, whiteboard Learning management system: Schoology Slide show presentation: PowerPoint	Do an example on the whiteboard to capture new knowledge. Save it to the web: "The body of a man whose weight is 690 N contains about 5.2×10^{-3} m^3 of blood. (a) Find the blood weight (b) Express it as a percentage of the body weight.
Active processing	9. Learning involves conscious and unconscious processes, and sleep 10. Neuroplasticity 11. Feedback and repetition 12. Memory 13. Attention 14. Prior knowledge	Mobile device: Laptop and data projector, whiteboard Learning management system: Blackboard Slide show presentation: PowerPoint	Do challenging problems in class (numbers 3, 8, 91, 100), discuss and give feedback.
Relaxed alertness	4. Engages the entire physiology 5. Physical activity and nutrition influence learning 6. Involve breaks in teaching sessions	Web 2.0: YouTube Mobile device: Laptop and data projector	Brain exercise: Mind move (confidence booster) Assure more stable and even brain waves. It puts one in the most resourceful mental and emotional state. Putting one's tongue against the palate is soothing and boosts the immune system and rhythm.
Relaxed alertness	2. Learning is improved by challenge and inhibited by depression, stress, threats and anxiety 4. Engages entire physiology 5. Physical activity and nutrition influence learning 6. Involve breaks in teaching sessions	Mobile device: Laptop and data projector Web 2.0: YouTube	Brain exercise**:** Mindfulness (deep breathing).
Relaxed alertness	4. Engages the entire physiology 5. Physical activity and nutrition influence learning 6. Involve breaks in teaching sessions	Web 2.0: YouTube Mobile device: Laptop and data projector	Brain exercise: Mind move (leg workout) Improves concentration, listening skills, comprehension, task completion and confidence.