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PAPER

Multi-Modal Virtual Reality in Engineering Education: A Design Case Study of Fostering Situational Interest through Project-Based Learning

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ABSTRACT

Engineering students struggle with abstract concepts and theory-practice integration, yet few studies systematically examine how to design virtual reality (VR) learning environments that sustain engagement beyond initial novelty effects. Multi-modal approaches that strategically integrate different technological affordances offer promising but underexplored solutions. This design case study demonstrates the development and implementation of a multi-modal VR learning environment integrating immersive Cave Automatic Virtual Environments (CAVE), non-immersive MATLAB simulations, and artificial intelligence (AI) motion tracking within project-based learning (PjBL). We investigate how different technological modalities can be strategically orchestrated to support situational interest development in undergraduate engineering education. We designed and implemented a four-week "Biomechanics of a Pitch" project in a Strength of Materials course, engaging 20 undergraduate mechanical engineering students. Using an exploratory case study approach with convergent mixed-methods data collection, we measured presence, representation fidelity, and situational interest through validated instruments (α = 0.92–0.93) and focus groups. Data was analyzed through reliability analyses, descriptive statistics, and thematic analysis to understand design effectiveness and student experiences. The multi-modal design enabled distinct complementary technological affordances: CAVE excelled in spatial presence (α = 0.93) and immersive understanding (M = 4.2, SD = 0.8), MATLAB supported analytical thinking and pedagogical usefulness, while AI motion tracking created personalized connections. Student interest evolved from pre-experience curiosity through maintained engagement during multi-modal experiences to post-experience learning motivation. Qualitative data revealed how strategic modality transitions sustained engagement beyond novelty effects. We present an integrated framework synthesizing interest development theory with multi-modal VR design principles, demonstrating how theoretically grounded VR implementations move beyond novelty effects through strategic technological orchestration. The study contributes a design framework, evidence-based design checklist, and practical implementation guidelines for engineering educators seeking to create effective VR-enhanced learning experiences.

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virtual reality (VR), engineering education, multi-modal learning, situational interest, project-based learning (PjBL), student engagement, cave automatic virtual environments (CAVE)

1 INTRODUCTION

Numerous publications, including reports from the American Society for Engineering Education (ASEE) [1], [2] and other global research proceedings [3], [4], [5], [6], have explored state-of-the-art approaches in engineering education and identified critical challenges faced by engineering students. The abstract nature of engineering concepts and the need to integrate knowledge from multiple disciplines can create significant learning challenges [2], [5], often leaving students struggling to bridge the gap between theoretical knowledge and practical application [6]. These challenges stem from the complex, multidimensional nature of engineering education, which requires students to synthesize theoretical knowledge across various scientific and technical domains.

A collaborative report by ASEE and the National Academy of Engineering (NAE) further emphasized these challenges [1], identifying systemic barriers in undergraduate engineering education, including an overreliance on abstract mathematical prerequisites and discipline-specific silos that hinder students from connecting theory to practice and calling for a shift toward student-centered, active learning pedagogies to address these educational barriers.

Addressing these pedagogical barriers requires understanding how students develop engagement with complex, abstract content. Educational research has long recognized the cognitive demands placed on students when confronting abstract and interdisciplinary learning environments. Hidi and Renninger's [7] framework of interest development provides crucial insights into the learning process, distinguishing between situational interest, a temporary state of engagement triggered by environmental factors, and individual interest, which represents a more stable, long-term personal investment in a topic. Situational interest is characterized by its momentary nature, typically induced by external stimuli that capture a learner's attention and create a temporary state of cognitive engagement [8].

Building on this understanding of interest development, research has indicated that thoughtfully designed learning environments can effectively mitigate the challenges associated with complex, interdisciplinary concepts. A particularly promising approach involves leveraging situational interest to stimulate deeper cognitive engagement. As Krapp et al. [9] suggest, situational interest can serve as a catalyst for individual interest, transforming temporary engagement into a more enduring personal connection with the subject matter. Mitchell [10] further supports this notion, arguing that well-structured learning experiences can convert initial, externally triggered curiosity into intrinsic motivation.

Inspired by the aforementioned research, including Hidi and Renninger's frameworks and Schraw and Lehman's work on interest development, our research delves into the cognitive and affective mechanisms underlying engagement and interest development in engineering undergraduate education. Considering the challenges associated with teaching and learning abstract engineering concepts, virtual reality (VR) presents a promising solution by providing immersive and interactive experiences that can reduce perceived complexity [11] and stimulate motivation and curiosity [12], [13], [14]. The interactive nature of immersive technologies amplifies situational interest by providing contextualized, hands-on learning opportunities that traditional methods cannot replicate [15].

Through a design case study approach, our study investigates how carefully designed VR-enhanced learning environments can stimulate engagement and facilitate understanding by providing immersive and interactive experiences that reduce perceived complexity, laying the foundation for exploring the potential transformation of situational interest into sustained interest. To achieve this goal, we designed a multi-stage VR-based project integrating immersive and non-immersive elements, including an immersive Cave Automatic Virtual Environment (CAVE) and non-immersive VR simulations enhanced by artificial intelligence (AI) technologies. Through a mixed-methods case study design, we investigate how these carefully crafted experiences influence students' engagement and learning within the context of an undergraduate Strength of Materials course. We focus on four primary dimensions and nine sub-dimensions of situational interest. While recognizing the importance of contextually triggered engagement, this exploratory case study serves as an initial investigation with 20 mechanical engineering students. By drawing on our empirical findings, we aim to develop a foundational framework for future VR-enhanced educational experiences and provide evidence-based recommendations to foster both short-term and long-term engagement of undergraduate engineering students.

The remainder of this paper is organized as follows: Section 3 presents a comprehensive review of relevant literature, Section 4 details our case study methodology and research design, Section 5 presents our findings, Section 6 discusses the implications of our results, and Section 7 concludes with recommendations for future research and practice.

2 LITERATURE REVIEW

2.1 VR technologies in educational settings

The integration of immersive technologies along the reality-virtuality continuum, including augmented reality (AR), mixed reality (MR), and VR, represents a transformative approach to engineering education [16], [6]. These technologies address critical pedagogical challenges, specifically related to the gap between theory and practical application, by providing innovative mechanisms for conceptual visualization and interactive learning experiences. Ivanov [6] comprehensively outlines how these technologies enable students to visualize complex, abstract concepts through tangible, interactive representations, integrate virtual and physical components in real-time simulations, and create immersive learning environments that transcend traditional pedagogical boundaries. This transformation from passive to active, experiential knowledge construction offers unprecedented opportunities for reimagining engineering education [17], [18], particularly addressing fundamental challenges in understanding abstract, multidimensional systems [5].

While VR technologies demonstrate significant potential in engineering education, their effective implementation faces several challenges. Studies by Billinghurst et al. [16] and Pellas et al. [17] have demonstrated positive impacts on student engagement and spatial reasoning, yet educators must address key implementation barriers. These include managing cognitive load in complex virtual environments, addressing technical limitations of current VR systems, and optimizing design elements to support specific learning outcomes. The effectiveness of VR experiences ultimately depends on the quality of instructional design, the level of student engagement, and the alignment with intended learning outcomes [19].

2.2 The development of student interest

Interest, as an affective-cognitive construct, involves focused attention on specific objects or topics, leading to repeated engagement and increased persistence [20], [7], [21]. The distinction between situational and individual interest [9] provides a fundamental framework for understanding how learners develop sustained engagement with complex subjects. While situational interest represents temporary, context-specific engagement triggered by stimuli, individual interest develops as a more enduring connection rooted in personal values.

Research on situational interest has revealed its potential as a precursor to individual interest [9] suggesting that temporary engagement can evolve into enduring personal connection. Mitchell [10] demonstrated how well-designed learning environments can transform initial curiosity into intrinsic motivation, while Schraw and Lehman [8] showed that momentary engagement can facilitate significant cognitive processing and knowledge acquisition. Studies involving high school and college students have demonstrated that educators can intentionally design learning environments to trigger and sustain interest [22], [23], [24].

The theoretical insights into interest development have important implications for emerging educational technologies. VR presents a particularly promising avenue for stimulating situational interest through immersive and interactive experiences that can reduce perceived complexity [11] and enhance motivation and curiosity [12], [13], [14]. The interactive nature of VR technology provides unique opportunities to design learning environments that can effectively trigger and maintain situational interest, potentially facilitating its transformation into more sustained engagement.

2.3 VR's role in fostering undergraduate student interest

Recent research in university undergraduate education has demonstrated significant potential for VR to trigger situational interest and enhance learning experiences, particularly across STEM disciplines. In civil engineering education, Fink et al. [12] conducted a two-group experimental study with 64 university students learning about railroad bridges. Their findings revealed that VR environments, particularly those created through 3D modeling, can effectively increase student interest, with post-test interest significantly influenced by initial interest and sense of presence. In computer science education, Huang et al. [13] investigated the impact of different levels of immersion (Oculus Go and Oculus Rift) on learning and motivation. Their study introduced the Transitional Immersion Hypothesis, suggesting that a gradual increase in immersion can maintain or boost learner engagement. By starting with lower-immersion environments and progressively introducing more complex VR technologies, educators can leverage novelty effects, address navigation challenges, and sustain motivation across multiple learning sessions. This flexibility makes VR accessible to institutions with varying technological and budgetary constraints. In laboratory science education, Makransky et al. [25] provided compelling evidence for VR's effectiveness in laboratory simulations, demonstrating that head-mounted displays significantly increased student interest and engagement in chemistry experiments.

Beyond STEM disciplines, research has demonstrated VR's broad applicability. In humanities education, Chin et al. [26] explored VR's capacity to generate situational interest for historic sites by leveraging unusual multimedia stimuli to create compelling educational environments that transcend traditional teaching methods. Further validating VR's potential across disciplines, Chen et al. [11] found that VR learning enhanced students' creative thinking and motivation in design education. In library science, Lin et al. [27] compared VR and traditional library orientation methods, revealing that VR guides increased students' situational interest and cognitive engagement through novelty, challenge, and meaningful learning opportunities.

Recent discipline-specific applications have yielded promising results. In forensic science education, Chang [28] demonstrated VR's effectiveness in training, where VR platforms generated heightened situational interest through exploration and novelty while maintaining optimal cognitive load. Their study further found that VR can enhance learning outcomes, particularly in terms of immediate and long-term retention. These findings collectively highlight VR's significant potential to transform learning experiences across various undergraduate disciplines.

Despite these promising applications, the field of VR in undergraduate education faces significant methodological challenges. While VR interventions have been shown to improve student motivation across multiple disciplines [29]–[34], as demonstrated in Jiang and Fryer's [30] comprehensive review, many studies rely heavily on the novelty effect of VR technology rather than robust pedagogical frameworks. This gap between technological implementation and pedagogical theory highlights the critical need for interest-development frameworks in VR design. Educational technology researchers such as Makransky et al. [29] advocate for more sophisticated VR educational design, stressing the need for rigorous theoretical and methodological underpinnings. The crux of the issue lies not merely in technological innovation but in the quality of the instructional environment. Research by Hidi [35] and Krapp [21] underscores the significance of positive emotional responses in fostering student interest within effective learning environments. Radianti et al. [36] further highlight VR's unique capacity to stimulate situational interest through intentional, emotionally resonant instructional design, particularly in undergraduate STEM education.

2.4 Research gap and questions

The integration of VR in educational research represents a critical juncture, presenting a promising yet complex avenue for investigating situational interest in VR-enhanced learning environments [23], [37], [38]. While previous studies have explored VR's potential, there remains a critical need to systematically investigate the intricate mechanisms of educational engagement and the complex dynamics of situational interest in VR-enhanced learning environments [22], [24].

We concur with Radianti et al. [36], who emphasize VR's unique potential to generate situational interest through purposeful, emotionally resonant instructional design. This perspective underscores the need to transcend a purely technological approach and adopt a more strategic, pedagogically and psychologically informed approach to learning environment design. Building upon this foundation and aligning with researchers like Makransky et al. [29], we stress the importance of robust theoretical frameworks in creating learning environments that deliberately generate situational interest. Our overarching goal is to fundamentally transform our understanding of VR, elevating it from a complementary technological tool [14] to a sophisticated medium for cognitive and emotional engagement.

With this goal in mind, a fundamental consideration is how VR environments can be designed to leverage established learning theories. An important one, assimilation theory [39], highlights how crucial the process of anchoring new knowledge to existing mental models is, based on the fact that building on prior knowledge is fundamental to effective instruction [39], [40], [41].

VR can facilitate this process by activating existing knowledge and creating connections to new information. In VR instructional design, this can be achieved by diagnosing learners' prior knowledge, creating scaffolded interactions that bridge familiar and novel concepts, and enabling learners to reconstruct and expand their understanding through interactive, contextually rich virtual environments. Cognitive science research underscores the role of mental representations in shaping conceptual understanding. By strategically connecting new information with learners' prior knowledge, VR creates a unique opportunity to make complex concepts more accessible. Loewenstein's [42] information-gap theory further suggests that VR can deliberately create cognitive tensions that motivate learning by revealing and addressing knowledge gaps.

The effectiveness of VR-based learning environments is further enhanced by the concept of presence. As explored by Jelfs and Whitelock [43] and Slater [44], presence in virtual environments represents a complex psychological and perceptual experience, encompassing spatial presence, social presence, and psychological involvement. While psychological involvement, the mental absorption in the virtual environment, is distinct from engagement, Dubovi [45] suggests that this deep psychological immersion can foster both cognitive and emotional engagement by creating conditions where learners are more receptive to and invested in the learning material. Empirical research by Petersen et al. [46] demonstrates that varying degrees of presence significantly affect situational interest development, with higher levels of immersion and interactivity positively correlating with situational interest.

High-fidelity representations serve as a crucial bridge between presence and understanding. As Mikropoulos and Natsis [47] emphasize, accurate and realistic representations can significantly enhance learners' comprehension and retention of information. These representations increase cognitive elaboration, enhance learner motivation, and facilitate deeper conceptual understanding by providing authentic and contextually relevant learning experiences [25]. However, as Fowler [19] cautions, it is essential to balance detailed representations with cognitive accessibility to avoid overloading learners. The psychological research conducted by Hidi [35] and Krapp [21] confirms that learning environments generating positive emotional responses, such as those facilitated by high-fidelity VR experiences, are particularly effective in inducing student interest.

Furthermore, student engagement emerges as a critical factor in successful learning, supported by Bandura's [48] social cognitive theory and self-determination theory [49], [50]. These theories highlight how VR can stimulate curiosity, foster intrinsic motivation, and enhance learners' self-belief, leading to deeper engagement and improved learning outcomes. This heightened engagement, in turn, contributes to the development of sustained interest in both the learning process and specific tasks.

Building upon these theoretical foundations, this design case study investigates the impact of a multi-staged VR-based simulation on students' situational interest through the following overarching research question: "To what extent does a multi-staged VR-based project set, combining immersive experiences (VR-based simulation in CAVE and learner motion tracking) and non-immersive experiences (Biomechanics of Bodies MATLAB software), influence students' situational interest through dimensions of presence, involvement, and representation fidelity?"

To address this comprehensive question, our investigation features a comprehensive workflow incorporating:

a) Immersive VR-based simulations in the CAVE and learner motion tracking
b) Non-immersive experiences using the Biomechanics of Bodies plug-in on MATLAB software
c) AR experiences using a depth-sensing camera for student motion tracking

Thus, through our exploratory case study, we examine three key constructs and conduct reliability analyses where appropriate:

1. *Presence*: Spatial presence (feeling of being there); Psychological involvement (mental absorption); Overall perceived realness.
2. *Technical Fidelity*: Visual quality; Spatial accuracy of the simulation.
3. *Learning Engagement*: Cognitive engagement; Emotional engagement; Situational interest; Motivation for further exploration.

These variables inform our specific sub-questions within the VR-based project set:

– Sub-Question #1: "How does the VR environment's presence impact students' situational interest?"
– Sub-Question #2: "How does representation fidelity of the VR simulation influence students' situational interest?"
– Sub-Question #3: "Which aspects of the overall VR experience most effectively engage, generating curiosity and learning motivation to learn more about the topic?"

Inspired by our literature review, we draw on the theoretical insights of Krapp et al. [9] and Hidi and Renninger [7] to focus on the development of situational interest and its transition into deeper engagement. By combining immersive and non-immersive experiences, we aim to capitalize on the novelty effect, address navigation challenges, and sustain motivation, as suggested by Huang et al. [13]. Following Chin et al.'s [26] approach to transcend traditional teaching methods, we incorporate PjBL strategies [51] to create an adaptable and innovative learning environment that supports diverse learning styles and preferences.

3 RESEARCH METHODS

3.1 Research approach and case context

This study employs a design case study approach [52] to systematically document and evaluate the development of a multi-modal VR learning environment within an authentic educational context. Case study research is particularly appropriate when investigating contemporary phenomena in real-world settings where design decisions, technological affordances, pedagogical strategies, and student experiences interact in complex ways [53]. We selected this approach for several methodological reasons: (1) our exploratory goal is to understand *how* multi-modal VR environments can be designed to support situational interest development, rather than to establish generalizable causal relationships; (2) the design complexity of integrating three distinct technological components (CAVE, MATLAB, and AI tracking) within a project-based learning (PjBL) framework requires examination of how these components interact and contribute complementary affordances; and (3) implementing the intervention within an authentic required course ensures ecological validity and practical relevance, while accepting the trade-off of reduced experimental control [54].

The case study focuses on a project-based course (MENG 2112: "Strength of Materials") offered in the Department of Mechanical Engineering at the School of Sciences and Engineering of the American University in Cairo. In the spring 2024 semester, twenty undergraduate students participated in a four-week mandatory course project, "Biomechanics of a Pitch," which required them to collaborate on calculating stress in a baseball pitcher's arm and reconstructing key phases of the pitching motion. Through this bounded case, we investigated the impact of a multi-stage, VR-based project on undergraduate engineering students' situational interest in learning new concepts in strength of materials.

We employed a convergent parallel mixed-methods design within the case study framework [55]. Quantitative data provides systematic measurement of presence, representation fidelity, and situational interest dimensions across the sample, while qualitative data from focus groups and open-ended responses provides rich descriptions of student experiences and explanatory insights into *how* and *why* design features influenced engagement. Integration occurs through triangulation during interpretation, using qualitative themes to explain quantitative patterns and quantitative patterns to contextualize the prevalence of qualitative themes.

Given the exploratory nature of this design case study, the sample size of 20 students is appropriate and aligns with established case study methodology. As Yin [52] emphasizes, case studies prioritize depth of understanding over breadth of generalization. This sample size allows for detailed qualitative analysis of student experiences while providing sufficient data for preliminary quantitative patterns. The goal is not statistical generalization to larger populations, but rather analytical generalization, developing theoretical insights and design principles that can inform future VR implementations in similar educational contexts [56].

3.2 Multi-stage VR implementation

To investigate our research questions, we strategically employed a project-based and VR-enhanced learning approach. This approach aimed to enhance student understanding, critical thinking, and problem-solving skills through a combination of non-immersive, immersive, and interactive VR experiences throughout the course project. By applying theoretical knowledge to real-world scenarios, students were expected to develop a deeper appreciation for and understanding of engineering principles.

The project implementation consisted of four sequential key stages, as illustrated in Figure 1, where both immersive and non-immersive VR were used to visualize and analyze the complex biomechanical movements of a baseball pitch, compute stress and strain in the pitcher's arm, and gain a deeper understanding of the underlying principles.

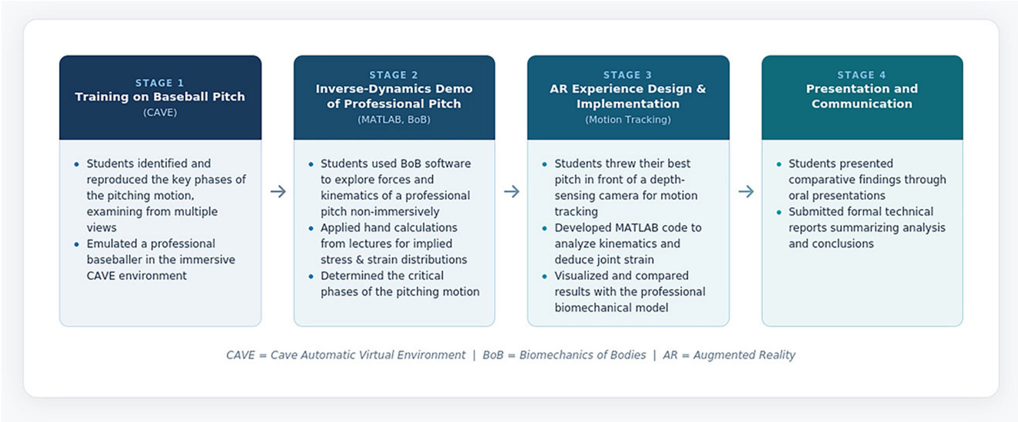

Fig. 1. Key stages of the project "Biomechanics of a Pitch"

Table 1 outlines the VR experiences that were integrated into the project. These experiences comprised two main components:

1. Immersive VR experience, in which students observed a professional baseballer's pitch in 3D within a CAVE, emulating the pitcher's movements and experiencing the corresponding muscle strain and joint stress firsthand.
2. Non-immersive VR experience, in which students analyzed a 3D skeletal view of a baseballer's pitch using Biomechanics of Bodies MATLAB software, identifying key planes of motion, timeframes of interest, and maximum internal forces and moments at each joint.

Each component included instructional tasks specifically designed for enhancing understanding, increasing engagement, and fostering learning. By integrating VR with PjBL, we aimed to create a dynamic and engaging learning environment that fosters deep learning and critical thinking.

Table 1. Alignment of instructional task design aims with VR experience types

Instructional Task Design Aim	VR Experience Type
Enhance Understanding: Provide intuitive visualizations, real-world context, and interactive exploration of complex spatial relationships and stress distribution.	Immersive
Increase Engagement: Engage multiple senses, evoke emotional connections, and make the material personally relevant.	Immersive
Foster Learning: Combine comprehensibility, vividness, and interactive exploration to create a memorable learning experience.	Immersive and non-immersive

3.3 Surveys and focus groups

This study employed a mixed-methods approach, combining quantitative and qualitative research methods to comprehensively investigate the impact of the VR-based learning experience. The research design involved the administration of two surveys and the conduct of focus group discussions. The statistical analysis in this study was conducted using R version 4.3.2, with the *psych* package (version 2.2.5) employed for reliability analyses. Cronbach's alpha coefficients were calculated to assess the internal consistency of the scales measuring presence, representation fidelity, and situational interest. Inter-item correlation matrices were generated to evaluate the coherence of the items within each scale. Descriptive statistics, including means and standard deviations, were computed to summarize participant responses, and correlation analyses were performed to explore the relationships between key variables, such as presence, representation fidelity, and situational interest. These analyses were conducted to ensure the reliability and validity of the measurement scales used in the study.

Survey # 1. Survey #1, also referred to as "Baseline Survey," provided foundational data to inform the design of the VR-based project set. While primarily focused on preliminary assessment, this survey's sections on prior knowledge, interest, curiosity, and motivation align with our theoretical framework on situational interest development [7] and helped establish baseline measures for understanding how students might experience presence and engagement in subsequent VR environments. Additionally, the survey explored the potential of collaborative learning within the VR environment, helping to inform the design of team-based problem-solving tasks. The survey consisted of eight sections (refer to Table 2), combining closed-ended and open-ended questions to gather both quantitative and qualitative data. Most questions were Likert scale questions, requiring participants to rate their responses on a 5-point scale ranging from "strongly disagree" to "strongly agree."

Table 2. Structure and thematic focus of the baseline survey (Survey #1)

Main Sections	Section Description	Key Features
Section 1	Familiarity with engineering concepts and procedures: Assesses participants' prior knowledge of engineering concepts related to strength of materials.	Exploration of the role of prior knowledge in shaping engagement with the topic.
Section 2	Prior VR experience: Gathers information about participants' previous exposure to VR technology.	Evaluation of participants' experiences with VR technology and collaborative learning.
Section 3	Experience with collaborative and cooperative work: Evaluates participants' experience with group projects, role-taking, teaching, and sharing experiences.	Evaluation of participants' experiences with VR technology and collaborative learning.
Section 4	Interest: Measures participants' interest in learning about various engineering concepts related to the strength of materials.	Focus on situational interest by assessing factors like perceived complexity, understanding, confidence, curiosity, and motivation.
Section 5	Curiosity: Assesses participants' curiosity about learning these engineering concepts.	Focus on situational interest by assessing factors like perceived complexity, understanding, confidence, curiosity, and motivation.
Section 6	Motivation: factors motivating participants to learn about the strength of materials.	Focus on situational interest by assessing factors like perceived complexity, understanding, confidence, curiosity, and motivation.
Section 7	Attitudes Towards Collaboration and Cooperation: Evaluates participants' comfort level with group work and collaboration.	Evaluation of participants' experiences with VR technology and collaborative learning.
Section 8	Learning preferences: Explores participants' perceptions of how VR could enhance their learning of engineering concepts.	Evaluation of participants' experiences with VR technology and collaborative learning.

Building on these survey sections, we identified five key focal points that informed the design and implementation of the VR-based project set:

- The relationship between prior knowledge and situational interest: By assessing students' existing knowledge and interest in engineering concepts, the survey provided insights into how prior knowledge can influence engagement and learning.
- The impact of VR on motivation and engagement: By comparing students' responses to questions about VR and their interest in engineering, the survey explored the potential of VR to enhance motivation and engagement.
- The effectiveness of collaborative learning in VR: The survey assessed students' experiences with collaborative work and their attitudes towards team-based projects, providing information on the potential benefits of collaborative learning in VR-enhanced learning environments.
- Students' perceptions of VR as a learning tool: By understanding students' beliefs about how VR can enhance learning, the survey helped to inform the design of the VR-based project set.
- The specific factors within VR that contribute to student engagement: The survey identified key VR features, such as immersion, interactivity, and realism, that can stimulate interest and motivation.

Survey # 2. Survey #2 was strategically administered in two phases to address our research questions about presence, representation fidelity, and engagement. The first section, the "VR Survey," administered after the immersive CAVE experience, focused on two key dimensions central to our research questions:

- *Presence* (addressing sub-question #1): measuring participants' sense of involvement, perceived realness, and spatial presence. This dimension assesses three key aspects of the VR experience:
  - Involvement: The participant's psychological immersion in the virtual environment
  - Realness: The perceived authenticity of the virtual experience
  - Spatial Presence: The feeling of being physically present in the virtual space
- *Representation Fidelity* (addressing sub-question #2): assessing the realism and precision of the virtual environment through:
  - Visual quality and clarity of the 3D simulation
  - Spatial accuracy of movements and distances
  - Overall realism of the baseball pitcher's movements

This section particularly examined how representation fidelity supported understanding of five key engineering concepts:

- Understanding how forces affect structural elements differently according to element strength
- Finding weakest points in a structure under different loads in 3D
- Calculating critical stresses and potential failure modes
- Measuring structural deformation under load using strain measures
- Presenting engineering results clearly

The second section, "Engagement and Learning: Stress Computation," was administered after both the non-immersive VR experience on MATLAB software and the AR-based motion tracking of student movement. This section investigated engagement factors (addressing sub-question #3) through nine dimensions that collectively measured how different aspects of the VR simulation influenced situational interest and learning motivation:

- *Prior Knowledge*: Assessed participants' existing knowledge of stress computation
- *Initial Interest*: Measured participants' initial level of interest in biomechanics
- *Curiosity*: Evaluated participants' desire to explore stress analysis further
- *Enjoyment*: Measured participants' enjoyment of the VR experience
- *Motivation*: Assessed participants' drive to learn stress computation
- *Focus and Attention*: Measured participants' ability to concentrate during the simulation
- *Pedagogical Usefulness*: Evaluated the educational value for understanding stress concepts
- *Personal Relevance*: Assessed how participants connected the experience to their engineering goals
- *Potential Future Engagement*: Measured interest in further exploring biomechanics and stress analysis

Both sections employed 1–5 Likert scales for quantitative measurement, supplemented by open-ended responses collected in focus groups for qualitative insights.

This survey design strategically connects with Survey #1, tracking key changes across:

- Prior understanding of stress computation concepts (linking to Survey #1's engineering concepts section)
- Changes in situational interest, curiosity, and motivation throughout the project
- Alignment between expected and actual VR learning experiences
- Impact of previous VR and collaborative work experience on project outcomes

Through these complementary surveys and their interconnected sections, we aimed to comprehensively assess how our multi-stage VR project set influenced students' engagement and understanding of stress computation concepts while tracking changes in their interest, motivation, and learning preferences throughout the experience.

4 FINDINGS

4.1 Survey #1

The Survey #1, or "Baseline Survey" results, informed the three-fold approach to tailoring instruction during the course project:

1. *Targeted Instruction*: By assessing students' prior knowledge of engineering concepts, the instructor was able to tailor VR-based tasks within the project set to specific learning outcomes and address areas where students needed more explanation. Students showed lower familiarity with core concepts, particularly deformation and stress distribution, with key misconceptions around how structures change shape under load. For example, students expressed curiosity about understanding how forces affect the strength of a structure, rating it as their highest area of interest, so a VR simulation was developed to allow them to experiment

with different force scenarios. The simulation incorporated color-coded visualizations for stress distribution and interactive tools to observe and manipulate deformation, addressing both interest and knowledge gaps. The survey revealed detailed patterns of situational interest, with students showing highest interest in finding weak points in structures and solving real-world engineering problems, which directly informed the design of interactive scenarios.
2. *Level of Guidance*: Understanding students' prior experience with VR helped the instructor determine the appropriate level of guidance and support needed, ensuring a smooth learning experience. Survey results revealed mixed prior VR exposure, primarily gaming-based, and some concerns about physical comfort. This led to implementing a graduated introduction to VR technology, incorporating comfort breaks, and providing alternative viewing options. Students' perceptions of VR's potential for learning were particularly enthusiastic about visualization capabilities, with many responses highlighting the value of "seeing inside" structures and experiencing "3D visualization" of concepts. These preferences directly shaped the development of visualization tools and immersive experiences in the project.
3. *Collaborative Learning*: Assessing students' comfort levels with collaborative work informed the instructor's choice of teaching approaches and technology support to promote effective teamwork. Students demonstrated high comfort with group work (4.24/5 rating), strong experience in role-taking (4.43/5 rating), and positive attitudes toward peer teaching (4.1/5 rating). This led to incorporating role-based team structures and peer-teaching components in VR activities. The survey revealed that students particularly valued the opportunity to deepen their understanding through explaining concepts to others and sharing different perspectives, which informed the design of collaborative VR tasks.

Aligned with these insights, the project comprised a multi-staged VR-based project set that included a combination of an immersive baseballer movement simulation in the CAVE, a non-immersive demo using Biomechanics of Bodies MATLAB software, and an immersive motion-tracking component, as well as the related instructional tasks. This integrated approach was specifically designed to address identified knowledge gaps—particularly in understanding stress distribution, deformation before failure, and identifying structural weak points—through visual and interactive learning, maintain student interest through practical applications (which rated 4.38/5 as a motivator), and support collaborative learning while accommodating different learning preferences. The design particularly responded to students' expressed desire for interactive experimentation and real-world applications, as revealed in Section 8 of the survey, where students emphasized the potential of VR for enhancing their understanding through hands-on experimentation with forces and materials.

4.2 Survey #2

Reliability analysis. To ensure the rigor of Survey #2, we conducted a comprehensive reliability analysis of the measurement scales used to assess presence, representation fidelity, and situational interest. Cronbach's alpha, a statistical measure used to assess the internal consistency reliability of a scale, was employed. The Presence, Representation Fidelity, and Situational Interest scales demonstrated excellent internal consistency, with Cronbach's alpha coefficients of 0.93, 0.88, and

0.92, respectively. These high reliability coefficients indicate that the scales reliably measure the intended constructs.

The Presence scale encompasses three key aspects aligned with our theoretical framework: involvement, realness, and spatial presence. To ensure the reliability of this scale, which directly measures one of the primary dimensions influencing situational interest, we utilized the statistical software R and the psych package to calculate Cronbach's alpha. This measure assesses the internal consistency of the scale items, determining whether they reliably capture the construct of presence as experienced by students in the VR environment. A reliable scale provides confidence that subsequent analyses linking presence to situational interest are based on sound measurements. The Presence scale showed strong reliability, with a Cronbach's alpha of 0.93. This indicates that the scale effectively measures the construct of presence, encompassing involvement, realness, and spatial presence.

The representation fidelity scale measuring VR simulation quality initially included four items:

- "When you visualize the movements in a 3D space, how realistic does the VR-based simulation look and feel?"
- "When you visualize the movements in a 3D space, how clear and high-quality are the visuals?"
- "When you visualize the movements in a 3D space, do you experience any motion sickness or discomfort while looking at the simulation?"
- "When you visualize the movements in a 3D space, how accurately does the VR-based simulation represent real-world spatial relationships and distances?"

However, we removed the motion sickness item, as it did not align with the other items' positive focus. The results indicated excellent internal consistency, with a Cronbach's alpha of 0.88. This suggests that the three items coherently measure the construct of representation fidelity. The inter-item correlation matrix (refer to Table 3) further supports this reliability, showcasing strong positive correlations between all item pairs. Additionally, each item's correlation with the total scale score was substantial, ranging from 0.71 to 0.87, underscoring the meaningful contribution of each item to the overall construct. These findings establish the reliability of the Representation Fidelity scale, enabling its effective use in examining the impact of representation fidelity on students' situational interest.

Table 3. Inter-item correlation matrix for the representation fidelity scale

	Q9	Q11	Q15
Q9	1.00	0.75	0.62
Q11	0.75	1.00	0.81
Q15	0.62	0.81	1.00

Note: Correlations are Pearson's r coefficients.

To enhance the reliability and the validity of the situational interest scale, we conducted a thorough analysis and refinement. The initial eleven-item scale was revised to a nine-item scale by removing items Q31 and Q35, which exhibited lower item-total correlations and misalignment with the underlying construct. The revised nine-item scale demonstrated excellent internal consistency, with a Cronbach's alpha of 0.92, and effectively captures key dimensions of interest, including attention, enjoyment, motivation, focus, and personal relevance. A correlation matrix (see Figure 2) further supports the scale's validity. The strong internal consistency and the meaningful contribution of each item establish the scale as a reliable and valid tool for assessing students' interest in VR-based learning experiences.

Fig. 2. Inter-item correlation matrix for the situational interest scale

Results. Based on the analysis of the results of Survey #2, we were able to address each of the research sub-questions posed in our study.

a) **Presence and situational interest.** A key sub-question in our study was: "How does the VR environment's presence impact students' situational interest?" To address this question, we analyzed the presence scale and found a high level of immersion among participants. The Cronbach's alpha of 0.93 indicates excellent internal consistency, suggesting that the scale effectively measures the construct of presence. The strong inter-item correlations further confirmed the reliability and validity of the scale. These findings suggest that the VR environment successfully transported participants to a virtual world where the student interacted with the critical phases of a pitcher's movements and where their emulations could be effectively compared. Also, students got the opportunity to "feel" in their own muscles the "strain and stress" they were asked to compute, rendering the involvement a first-hand experience. Specifically, participants reported high levels of involvement (M = 4.2, SD = 0.8), realness (M = 4.1, SD = 0.7), and spatial perception (M = 4.3, SD = 0.6). These factors contributed to a sense of presence, driven by the immersive design of the baseballer movement simulation in the CAVE. The realistic 3D graphics, interactive elements, and spatial and sensory experiences that mimicked real-world interactions effectively captured students' attention, minimized distractions, and optimized their cognitive processing. For a more detailed analysis of the presence scale, please refer to Tables 4 and 5. Figures 3 and 4 provide visual representations of the distribution of the scale scores and item responses, respectively.

Table 4. Reliability statistics for the presence scale

Statistic	Value
Number of Items	3
Cronbach's Alpha	0.93
Average Inter-Item Correlation	0.83
Mean of Scale	3.5
Standard Deviation of Scale	1.1

Table 5. Item statistics for the presence scale

Item	Item-Total Correlation	Mean	Standard Deviation
Q3	0.87	3.9	1.1
Q5	0.88	3.4	1.2
Q7	0.85	3.1	1.2

Note: Q3 = Involvement, Q5 = Realness, Q7 = Spatial Presence. See Section 4.3.2 for full item descriptions.

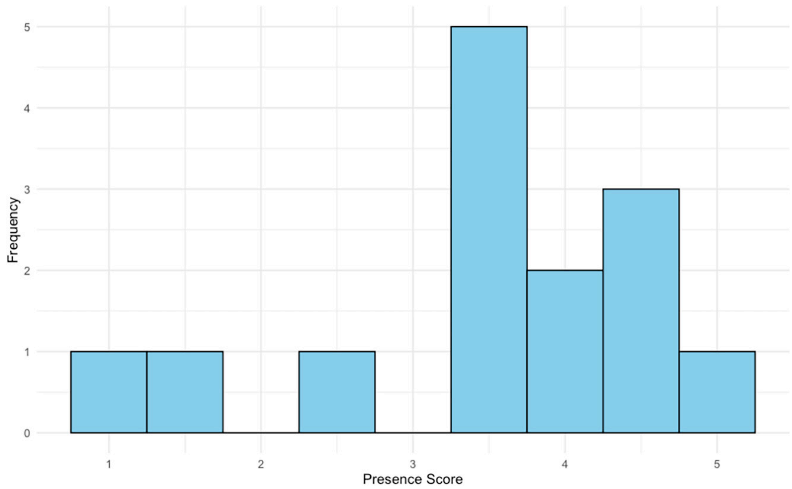

Fig. 3. Distribution of presence scale scores

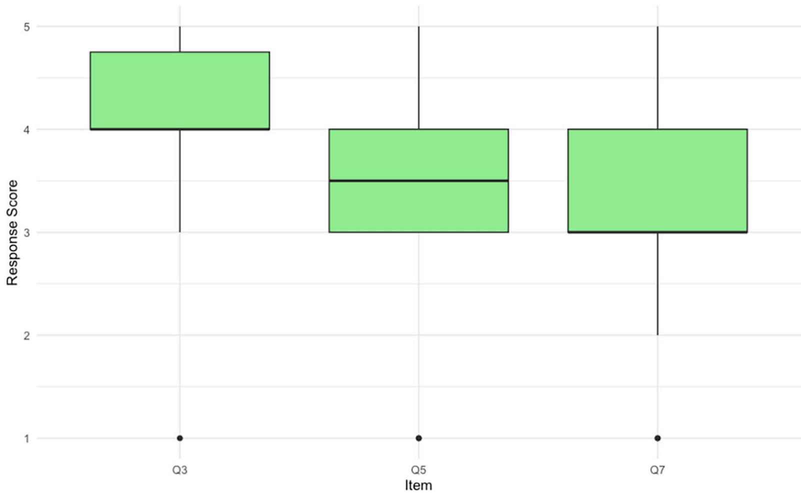

Fig. 4. Distribution of responses for presence scale items

b) **Representation of fidelity and situational interest.** Our second key sub-question asked: "How does the representation fidelity of the VR simulation influence students' situational interest?" To answer this question, we analyzed the representation fidelity scale and found good reliability (Cronbach's alpha = 0.88) after removing the motion sickness item. The strong correlations between items such as visual realism ($r = 0.75$) and spatial accuracy indicated that the baseballer movement simulation in the CAVE provided a high-quality and immersive experience. These factors contributed to improved understanding and retention of information. The project set utilized a high-fidelity 3D model of a professional pitch, allowing students to interactively explore its complex kinematics from multiple viewpoints. This immersive experience facilitated rapid training and emulation of the pitch for motion tracking analysis. By comparing stress and strain in 3D, students gained a deeper understanding of how forces affect structural elements differently based on their strength. They were able to identify weak points, calculate critical stresses and potential failure modes, measure deformation under load, and effectively present their engineering findings. This contextually relevant simulation helped students develop a strong grasp of real-world scenarios and the above engineering concepts. Additionally, the use of high-quality visuals made the learning process engaging and memorable.
c) **Situational interest and learning.** Our last sub-question asked: "Which aspects of the overall VR experience most effectively engage, generating curiosity and learning motivation to learn more about the topic?" The situational interest scale, with a Cronbach's alpha of 0.92, exhibited excellent reliability. The analysis revealed that the VR overall exposure successfully captured students' attention, generated curiosity, and motivated students to learn more about strength of materials. The high mean scores for items such as attention capture ($M = 3.4$), motivation to explore ($M = 3.6$), and desire to know more ($M = 3.9$) indicate that the VR overall experience was highly engaging and stimulating. The strong correlations between items on the situational interest scale further support its reliability and validity. For example, the correlation between attention capture and motivation to explore was 0.823, suggesting a strong relationship between these two constructs. This indicates that the VR experience not only captured students' attention but also motivated them to delve deeper into the subject matter.

This finding was corroborated by focus group discussions conducted at the end of the semester, where themes of increased motivation and persistence emerged. Learners reported feeling more interested and engaged than at the beginning of the course, as evidenced by the respective responses in Survey #1 and in the second section of Survey #2. Consequently, they were motivated to actively participate in learning activities, seek out additional information, and apply their knowledge to real-world problems. In answering the main research question of this study: "To what extent does a multi-staged VR-based project set, combining immersive experiences (VR-based simulation in CAVE and learner motion tracking) and non-immersive experiences (Biomechanics of Bodies MATLAB software), influence students' situational interest through dimensions of presence, involvement, and representation fidelity?" the strong reliability of these scales provides confidence in the validity of the findings. The high levels of presence, representation fidelity, and situational interest reported by participants highlight the potential of VR to create engaging and effective learning experiences.

4.3 Implications

This study offers a significant contribution to the field of educational technology, particularly in the domain of VR-enhanced learning environments. By employing a rigorous methodological approach and systematically examining item-total correlations and content validity, this study demonstrates a sophisticated approach to scale development. This empirical support for the multidimensional nature of presence, representation fidelity, and situational interest in VR environments extends existing theoretical frameworks and provides valuable insights into the psychological processes underlying VR-based learning.

The findings have profound implications for the design and implementation of effective VR-based learning experiences across various disciplines. While this study specifically focuses on undergraduate engineering education, the principles and insights gained can be applied to a wide range of educational contexts, including other disciplines within higher education, various subjects in K-12 education, and industries like healthcare, manufacturing, and aviation in corporate training.

This study provides a solid foundation for educators and training professionals seeking to understand the underlying mechanisms of VR-based learning, ultimately optimizing the design and delivery of VR experiences to maximize their impact on student and employee learning and engagement. Educators and trainers, for example, can apply these findings by prioritizing the development of VR experiences that offer high levels of presence and representation fidelity, ensuring that the virtual environments are not only visually appealing but also accurately reflect real-world phenomena. Incorporating elements that foster collaboration and peer-to-peer learning within VR environments can enhance student engagement and deepen understanding.

5 CONCLUSION

Through this design case study combining PjBL strategies and a multi-dimensional framework, we investigated the mechanisms of interest generation and the development of situational interest across various stages of a VR-based project. Our findings highlight the importance of designing VR experiences that are not only immersive but also intellectually stimulating and that align with well-established pedagogical principles.

This study addresses two significant gaps in the field of educational technology, particularly in the context of VR-based learning. First, the research addresses the challenge of teaching abstract and interdisciplinary engineering concepts. By leveraging the immersive capabilities of VR, this study explores how to create engaging and effective learning experiences that can help students overcome these challenges. The multi-dimensional framework proposed in this study can serve as a valuable tool for designing VR-based learning experiences that can support student learning and motivation.

Second, the study responds to the need for a more purposeful and emotionally resonant approach to VR-based instructional design. By drawing on theories of motivation, engagement, and cognitive psychology, this study provides a framework for designing VR experiences that can effectively capture and sustain student interest, leading to deeper learning. The study highlights the importance of considering factors such as personal relevance, pedagogical usefulness, and potential engagement when designing VR-enhanced learning environments. By addressing these two key gaps, this study contributes to a more nuanced understanding of the potential of VR as an educational tool, targeting the engineering undergraduate educational context. This study represents a significant step toward a more nuanced understanding of VR as an educational tool. By shifting the focus from technology-centric approaches to a learner-centered perspective, we have explored the potential of VR to foster deep, meaningful learning experiences. VR, when thoughtfully integrated into education, can create innovative and engaging learning environments that enhance student motivation and learning outcomes.

5.1 Limitations and future research and practice

As with any exploratory case study, this study, while providing valuable insights into the potential of VR for undergraduate engineering education, presents certain limitations that should be acknowledged. Firstly, while the study demonstrates a positive overall impact of the VR project set on student interest, further research is needed to investigate the dynamics of interest over time. Tracking student responses to key questions (e.g., interest, motivation) across different stages of the VR project set would provide valuable insights into how student interest evolves throughout the learning process. Secondly, the reliance on self-reported measures may introduce potential biases. As is characteristic of case study research, the goal is analytical generalization to theory rather than statistical generalization to populations [52]. The findings provide theoretical insights and design principles that can inform implementations in similar contexts, though validation in diverse settings would strengthen these contributions. To address these limitations, future research should consider integrating motivational theories like SDT. By designing environments that support students' psychological needs and creating experiences that transform temporary interest into sustained motivation, researchers can enhance the effectiveness of VR-based learning. Thirdly, as a bounded case study, the research focused on a specific course in mechanical engineering at one institution. The design principles and theoretical insights may transfer to other STEM disciplines and institutional contexts, though such transferability should be investigated through additional case studies and comparative research. Finally, the study primarily focused on the immediate impact of the VR experience. Future research could explore the long-term effects of VR on student learning outcomes, such as retention of knowledge, application of skills, and overall academic performance. Additionally, future research could investigate the optimal design principles for VR-based learning experiences, considering factors such as instructional design, pacing, and the level of learner autonomy.

5.2 Abbreviations

AI – Artificial Intelligence
AR – Augmented Reality
ASEE – American Society for Engineering Education
BoB – Biomechanics of Bodies
CAVE – Cave Automatic Virtual Environment
MATLAB – Matrix Laboratory MR Mixed Reality
NAE – National Academy of Engineering
NSF – National Science Foundation

PjBL – Project-Based Learning
SDT – Self-Determination Theory
STEM – Science, Technology, Engineering, and Mathematics
VR – Virtual Reality

5.3 Statements and declarations

Data availability statement. To protect participant privacy and comply with research ethics protocols, the data that support the findings of this study are available upon reasonable request from the corresponding author. The dataset contains sensitive information from a small group of undergraduate engineering students (N = 20) that could potentially make participants identifiable. Access to anonymized data may be granted following review of research purposes and signing of a data sharing agreement.

Conflict of interest statement. The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Statement of AI. By submitting this manuscript, we confirm that we have adhered to appropriate ethical guidelines or approvals for the human subjects' research conducted in this study, including taking into consideration any federal requirements and institutional guidelines concerning the use of AI in human subjects' research.

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