Crystal Vision: An Interactive Video Game for Engineering Materials

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Abstract

Materials science underpins nearly all engineering and science disciplines, yet many foundational concepts are perceived by undergraduates as abstract, cognitively demanding, and difficult to visualize. To address these challenges, this study explores game-based learning as an accessible instructional intervention for engineering materials education. An initial virtual-reality (VR) educational game, Crystal Vision, demonstrated strong student engagement, enjoyment, and perceived learning usefulness when implemented with 84 undergraduate civil engineering students. However, user comfort issues and hardware requirements limited scalability. Building on these findings, a computer-based version, Crystal Vision 2.0, was developed to reduce usability barriers and evaluated with 82 undergraduate students. Comparative results show that the computer-based game produced a 9% higher post-game conceptual quiz score and a 10% reduction in quiz completion time compared to the VR implementation. While students valued both platforms, hardware accessibility emerged as a key limitation. These findings highlight the potential of lightweight, platform-agnostic educational games to reduce access barriers, support inclusive learning, and expand participation in materials science education.

Overview and Motivation

Materials knowledge supports a wide range of engineering and scientific applications, yet students often struggle with key concepts because of the need for 3D visualizations. Traditional pen-and-paper instructional approaches may limit opportunities for visualization and interactive exploration, thereby increasing cognitive load and reducing engagement [1]. Game-based learning offers an alternative instructional approach by enabling active interaction with complex material behaviors [2]. Immersive platforms such as virtual reality have shown promise in this context, but can introduce usability and accessibility challenges that restrict participation [3]. To address these limitations, this study examines a computer educational game implementation, a virtual reality version, and an online gaming platform, developed for an undergraduate engineering materials course, *CEE 300: Behavior of Materials*. The comparison focuses on differences in post-game conceptual tests. The findings highlight the role of platform choice in shaping accessibility and learning experiences and underscore the need for lightweight, scalable game designs to support inclusive materials science education.

The entire research is guided by two research questions:

1. How do students' perceptions of usability, comfort, and hardware accessibility vary across different educational gaming platforms and their implementations in an engineering materials course?
2. How do different educational gaming platforms and successive enhancements in game design influence student learning outcomes and task efficiency in engineering materials education?

Literature Review

Immersive and game-based learning approaches are increasingly used in engineering education to support visualization, active learning, and student engagement. Virtual reality (VR) enables immersive 3D visualization and spatial interaction, allowing students to directly explore abstract engineering structures and processes that are difficult to represent using traditional instruction [4]. These features make VR particularly appealing for spatially complex topics in materials science. However, prior studies consistently report usability and accessibility challenges, including motion sickness, visual and physical discomfort, cognitive overload, and dependence on specialized hardware [5]. Such limitations can restrict scalability, equitable access, and sustained engagement, especially in large undergraduate courses.

In parallel, computer-based educational games have emerged as an effective and more accessible alternative for enhancing learning outcomes, motivation, and engagement [6-8]. Prior studies indicate that computer-based games can support 3D visualization, exploratory interaction, and immediate feedback while incorporating targeted game design and game elements such as goals, challenges, and narrative to promote motivation [9]. Because they operate on widely available devices and do not require immersive hardware, computer-based games offer greater flexibility and scalability. As a result, they are increasingly viewed as a practical platform for delivering interactive, engaging engineering education experiences while minimizing user discomfort and accessibility barriers [10-12]. However, games made with engines like Unreal Engine and Unity, which include many assets to create an appealing adventure game, require a computer with a powerful graphics processing unit (GPU) to run, which might not be accessible to all students.

Web-based game platforms, particularly those built with WebGL, offer a scalable and accessible approach for engineering education. WebGL enables interactive 3D content to run directly in standard web browsers, eliminating the need for specialized software or high-end hardware. This allows educational games to be deployed across devices and operating systems, making them suitable for large and diverse student populations. Prior work shows that browser-based games support rapid dissemination, repeated access, and sustained engagement through interactive visualization, real-time feedback, and self-paced exploration. Because WebGL games are platform-agnostic and easily updated, they are increasingly viewed as a practical solution for supporting mass participation and consistent learning experiences across contexts [13-14]. For these reasons, this project is currently working on adopting a lightweight, web-based game development approach to maximize accessibility, scalability, and repeated student engagement while preserving interactive and visual learning affordances.

Methodology

This project followed a progressive game development approach to examine trade-offs between immersion, gameplay complexity, and accessibility. The initial virtual reality (VR) game was developed using Unreal Engine 4.27 and implemented with the standard VR template. The VR experience was designed as a basic, level-based environment utilizing teleportation-based navigation and embedded 3D in-game quizzes to support conceptual learning while minimizing interaction complexity. Although the VR format enabled immersive visualization, its design intentionally prioritized simplicity to reduce cognitive and physical load.

Building on the initial VR-based effort, a successive computer-based educational game was developed using Unreal Engine 5.3 to address usability and accessibility limitations while preserving interactive learning affordances. This version incorporated commercially available visual assets and enhanced graphical capabilities to create a visually engaging, adventure-style learning environment suitable for desktop use. The objective of the game was to use it as a single-session teaching tool to motivate students to learn basic knowledge of materials in an enjoyable way. The computer-based game was structured around multiple progression levels that gradually introduced basic crystallography concepts as 3D models within the game, allowing students to advance through increasingly complex challenges, i.e., from easier to harder MCQs (Multiple Choice Questions) and quizzes on 3D models of these concepts.

The computer video game was built as a first-person game where the player would explore the map, take MCQ and 3D quizzes after watching some 3D unit cells with different crystallographic structures. The progressive challenging levels allowed students to take and progress through increasingly complex conceptual questions. Common game mechanics, including enemies, collectibles, and reward systems, were integrated to support motivation and sustained engagement. In addition, interactive sound and visual effects were employed to provide feedback and reinforce player actions. By removing the requirement for immersive hardware, the computer-based implementation aimed to reduce user comfort constraints while maintaining an interactive and exploratory learning experience.

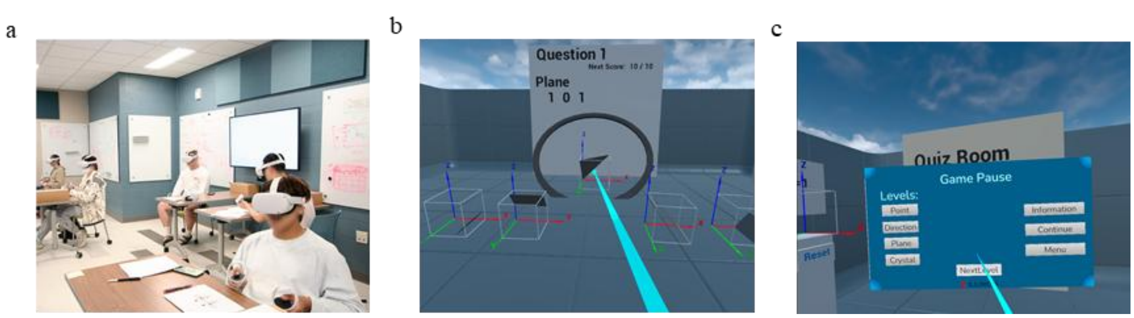

Figure 1: VR gaming intervention project showing (a) students playing VR game, (b) in-game screenshot of a 3D visualization-based quiz, (c) in-game screenshot of a simple user interface (UI) to navigate through the game [3].

To further address accessibility and scalability limitations, a WebGL-based version of the game is currently under development using three.js. This implementation aims to support browser-based access through a shareable link, enabling repeated use from any location and device. The WebGL game is being designed to incorporate widely recognized gameplay mechanics and progression strategies while maintaining compatibility across diverse hardware configurations.

Figure 2: In-game screenshot from the adventure level-based computer video game showing (a) in-game 3D visualization, (b) game graphics developed following commercial games.

Significance in the Engineering Field

A strong understanding of materials is fundamental to civil engineering practice, as the performance, durability, and safety of civil infrastructure are directly governed by material behavior [1]. Civil engineers routinely design and evaluate structures and systems, such as buildings, bridges, pavements, and water infrastructure, that rely on materials including concrete, steel, asphalt, composites, and geomaterials [15]. The mechanical, chemical, and physical properties of these materials influence load-bearing capacity, deformation, failure mechanisms, and long-term service life under environmental exposure. Without a solid grasp of material behavior, design decisions may fail to account for time-dependent effects such as creep, shrinkage, corrosion, or chemical degradation [15-17]. On the other hand, gaming interventions in the engineering field have shown promise in recent years [18-19]. There are fewer gaming intervention approaches in the civil engineering field compared to software engineering or biomedical engineering. Again, beyond structural performance, understanding materials is increasingly critical for addressing sustainability, resilience, and lifecycle considerations in civil engineering. Material selection and processing affect embodied energy, carbon emissions, constructability, and maintenance requirements. As infrastructure systems are expected to perform under increasingly complex loading and environmental conditions, civil engineers must be able to connect material composition, microstructure, and processing to macroscopic performance. Developing this multiscale understanding early in undergraduate education is therefore essential for preparing students to make informed design decisions and to adapt to emerging materials and technologies in civil engineering practice.

Results

The initial VR game developed in Unreal Engine 4.27 used a simplified, level-based design with teleportation navigation and embedded 3D quizzes to support conceptual learning while minimizing cognitive and physical load. While the VR format enabled immersive visualization, hardware and comfort constraints reported by students and supported by the literature on VR's limitations [5] narrowed its scalability. Building on these findings, the computer-based version was developed in Unreal Engine 5.3 to improve usability and accessibility.

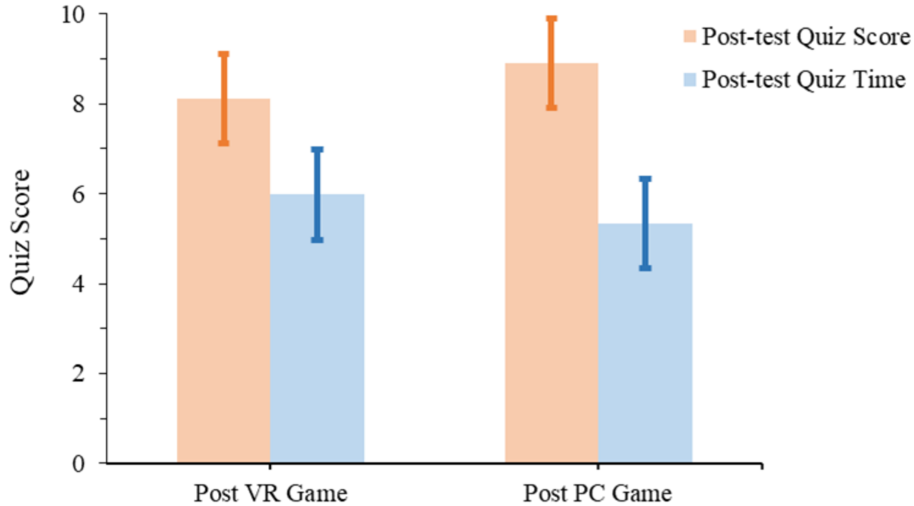

Figure 3: Comparison of post-test quiz score and completion time for VR and computer-based games

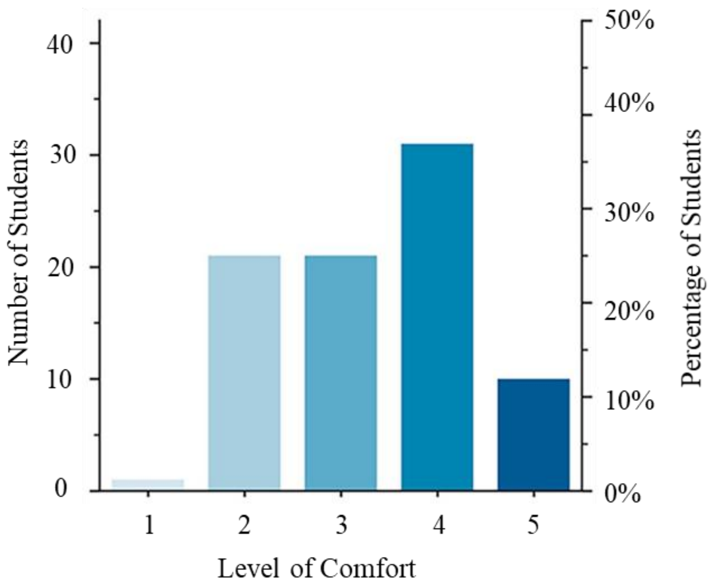

Figure 4: Comfort issues reported by students during the VR game through a Likert chart where 1 stands for very uncomfortable and 5 stands for very comfortable [3].

In addition to quantitative post-test results, selected student quotes from the gaming intervention are presented (Table 1) to visualize students' experiences of engagement and perceived learning value. The desktop game featured multi-level progression, enhanced visuals, and common game mechanics to sustain engagement while preserving interactive materials science learning without immersive hardware. The feedback comments from students and post-test results provide a comparative picture that addresses RQ1 and RQ2. The PC game students scored 9% higher than the VR game students, and they also took 10% less time to complete the test (Fig. 3). Both tests were multiple-choice, with the same difficulty level and number of questions. Again, student feedback illustrates their comfort level with the VR game (Fig. 4) and their experiences with the computer game (Table 1).

Table 1: Example of written feedback for an open-ended question on computer gaming experience

Student No.	Written Feedback Sentences
39	"Many topics of CEE 300 are covered in the game. It is a good way to review what I learned in the semester."
28	"Great start, might need more guidance for the players."
59	"It was enjoyable and more visual to learn crystallography."
27	"Jump sound and the planes annoyed me. Other than that, no issues"
73	"3D game made dizzy."

Conclusion

This study demonstrates that game-based learning can enhance undergraduate students' understanding of materials science, which is an essential foundation for civil engineering, while emphasizing the importance of accessible platforms to ensure inclusive participation. Compared to the VR implementation, the computer-based game achieved higher post-test quiz scores and reduced completion time, suggesting improved learning efficiency with fewer usability constraints. Although VR offered strong visualization benefits, hardware and user-comfort challenges limited scalability. Student feedback supported the educational value of both approaches. These findings motivate ongoing development of a lightweight WebGL-based game to reduce access barriers and enable scalable, repeatable, and inclusive materials science learning beyond traditional classroom and institutional settings.

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