BioLabVR: A Virtual Reality Application for Interactive Learning with Student Engagement Analytics

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ABSTRACT

This paper presents BioLabVR, an immersive educational system using Virtual Reality on Meta Quest 2 to improve the way students interact with biological concepts. Integrating hand-tracking, the application enables learners to navigate detailed 3D anatomical models, examine microscopic structures, and engage in quizzes aligned with curriculum objectives. Developed in Unity and enhanced with Cognitive3D analytics, the platform integrates intuitive interaction with behavioral data collection, offering insights into learner engagement and performance. By shifting from passive content delivery to hands-on exploration, the system enhances cognitive immersion, sustained attention, and a stronger connection between students and the concepts they study, encouraging deeper understanding in a modern educational context.

Author Keywords
Virtual Reality; immersive learning; anatomy education; learning analytics; educational application

ACM Classification Keywords
H.5.1. Multimedia Information Systems: Artificial, augmented, and virtual realities
H.5.2. User Interfaces: Interaction styles (e.g., commands, menus, forms, direct manipulation).

General Terms
Human Factors; Design; Measurement.

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INTRODUCTION
Modern education faces the ongoing challenge of keeping pace with the rapid evolution of technology and the changing expectations of learners. While traditional classroom instruction has long relied on passive methods such as textbooks, lectures, and static visuals, today's students require learning environments that are more interactive, engaging, and responsive to their needs.

In this landscape, Virtual Reality (VR) has emerged as a powerful educational tool. Its ability to create immersive 3D environments transforms how students engage with content, turning abstract concepts into experiences they can see, hear, and manipulate. VR does not simply replicate the classroom; it reimagines it, offering new ways to explore complex subjects like biology that often suffer from limited access to hands-on experiences [1], [5].

Middle school biology, for example, frequently depends on textbook illustrations and theoretical explanations. Yet the subject matter, whether the structure of the skeleton or the behavior of cells, demands spatial understanding and interactive exploration. In many schools, access to anatomical models, microscopes, or well-equipped labs is limited, making it challenging for students to achieve deep comprehension or lasting interest. These limitations have a direct impact on students' ability to engage with biological concepts in a meaningful way.

To address this gap, we introduce *BioLabVR*, a VR application developed for the Meta Quest 2 headset that invites students to interact with biological systems through intuitive and guided experiences. From examining the human skeleton and muscular groups to analyzing cellular slides under a virtual microscope, the application encourages students to learn by doing. Some modules conclude with a quiz that includes both multiple choice and interactive tasks, offering immediate feedback to reinforce key concepts.

The design of BioLabVR is rooted in proven educational theory. It supports embodied cognition, spatial reasoning, and multimodal learning by combining visual, auditory, and kinesthetic elements. The use of hand tracking, controller input, and audio narration ensures accessibility across a range of learning preferences. Importantly, the application runs offline and is optimized for the constraints of standalone VR hardware using low polygon assets and performance focused architecture built in Unity.

To better understand how students interact with the environment and where they may struggle or succeed, BioLabVR integrates *Cognitive3D* [4], an analytics platform designed specifically for immersive experiences. This tool enables the collection of spatial data, gaze tracking, and interaction metrics, which can help educators gain valuable insights into user behavior and learning patterns. By analyzing these data points, instructors can assess learning outcomes beyond traditional testing and adapt future content to better meet student needs.

With a modular structure, BioLabVR can easily expand to include additional systems or lessons. Its design makes it appropriate even in classrooms with limited resources, and its gamified components support long-term understanding and continuous engagement [3].

This paper presents the development and testing of BioLabVR, a virtual reality educational application designed to enhance biology learning. We begin by outlining the pedagogical principles that guided the project, followed by an overview of related research and the conceptual architecture. The following sections cover the technical implementation and insights from early user testing, before concluding with a discussion on educational outcomes and potential future directions.

RELATED WORK

Virtual Reality is increasingly recognized as a valuable tool in education, offering interactive environments that shift the focus from passive to active learning. Research has emphasized its potential to support student-centered approaches and deepen conceptual understanding. For example, immersive environments have been shown to improve motivation and engagement compared to traditional methods such as textbooks or lectures [1], [11]. Makransky and Lilleholt [7] found that VR enhances intrinsic motivation by creating emotionally engaging and memorable experiences. As education systems adopt more active learning models, VR is becoming a practical component of modern pedagogy.

One of the key benefits of VR is its ability to enhance student engagement and motivation through immersion. A systematic review by AlAli and Wardat [1] reports that 70–90% of students show increased involvement when using VR-based tools. The sense of presence in immersive environments helps learners connect more deeply with the content. This is particularly relevant in biology, where abstract and spatially complex concepts are difficult to understand using static images. Immersive 3D environments support both cognitive and emotional engagement, improving the quality of the learning experience.

In addition to engagement, VR also improves learning outcomes and information retention. As access to digital devices increases, students are exposed to more interactive formats, while attention spans tend to decrease. VR addresses these challenges by aligning with the preferences of learners raised in the information age [7], [11]. Moreover, it enables adaptation to different learning styles and paces [6]. Studies [1] show that students using VR achieve higher scores on assessments, with improvements ranging from 15% to 30% compared to traditional methods. These results demonstrate the potential of VR to complement conventional instruction and improve the way students retain and apply new information.

Makransky and Lilleholt [7] also proposed a structural equation model that describes the factors contributing to successful learning in VR environments. The model identifies key mediators such as presence, motivation, enjoyment, cognitive benefit, and reflective thinking. According to their findings, presence plays a central role in emotional and cognitive engagement, which in turn supports perceived learning outcomes. Additional factors like ease of use and active learning contribute indirectly by enhancing cognitive absorption and satisfaction.

These theoretical foundations support the use of VR in education and inform the design of applications like BioLabVR, which aims to promote presence and active control through meaningful interaction [5], [11].

Biology is well suited for VR-based learning. Many biological systems are complex, dynamic, or invisible to the naked eye. VR enables detailed visualization and interaction with anatomical structures and microscopic entities, offering a level of spatial understanding that static materials cannot provide. Virtual microscopes and anatomical simulations can be useful in teaching cell biology and human anatomy, particularly when physical lab access is limited.

The effectiveness of VR in learning is also supported by constructivist learning theory, which emphasizes active knowledge construction through experience and reflection. In this context, VR offers a platform for meaningful engagement, allowing students to explore and interact with content [3]. Makransky [7] found that students in VR environments experience flow states more frequently than those in traditional settings, which correlates with better academic outcomes and longer retention.

Teacher perspectives also influence VR adoption in the classroom. Although most educators acknowledge its pedagogical value, some hesitate to implement it due to lack of training or institutional support. Southgate [12] argues that successful integration requires not only technical familiarity but also alignment with curriculum standards and assessment methods. Minocha [9] notes that VR should be viewed as a complement to traditional teaching, not a replacement.

Several VR applications for biology education have emerged in recent years. BioDigital Human [2] offers interactive 3D models of the human body with guided exploration and customizable layers, mostly aimed at higher education. Sharecare YOU [10] allows users to examine anatomy and disease progression in real time, providing insights into physiological processes. ClassVR [13] offers a school-ready ecosystem that includes VR headsets, lesson control for teachers, and curriculum-aligned content.

These platforms demonstrate the growing interest in VR for science education but differ in their pedagogical structure. BioLabVR distinguishes itself by focusing on guided, modular learning with interaction-dependent progression.

Rather than offering passive visualization, it integrates content delivery with checkpoints, feedback, and context-aware narration tailored to middle school learners. The application also addresses interaction logic, requiring students to complete tasks before advancing, reinforcing understanding at each stage.

While many existing VR platforms offer detailed visuals or flexible content navigation, BioLabVR emphasizes consistency, simplicity, and classroom readiness. The application was developed with standalone use in mind, requiring no external infrastructure or complex setup. Its integration of real-time analytics and offline functionality makes it particularly suited for schools with limited resources, where ease of deployment and insight into student interaction are equally important.

Overall, existing research confirms that VR can improve engagement, cognitive focus, and learning outcomes. BioLabVR builds on these findings to provide an accessible and structured learning experience. Its design is informed by theoretical models and practical insights from existing tools, aiming to enhance student understanding through immersive, hands-on learning.

PROPOSED SOLUTION

The development of BioLabVR was guided by both pedagogical goals and technical constraints, with the aim of delivering an immersive, interactive learning experience that remains accessible on standalone VR devices like Meta Quest 2. The application was built using the Unity engine, integrating multiple components to manage interaction, input, analytics, and performance.

The conceptual architecture of the system, as seen in Figure 1, reflects this layered approach. The VR lab environment includes core packages such as the XR Interaction Toolkit for managing controller and hand input, the Meta XR SDK for accessing native headset features, and the Cognitive3D SDK for analytics. These components are handled by Unity's XR Plug-in Management system and operate through the OpenXR API, ensuring compatibility with a wide range of XR hardware. This design enables the application to deploy seamlessly to the Meta Quest 2, supporting native interaction features and smooth performance.

BioLabVR was developed as a modular VR application tailored for standalone devices, with the goal of enhancing biology education through immersive and interactive exploration. The application is built using Unity and designed to run efficiently on the Meta Quest 2 headset, using its support for hand tracking and controller input.

The application is structured around individual learning scenes, each focused on a specific topic such as the skeletal system, muscular system, or cellular biology. Navigation between scenes is managed through a centralized mechanism that loads the corresponding module based on user choices from the main menu. To maintain optimal performance on standalone VR hardware, the application uses direct scene loading. Each time a new scene is accessed, it replaces the previous one entirely. This approach avoids memory overload by keeping only the active learning environment in use at any given time, without the need for explicit unloading logic.

Transitions are instantaneous and maintain a sense of continuity by preserving user preferences and learning state. Student progress is persistently tracked across modules using Unity's PlayerPrefs, a lightweight key-value storage system designed for local data persistence. As users interact with essential scene elements, the application marks each as completed by updating the corresponding keys in PlayerPrefs. This local storage approach allows the application to implement conditional behaviors, such as unlocking quizzes or showing completion indicators, while

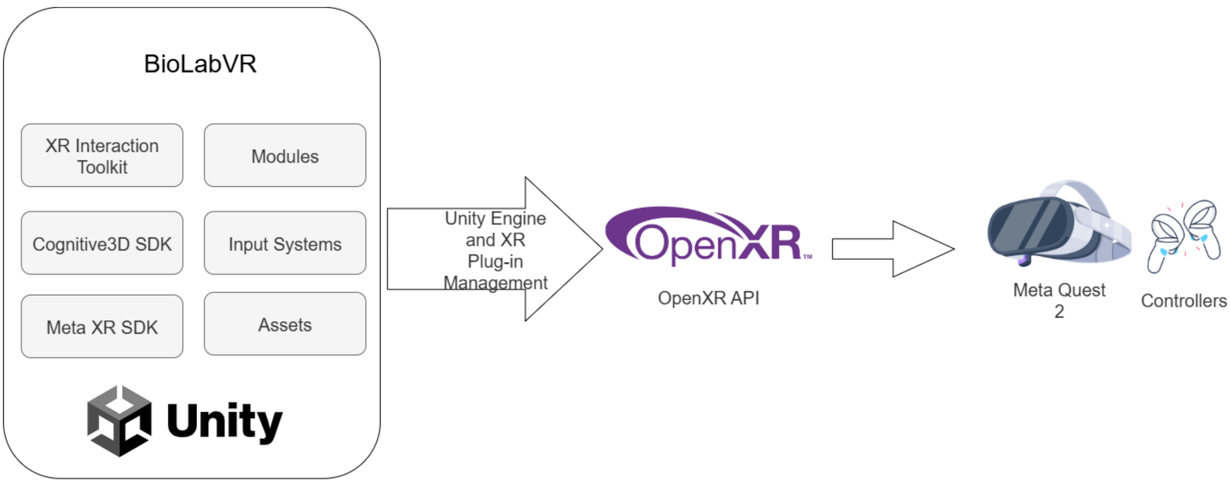

Figure 1. Conceptual Architecture of BioLabVR

maintaining full offline functionality on standalone VR devices. Each module encourages active exploration through spatial interaction. Users can approach, rotate, and manipulate objects using hand gestures or controller input.

Certain objects are augmented with explanatory text or audio, promoting multimodal learning. In some scenes, users are presented with quizzes that include multiple-choice questions or interactive challenges requiring them to select specific objects within the scene.

To provide useful insights into user behavior and learning outcomes, BioLabVR integrates Cognitive3D, a spatial analytics platform designed for XR applications. During usage, the application collects non-intrusive interaction data, such as time spent on tasks, selected objects, gaze direction, and hand movement. This data is transmitted to the Cognitive3D dashboard, where instructors or researchers can visualize and analyze usage patterns. One key feature used of Cognitive3D is SceneExplorer, which enables a spatial replay of each session, allowing developers and educators to review the user's path, focus of attention, and decision-making process within the 3D environment. This feature supports the evaluation of learning engagement and allows for evidence-based improvements to future versions of the application.

The system's architecture supports future expansion by encapsulating each functional module within its own dedicated Unity scene. This modular separation allows new biological content to be added simply by creating additional scenes and registering them in the existing navigation logic. Because each module functions independently (see Figure 2), updates or changes can be made without affecting the rest of the application.

To ensure smooth performance on the Meta Quest 2, several optimization techniques were applied. All 3D models are designed or imported as low-polygon assets, reducing the number of vertices the device must process. The application maintains a stable framerate by using baked lighting, compressed textures, and lightweight shaders, all optimized to reduce GPU load and memory consumption.

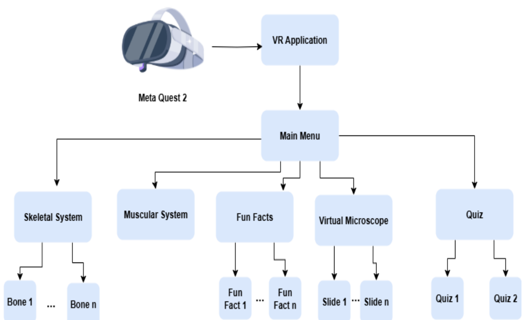

Figure 2. Modules of BioLabVR

USER INTERFACE

Input Type	Supported Modules	Action Type
Hand Tracking	All modules	Select, Grab, Point, Trigger Audio
Controller Input	All modules	Select, Teleport, UI interaction

Table 1. Table of Input Types and Associated Actions

The user interface (UI) of BioLabVR was designed to be simple and clear, especially considering the needs of middle school students using standalone VR headsets like the Meta Quest 2. Each UI element was placed strategically to minimize head and neck movement, reduce visual clutter, and support a natural interaction flow.

Navigation through the application relies on large, colored buttons with consistent positioning across scenes. This ensures that users can easily recognize interactive elements and understand their functions without prior instruction. In each module, contextual interfaces are kept minimal to avoid obstructing the view of 3D content. For example, anatomy modules use floating UI panels, allowing learners to stay focused on the model while accessing interactive features.

Interactive cues are used throughout the application to guide users without interrupting immersion. Visual arrows indicate clickable bones, while color changes and subtle animations provide feedback when selections are made. This reduces cognitive load and supports intuitive exploration.

To maintain consistency, the same visual language is applied across all modules: rounded corners, soft pastel tones, and high-contrast text for readability. These design decisions also help reduce visual fatigue during longer sessions. The UI dynamically adapts to user progress. Certain elements, like quiz buttons, become available only after prerequisite actions have been completed. This conditional logic ensures a structured flow through each learning module and reinforces the idea of progression.

Figure 3. Main Menu Scene

Design Across Modules

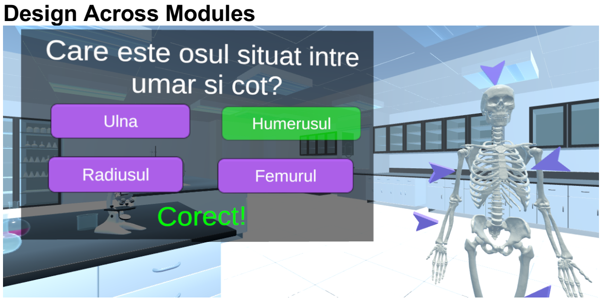

Figure 4. Interactive Quiz Scene

The skeletal system module displays a low-poly but anatomically structured model of the human skeleton. Interactive arrows point toward selectable bones. This design reinforces spatial learning and encourages active exploration. The bones can be selected directly using hand tracking or controllers, and selecting a bone triggers contextual information or quiz activation logic.

Muscle selection follows a similar structure to the skeletal module. On the right side of the user interface, a panel lists major muscles such as Biceps, Deltoid, and Quadriceps. When a muscle is selected, the model visually highlights the area, and an arrow is animated toward it to guide the learner's attention. This interactive flow strengthens the connection between the abstract term and its anatomical representation.

In the lab room, realistic but simplified 3D assets are placed on a desk to simulate real laboratory equipment. These elements act as entry points to detailed microscopy scenes, where users can view cell samples. Assets were kept low-poly to maintain smooth performance on the Meta Quest 2 without sacrificing educational clarity.

As seen in Figure 4, the quiz system supports both traditional multiple-choice formats and interactive questions. Multiple choice uses a four-button grid layout, and buttons are large enough for precise selection in VR. Interactive questions require users to select a body part directly in the scene, reinforcing knowledge through action. These two quiz types alternate to maintain engagement and encourage different cognitive skills.

After each answer, the user receives immediate feedback, displayed prominently in the scene using large text and color cues (green for correct, red for incorrect). At the end of each quiz module, a summary screen presents the final score. This design supports positive reinforcement and helps learners self-assess their understanding. These elements were positioned to remain visible within the user's natural field of view, minimizing disorientation or neck fatigue.

EXPERIMENTAL WORK

The experimental phase of this project focused on assessing the technical stability, user experience, and learning flow of BioLabVR through a series of internal testing sessions. The internal testing sessions involved test runs conducted by fellow engineers, using Meta Quest 2 headsets in an indoor setting simulating classroom conditions. By classroom-simulated conditions, we refer to a controlled indoor environment with natural lighting, and freedom of movement within a limited physical space, similar to how the application would be used in an actual classroom. These sessions aimed to evaluate the readiness of the application for future deployment in educational settings.

Each session involved exploring individual modules with attention paid to scene transitions, performance consistency, interaction reliability, and content accessibility. No formal testing with middle school students has been conducted at this stage; however, the observations made during development cycles have informed interface adjustments and interaction logic.

The application was tested under classroom-simulated conditions using the Meta Quest 2 headset. Quiz navigation, scene transitions, and object selection were evaluated for responsiveness and intuitiveness. During these sessions, there were simulated typical user actions like selecting bones, zooming through microscope levels, answering quiz questions, to assess how well each feature aligned with the intended pedagogical flow.

The analytics platform Cognitive3D was configured and used to record session data such as interaction hotspots and time spent per module. Although the data was not collected from real students, it validated that session tracking and data export were functioning correctly, and that visual heatmaps could be generated successfully through the Scene Explorer feature. In addition to qualitative observations, session analytics collected with Cognitive3D provided metrics on application performance, comfort, and immersion.

The dashboard in Figure 5 summarizes data recorded during internal test sessions.

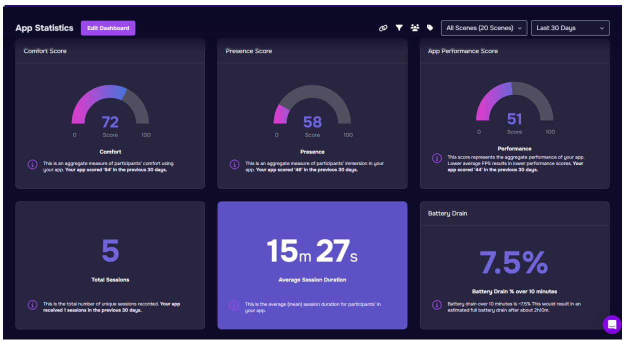

Figure 5. Cognitive3D Dashboard

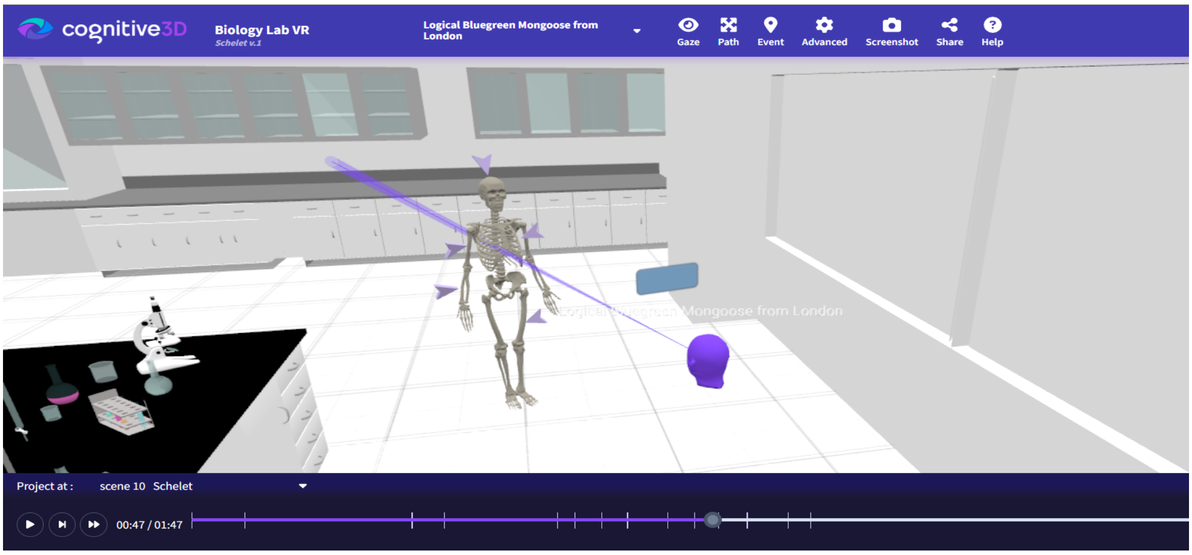

Figure 6. Cognitive3D SceneExplorer

The comfort score averaged 72, suggesting that the current experience design, including interaction speed, animation pacing, and UI layout, offers a relatively pleasant experience for users during short to medium-length sessions. According to Cognitive3D's metric model, this score is computed from factors such as head and controller movement stability, sudden rotational changes, and camera jitter. A higher score typically indicates that the user is not exposed to discomfort-inducing motions or abrupt visual changes, and that the system maintains consistent frame pacing.

The *presence score* recorded was 58, reflecting a moderate level of user immersion. This metric is calculated using session-level gaze data, engagement duration, fixation patterns, and interaction density within the scene. A higher presence score implies sustained attention and a strong sense of "being there." In this case, the moderate result may indicate that while users were engaged, deeper immersion could be supported by additional feedback mechanisms, narrative context, or task variation to increase involvement.

The *application performance score* was measured at 51, primarily influenced by rendering and frame rate stability. This score is based on internal telemetry logs capturing frame drops, latency in user input response, and the computational complexity of loaded scenes. While the system maintained usability across all modules, scenes with higher geometric detail produced brief performance dips on the standalone headset.

These scores provide meaningful data for future optimization. The metrics, as defined by Cognitive3D, offer quantifiable insights grounded in user interaction and device performance data, allowing for targeted refinements in future development cycles.

Other session metrics indicate that the average session duration was approximately 15 minutes and 27 seconds, with a total of 5 unique sessions recorded. This aligns with the expected flow of a complete learning module. Battery consumption was measured at 7.5% per 10 minutes, suggesting a full battery depletion time of around 2 hours on Meta Quest 2 hardware, which is acceptable for classroom usage.

These early-stage metrics confirm that the application is stable and performant enough for extended use and lay the groundwork for formal usability testing with students in future research.

In addition to the global session metrics, the *SceneExplorer* tool provided by Cognitive3D allowed for a detailed visual reconstruction of the user's navigation and gaze behavior during each module. As illustrated in Figure 6, SceneExplorer renders a 3D playback of user sessions, showing where participants looked, moved, and interacted within the scene. Gaze vectors and fixations are mapped over time, revealing focal attention patterns and interaction hotspots. In the skeletal module, for instance, gaze activity was concentrated on the upper torso and head regions of the model, suggesting that these areas were more visually notable or more intuitively guided by the interface.

The timeline at the bottom of the interface displays the sequence of scene events, while real-time gaze overlays revealed whether learners visually processed key interactive elements such as floating arrows or text prompts. This kind of spatial-temporal data is particularly valuable for evaluating instructional design, as it highlights which parts of the environment capture the attention, and which may require better visual prioritization or guidance.

Together, these analytics tools allowed for more than just performance validation, they supported qualitative assessment of user attention, progression, and interaction fidelity. By replaying actual user behavior and correlating it with event timelines, SceneExplorer helped pinpoint several interface refinements, particularly in the placement of interaction triggers and the pacing of instructional prompts.

In parallel with spatial visualization tools like SceneExplorer, Cognitive3D also provides session-level analytics in the form of automatically generated *Session Overview Reports*. These reports consolidate interaction data and summarize key metrics captured during a VR session, such as session duration, completed events, scene transitions, and engagement indicators. *Teachers and educational researchers* can use these reports to trace how students progress through the application, identify how much time they spend in each scene, and verify whether learning tasks have been successfully carried out.

Table 2 presents a chronological log of scene transitions recorded during a VR session in BioLabVR using Cognitive3D. Each row captures an event such as a scene being loaded or unloaded, along with its timestamp, scene name and unique identifier. The log helps visualize how the user navigated through modules like "Skull" or "Humerus," and provides useful insights for evaluating both technical flow and user engagement during the session.

Each report includes a detailed timeline of events, capturing actions like scene loading, object selection. This enables instructors to detect behavioral patterns, such as hesitation, repetitive actions, or skipped content. If wanted, the reports can also include responses to exit poll questions, and learning objective completion, offering a more comprehensive view of the student’s experience.

By using these reports, teachers gain valuable insights into how students interact with the virtual content, not just whether they reach the end of a module, but how they navigate, what they focus on, and where they might need additional guidance. This makes Session Overview Reports a valuable pedagogical tool, supporting both instructional evaluation and the personalization of learning strategies.

These initial experiments confirm that BioLabVR is technically stable, pedagogically aligned, and functionally ready for real-world classroom trials. The integration of Cognitive3D has proven essential not only for measuring comfort, performance, and presence, but also for understanding user behavior through spatial analytics and session reports. While the current insights are based on internal testing rather than tests with students, they offer a reliable foundation for further refinement.

The combination of observational feedback, interaction metrics, and immersive session replays helps continuous improvement of both content and experience design.

Event	Scene Id	Scene Name	Time
c3d.Scene Unload	4e74df90-88e8-46cc-87df-18cce75e422b	Skeleton	00:03s
c3d.Scene Load	b3e07931-d38d-496e-a2c3-9803a5be10be	Skull	00:25s
c3d.Scene Unload	25ce38b8-e314-4ae3-b6d2	Humerus	01:23s

Table 2. Cognitive3D Event Log Format

As the application moves toward formal evaluation in educational settings, the groundwork laid through this experimental phase ensures a strong starting point for measuring impact, usability, and learning outcomes.

DISCUSSIONS

The testing sessions provided useful feedback on how BioLabVR behaves in real usage scenarios. Most interactions worked as intended, with stable performance and responsive controls across all modules. The comfort score of 72 and presence score of 58 suggest that users were able to stay focused and navigate the experience without issues like motion sickness or visual overload.

Heatmaps and gaze data showed that attention was directed toward the expected areas such as interactive arrows, bones, or quiz elements, which indicates that the interface successfully guides users through the content. This kind of feedback is especially important in VR, where visual cues and pacing can easily confuse or fatigue users if not well-balanced.

Compared to other educational VR platforms, BioLabVR adds value through its structured progression and built-in quizzes. The integration of Cognitive3D also gives teachers and developers access to detailed interaction data, which can be used to improve future versions without needing to rely only on student test scores.

Although these results come from internal testing and not real classroom use, they show that the application is technically ready and user-friendly. The next step will be to validate its educational impact in real conditions, with middle school students and teachers involved in the process.

CONCLUSIONS

This work presented the development and internal testing of BioLabVR, an immersive educational application designed to support biology learning for middle school students using virtual reality technology. Through its modular architecture and hands-on interaction system, BioLabVR allows students to explore anatomical structures, engage with virtual microscope slides, and assess their understanding through quizzes, all within an intuitive and performance-conscious environment.

The technical implementation, informed by cognitive and pedagogical theories, emphasizes accessibility, guided learning, and interactive progression. The integration of tools such as Cognitive3D enabled the collection of valuable session analytics, helping validate the application's stability, usability, and instructional design. Notably, metrics such as comfort, presence, and system performance provided a quantifiable baseline for evaluating the learning experience, while tools like SceneExplorer and session reports can offer granular insights into student attention and interaction behavior.

While real student testing is still pending, internal evaluations confirmed that scene transitions, input methods, and user guidance are functional and ready for broader deployment. The ability to visualize user focus and engagement across different modules has proven essential in refining interface elements and adjusting instructional pacing to better align with how students naturally explore virtual environments.

Looking forward, the next phase of the project includes conducting formal classroom studies with middle school students to evaluate the app's impact on knowledge retention, engagement, and ease of use. Additional modules (e.g., circulatory or nervous systems), adaptive feedback mechanisms, and multilingual support are also being considered to enhance inclusivity and curriculum coverage. Furthermore, deeper analysis of user interaction patterns will support data-driven refinement of both content and interaction logic.

BioLabVR demonstrates that standalone VR systems, when carefully designed, can provide scalable and effective alternatives to traditional biology instruction. By combining immersive visualization, intuitive interaction, and analytics-driven evaluation, the project lays the groundwork for a broader integration of immersive technologies in the classroom.

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