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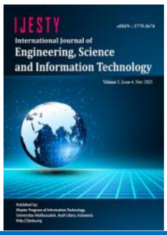

Evaluating User Experience of a Virtual Reality-Based Adaptive Learning Application on Chemical Compound Structures for High School Students

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Abstract

Recognizing the significant spatial visualization challenges that high school students face in understanding abstract chemical compound structures—a limitation often inherent in conventional teaching methods based on 2D diagrams—this research presents the comprehensive development and user experience (UX) evaluation of an innovative adaptive learning application in Virtual Reality (VR). The application, developed using the Unity 3D engine and configured via XR Plugin Management to ensure broad hardware compatibility, places students in an interactive virtual laboratory. Within it, students can directly manipulate meticulously designed 3D atomic models to build molecules, observe the formation of covalent and ionic bonds, and interact with dynamic chemical processes. Its key innovation is the integration of an intelligent adaptive learning algorithm, which utilizes a Firebase cloud database to analyze user performance metrics—such as accuracy, completion time, and recurring areas of difficulty. Based on this data, the system dynamically personalizes learning pathways by recommending remedial content or more challenging topics. Furthermore, assessment materials such as quizzes were efficiently generated using large language models (LLMs) to ensure relevance and quality. An in-depth UX evaluation was conducted with high school students using a mixed-methods approach, combining standardized questionnaires to quantitatively measure metrics like usability, engagement, and satisfaction, with qualitative feedback sessions for contextual insights. The results indicate a highly positive user experience; participants reported that the ability to directly manipulate molecules in 3D space significantly enhanced their conceptual understanding, bridging the gap between theory and visualization. The adaptive system was highly valued for its ability to adjust to individual learning paces, which was shown to boost confidence and reduce frustration. This research provides strong evidence that VR-based adaptive learning platforms are powerful pedagogical tools, capable of transforming chemistry education by making complex scientific concepts more accessible, engaging, and comprehensible.

Keywords: *Adaptive Learning, Compound Structure, Virtual Reality, User Experience Questionnaire.*

1. Introduction

Over the years, the world of education has changed significantly, especially with the arrival of technology. Traditional methods are now beginning to merge with digital platforms, completely transforming how knowledge is taught. The emergence of technologies like Augmented Reality (AR) [1] and Virtual Reality (VR) [2] is further reshaping the educational landscape, promising immersive and interactive learning experiences. Currently, many VR technology companies, both domestic and international, are showing great interest in applying their technology in schools. Although a few pioneering institutions have started experimenting with VR labs and training modules, its widespread adoption is still in its early stages, particularly in Indonesia.

Looking at the situation in Indonesia, while the adoption of VR in education may seem slower than in other parts of the world, the potential is immense. With a large population and a rising demand for innovative learning solutions, there is a huge, untapped market for VR technology in the education sector. It's also worth noting that major tech companies and educational institutions in Indonesia are beginning to invest in VR training initiatives, which signals a growing recognition of VR's role in shaping the future of education. As the educational landscape evolves, incorporating VR into teaching methods holds the promise of delivering more engaging and effective learning experiences for students throughout Indonesia.

Adaptive virtual learning environments have made significant progress in tailoring education to individual student needs to optimize learning outcomes. For example, research by Alam and Ullah (2021) on Adaptive 3D-Virtual Learning Environments (3D-VLEs) highlights how these systems can dynamically adjust content to meet each student's specific learning goals [3].

In a related study, Liu et al. (2020) investigated the effects of an adaptive learning program on student performance across several disciplines. The program provided remedial instruction in biology, chemistry, mathematics, and information literacy to first-year students in a professional pharmacy degree program. Using a mixed-methods approach, the researchers analyzed learning outcomes, student engagement with the system, and various characteristics that influenced participation.

Notably, the findings showed that the adaptive program was highly effective at closing knowledge gaps specifically in chemistry [4], though similar effects were not observed in other subjects. While students reported positive overall experiences, the research also revealed that time constraints and design flaws within the system may have hindered students from achieving optimal success [5].

This study employs the User Experience Questionnaire (UEQ) to evaluate the user experience within the adaptive virtual reality learning environment. Unlike conventional methods that often rely solely on objective performance data, the UEQ provides a comprehensive framework for capturing subjective user feedback and perceptions.

By administering the questionnaire to participants after their interaction with the virtual environment, this research aims to gain detailed insights into key dimensions of their experience. These include the system's attractiveness, usability, efficiency, dependability, as well as the levels of stimulation and novelty it provides.

In this study, we are involving the key people who will be affected—namely students and teachers—in the design and evaluation of the adaptive virtual reality learning environment. By including their different perspectives, we aim to make the development process better. This helps us ensure that the final learning platform truly matches what its users need and want.

2. Literature Review

Virtual Reality (VR) is a modern technology that lets users enter a three-dimensional, simulated world created by a computer. By wearing special gear like headsets and gloves, people can interact with and move through this virtual world, which is made to feel very similar to real life. Using computer graphics, sensors, and other tools, VR systems create an interactive digital space where users can see, hear, and sometimes feel things as they happen.

At the heart of VR technology are advanced systems that constantly monitor and update the virtual world based on what the user does [6]. This immediate feedback lets users freely explore and interact with virtual objects, which gives them a strong feeling of being present and in control. Unlike traditional media like movies or photos, VR isn't flat. It goes beyond a 2D screen and gives users a sense of depth, scale, and space with incredible realism.

VR technology is now used in many different fields, including entertainment [7], education [8], healthcare, and professional training. In education, VR offers some clear advantages. First, it helps teachers present complex topics or show environments that are difficult to explain with traditional methods [9]. By using these immersive simulations, students can engage with abstract or hard-to-access subjects in a direct and hands-on way, which helps them understand and remember the information better[10], [11].

Virtual Reality (VR) systems use many different technologies and designs, but they all share the same goal: to create immersive and interactive experiences for the user. We can generally group these systems into three main types based on how they function and are built.

These simple virtual reality systems, often just called desktop VR, use a standard computer monitor to show the virtual environment. Users can interact with objects in this virtual space using common input devices like a mouse, 3D controllers, joysticks, or sometimes special glasses and sensors. While these desktop VR systems are flexible and affordable, their main weakness is that they don't feel very immersive. This is because users are still fully aware of their real-world surroundings. Despite this drawback, desktop VR is still widely used for many purposes, including in education to create virtual course materials and learning environments.

Immersive virtual reality systems offer a much stronger sense of being "inside" the experience compared to desktop VR [12]. These systems use special display devices, like headsets, to completely block out the sights and sounds of the real world, fully placing the user in the virtual environment. To interact, participants use hand-controlled devices such as data gloves and trackers. This allows them to move around and handle virtual objects within this closed, immersive space. The system used in this program is an immersive one, which we chose to give users a highly engaging and interactive learning experience [13].

Shared virtual reality systems are designed to allow multiple users to enter the same virtual environment at the same time over a network [14]. By using immersive VR technology, these systems make it possible for people in different physical locations to learn and have experiences together.

In this shared space, all participants can interact with and observe the same virtual objects, which is great for collaborative learning and remote education. This type of VR has a lot of potential for applications like virtual operating rooms or group training simulations, allowing users to learn together in an immersive way, no matter where they are in the world.

Adaptive learning is a modern educational method that uses technology to adjust the learning experience for each student's unique needs and abilities. In a traditional classroom, everyone is taught the same way. Adaptive learning is different; it uses smart computer programs and data to customize the lessons, pace, and teaching style for every single student.

One of the key features of adaptive learning is its ability to give personalized instruction. The system constantly checks what a student is good at, what they struggle with, and how they prefer to learn. Based on that information, it creates a unique learning path for each person. This personal approach ensures students get instruction that matches their skill level, allowing them to learn at their own pace and focus on areas where they need more help.

Furthermore, adaptive learning platforms constantly adjust the material based on a student's answers and progress [15]. They present information in logical steps, increasing the difficulty only after a student has mastered the previous level. This method keeps students feeling challenged but not overwhelmed. The platforms also offer personal feedback and extra help, giving students the support they need to understand difficult topics.

Beyond helping individual students, adaptive learning also provides valuable information to teachers about their students' learning patterns and performance [16]. By analyzing data on student engagement, progress, and areas needing improvement, teachers can get a deeper understanding of each student's needs. This data helps teachers make better-informed decisions and change their teaching methods to improve student results.

In short, adaptive learning represents a major shift in education. It offers a dynamic and personal approach that helps students achieve their full potential [17]. By using technology to create custom lessons, provide targeted feedback, and track progress, adaptive learning helps educators create more effective and engaging experiences that meet the diverse needs of today's learners.

The User Experience Questionnaire (UEQ) is a tool used to measure a user's personal feelings and thoughts when they interact with a product, system, or service [18]. It gives designers and developers valuable information about user satisfaction, how easy the product is to use, and how it makes people feel. This helps them understand how their designs are truly perceived and experienced.

Typically, a UEQ consists of a standard set of questions that users answer after trying a product. These questions cover different aspects of the experience, such as usability, appearance, efficiency, and whether the product feels new or exciting. Users rate each item on a scale (like a Likert scale) to show how they feel about it.

One of the main benefits of the UEQ is its ability to capture these personal feelings and emotions. This provides important 'qualitative' data (about feelings) that complements the 'quantitative' data (about numbers and performance) from other tests. By understanding these emotional responses, designers can better identify what users need, what they like, and what frustrates them, which is essential for making improvements.

The UEQ is made up of six main scales that cover a total of 26 different items. Each item is rated on a 7-point scale, from -3 (very bad) to +3 (very good). These scales measure various aspects of the user experience. For instance, Attractiveness assesses the product's overall appeal. Clarity evaluates how easy it is to understand, while Efficiency measures how quickly users can get things done. Furthermore, Dependability looks at whether the user feels in control and trusts the product. Stimulation measures how exciting the product is to use, and finally, Novelty assesses if it feels creative and innovative.

Overall, the UEQ is a valuable tool for understanding how users truly feel about a product or system [19]. By capturing these personal experiences, it allows designers to create products that are more intuitive, engaging, and user-focused, which helps meet the actual needs and expectations of their audience [20].

3. Methods

First, the research and development process commences with the Modeling and Importing of 3D Objects. This foundational stage involves the creation of all necessary visual assets using industry-standard 3D modeling software like Blender or Autodesk Maya. We meticulously design and build the core components of the virtual environment, which include the interactive 3D Menu Area for navigation, the immersive 3D Area Stage that serves as the main laboratory space, and detailed 3D Atom Objects representing various elements. These models are then optimized for real-time rendering and exported in the FBX (Filmbox) format, a versatile file type that preserves geometry, materials, and animation data. Subsequently, these FBX files are imported into the Unity 3D engine, which serves as the central platform for development.

Within Unity, the initial step is to Configure the XR Plug-In for VR. This is a critical technical procedure where we set up Unity's XR (Extended Reality) Plugin Management framework to interface with target virtual reality hardware. This configuration ensures seamless compatibility with devices like the Meta Quest or HTC Vive, enabling the application to correctly interpret tracking data from the headset and controllers. This allows for an intuitive and immersive user experience where physical movements are accurately translated into the virtual world.

Following the hardware setup, the process moves to Scripting & Animation. Using the C# programming language, we develop the core mechanics and interaction logic of the virtual lab. This involves writing scripts that govern how users can manipulate objects, for instance, by allowing them to pick up, inspect, and combine atoms to form chemical compounds. Animations are also integrated to provide visual feedback and make the learning process more dynamic, such as illustrating the formation of a covalent bond or the transfer of electrons in an ionic bond.

A key innovation of this system is the implementation of an adaptive learning algorithm. This intelligent component is designed to personalize the educational journey for each user. The algorithm continuously analyzes user performance by tracking metrics such as completion time, accuracy, and recurring errors on specific tasks. Based on this data, it recommends new content or suggests repeating certain modules where the user has shown difficulty, thereby tailoring the experience to their individual learning pace and style.

To support this personalization, we integrate the application with Firebase Firestore, a flexible and scalable NoSQL cloud database. The system sends user data—including progress, quiz scores, and interaction patterns—to Firestore for storage and retrieval. This data persistence allows users to continue their sessions later and provides the necessary input for the adaptive algorithm to function effectively.

For the creation of assessments, such as placement tests and quizzes, we leverage the capabilities of large language models (LLMs). This modern approach is both highly efficient and effective. By training on vast datasets, LLMs can generate a wide range of relevant and contextually accurate questions. For example, we use carefully crafted prompts to produce test items on topics like chemical bonding and valence electrons. Prompts such as, "Generate 10 multiple-choice questions of increasing difficulty to identify the type of chemical bond (ionic, covalent, or metallic) in various compounds, including answer choices and detailed explanations for the correct answers," allow us to quickly create high-quality assessment materials.

The penultimate phase is a rigorous Evaluation cycle. This involves comprehensive Testing that covers both technical functionality (e.g., bug detection, performance optimization) and pedagogical effectiveness. Feedback is collected from trial users to assess the application's usability, engagement, and educational impact. As depicted by the revision loop in the architecture diagram, the insights gained from this evaluation are used to iteratively refine and improve the system's features, scripting, and user interface.

The final Result of this entire process is a fully-functional Virtual Lab for Learning Compound Structure. As summarized in Figure 1, this application provides an immersive, interactive, and personalized educational tool that enables students to explore and understand complex chemical concepts in a way that is not possible through traditional teaching methods.

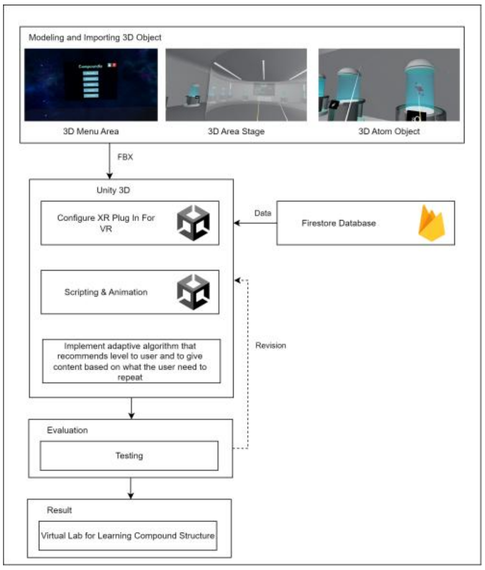

Fig 1. Research Flow Diagram

The experimental procedure begins with selecting a diverse and representative group of participants from tenth-grade high school students. Once selected, we guide the participants on how to log into the Virtual Reality (VR) application using their unique usernames. After logging in, each participant is directed to take a placement test, which is shown in Figure 2. This test is designed to measure their current understanding and skill level in the subject. The results from then used by the adaptive learning algorithm, which analyzes the answers to recommend the most suitable starting level for each student within the VR application.

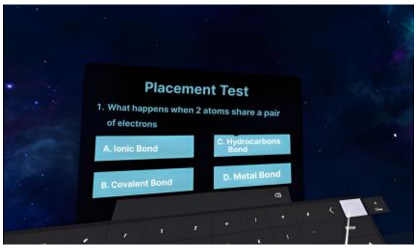

Fig 2. Placement Test UI

The main purpose of this tutorial is to get them familiar with the VR controls, how to move around, and how to interact with objects. This step ensures that all participants are comfortable and skilled enough to navigate the virtual space before they begin the main part of the study.

Fig 3. Tutorial Level

In the VR application designed for learning about chemical molecular structures, the gameplay revolves around constructing compounds using atoms within a virtual environment. Upon loading into a level, the game presents the player with a set of four compounds that they are tasked with constructing. The atoms necessary to build these compounds are scattered throughout the virtual space, each encapsulated with their atom symbol and corresponding number displayed on the capsule as shown is figure 4.

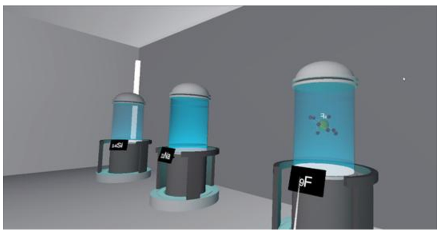

Fig 4. Atom Capsule

Players can interact with these atoms by grabbing them and placing them within a designated combining area as shown in figure 5. The objective is to connect the atoms in a manner that accurately represents the compound displayed on the screen before the allotted time runs out.

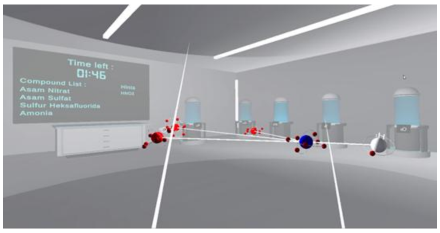

Fig 5. Combining Area

After finishing the tutorial, participants begin playing the main levels within the VR application. The adaptive learning algorithm automatically recommends these levels for each student. Participants are instructed to play each recommended level three times to ensure they get enough practice and exposure to the material.

As they play, the adaptive learning algorithm constantly monitors their performance and adjusts the recommendations, as illustrated in Figure 6. For example, if a student shows they are improving or have mastered a topic, the algorithm might suggest a more challenging level. On the other hand, if a student is struggling with a specific concept, the algorithm may recommend that they repeat a previous level or offer them additional support.

Fig 6. Game Over Menu UI

After the participants have finished the gameplay sessions, we ask them to provide feedback on their experience by using the User Experience Questionnaire (UEQ). This questionnaire prompts them to evaluate different aspects of the VR application, including its attractiveness, clarity, efficiency, dependability, stimulation, and novelty. We then collect and analyze these responses to get a better understanding of their perceptions and personal experiences with the application.

Finally, we analyze all the data we've gathered—from both the gameplay sessions and the UEQ answers—to see how effective the VR application was at improving the students' understanding of chemical molecular structures. By looking for connections between student performance, their UEQ ratings, and their learning results, we can draw conclusions about how well our VR-based adaptive learning approach works. This helps us determine if we were successful in creating a personalized and engaging learning experience for high school students.

4. Results and Discussion

Based on the results of the User Experience Questionnaire (UEQ) completed by 31 participants, the evaluation of the Virtual Reality (VR) application reveals a consistently positive user perception across all measured aspects. The data analysis, conducted with a 95% confidence level (p=0.05), shows that all assessment scales received a mean score above 1.0 on a range from -3 to +3, indicating a favorable user experience. Overall, the application's Attractiveness was rated positively with a mean score of 1.301, reflecting a pleasant general impression among users.

The primary strength of this VR application lies in its hedonic qualities, particularly in Stimulation, which achieved the highest mean score of 1.806. This value clearly indicates that users found the application highly engaging, exciting, and motivating to use. On the other hand, the other hedonic quality, Novelty, recorded the lowest mean score of 1.177. Although this score is still positive, it suggests that the application was not perceived as particularly innovative or creative by its users.

In terms of pragmatic quality or usability, the application also demonstrated excellent performance. Dependability earned a high score of 1.419, meaning users felt the application was controllable, predictable, and reliable during use. Furthermore, Efficiency was also rated very well with a mean score of 1.347, supported by the lowest standard deviation (0.755), which indicates a uniform opinion among users that the application allows tasks to be completed quickly and without excessive effort. The Perspicuity aspect, with a score of 1.218, shows that the application was easy to understand, although it had the highest standard deviation (1.064), suggesting a more varied level of understanding among the participants.

Statistically, the positive mean scores across all scales, combined with confidence intervals entirely above zero, significantly confirm that the user experience of this VR application is overwhelmingly positive. The varying standard deviations provide additional insight, showing that while the general perception is favorable, there are certain aspects like clarity where individual experiences were more diverse compared to others like efficiency.

Table 1. UEQ Result

Scale	Mean	Std. Dev.	Confidence	Confidence Interval
Attractiveness	1,301	0,968	0,341	0,960
Perspicuity	1,218	1,064	0,375	0,843
Efficiency	1,347	0,755	0,266	1,081
Dependability	1,419	0,936	0,330	1,090
Stimulation	1,806	0,993	0,350	1,457
Novelty	1,177	0,854	0,301	0,877

(N=31, CONFIDENT INTERVAL P=0.05 PER SCALE)

As shown in Figure 7, the results from the User Experience Questionnaire (UEQ) were very positive. The application received an "Above Average" score in four key areas: Attractiveness, Perspicuity (Clarity), Efficiency, and Dependability.
The results for Stimulation were even better, earning an "Excellent" rating. This places our application in the top 10% of all products compared in the UEQ database. Similarly, Novelty received a "Good" rating, meaning it performed better than 75% of the other benchmarked products.
Overall, these findings point to a very positive user experience. The excellent score for Stimulation is especially important, as it highlights just how immersive and engaging our virtual reality application is for users.

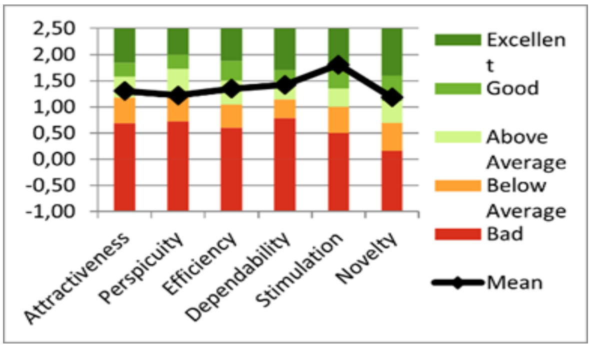

Fig 7. Confidence Intervals per Sauce UEQ

The positive ratings from the User Experience Questionnaire (UEQ) align with the positive impact we expected the application to have on learning behavior. The "Above Average" scores in Attractiveness, Perspicuity (Clarity), Efficiency, and Dependability suggest that users find the application engaging, clear, and easy to use. These are all crucial factors that encourage students to participate more actively in their own learning.
Furthermore, the "Excellent" rating for Stimulation, which places our application in the top 10% of all benchmarked products, shows how successful it is at capturing users' interest and motivation. This can greatly enhance their entire learning experience.
This strong connection between the favorable UEQ results and the app's ability to engage users proves its effectiveness. By making learning more stimulating, the application positively influences student behavior, which leads to increased participation, better understanding, and stronger retention of the educational material.

5. Conclusion

The results from the User Experience Questionnaire (UEQ) show that our immersive VR application had a positive impact on student learning. The application received above-average scores in key areas like Attractiveness, Perspicuity (Clarity), Efficiency, and Dependability. This indicates that users found the application engaging, clear, and easy to use, which suggests it successfully encourages active learning and understanding.
One particularly noteworthy finding was the "Excellent" rating for Stimulation from the UEQ, which places our application in the top 10% of all products compared using this tool. This highlights the app's ability to capture users' interest and keep them motivated throughout their learning journey. This strong connection between the high UEQ ratings and the app's power to engage users shows it has a real, positive influence on learning.
By helping students to participate more, understand better, and retain information, we believe this VR application shows great promise. It has the potential to help change the educational landscape and shape the future of learning.

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