



Exploring the Application of Virtual Reality in Mechanical Engineering Education

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Abstract. The advent of consumer-based virtual reality (VR) opens up opportunities to enhance digital teaching by immersing users in interactive learning experiences. This study focuses on the application of VR in mechanical engineering education. Specifically, the implemented VR scenario enables users to learn the process of assembling an internal combustion engine within a virtual environment. To compare the practicality of the implemented VR application, an A/B study was conducted comparing the VR method with a traditional lecture. Participants in both groups expressed their experience using post-questionnaires. The traditional lecture was praised for personal engagement and the ability to ask questions, while the VR group found animations and acoustic cues particularly valuable in ensuring correct assembly. Additionally, the use of virtual reality has a positive impact on user engagement while reducing temporal demand. In conclusion, the combination of VR applications with traditional teaching methods shows promise for enhancing student learning outcomes.

Keywords: Virtual Reality, Gamification, Education.

1 Introduction

Motivating and encouraging students to engage in school-related activities can be a challenging endeavor [1]. The nature of an effective learning experience undergoes significant transformations due to the growing cultural diversity among students [2]. As a result, teachers must adapt their instructional approaches to capture and maintain students' attention. Nowadays, educators employ a blended teaching methodology that combines traditional classroom instruction with technology-enhanced learning.

With the increasing presence of technology in the lives of children and students, digital learning has become increasingly relevant. Presently, online education provides opportunities for individuals who prefer the flexibility of remote learning [3]. Particularly during the Covid-19 pandemic, significant changes have occurred in educational settings [4]. Schools and other institutions were compelled to swiftly transition to remote education.

With the advent of digital learning, there exists a significant opportunity to enhance teaching and learning through the utilization of digital tools. The incorporation of digital learning tools can greatly enhance learning experiences [5]. One effective approach to improve the learning experience is by integrating gaming elements into the teaching process. The realm of gaming offers a wealth of concepts that can be applied to educational instructions, making tasks more engaging and enjoyable. This application of game elements to other subjects, such as education, is commonly referred to as gamification [6]. Gamification not only motivates students to actively participate in learning and classroom activities but also fosters collaboration within groups and encourages problem-solving skills [7].

While certain subjects, such as software engineering or languages, can be effectively taught online with relative ease, there are topics and lectures that pose greater challenges in terms of online instruction [8]. Specifically, subjects that necessitate hands-on experience, such as laboratory experiments, can be more difficult to convey through remote teaching. Access to laboratory equipment may be limited or prohibitively expensive in some cases. Finding a solution that utilizes digital content to simulate laboratory conditions can offer significant benefits. By

providing the opportunity to experience laboratory conditions through digital content, students can still engage in practical learning experiences. This approach can bridge the gap and provide valuable learning opportunities for those who lack access to physical laboratory equipment.

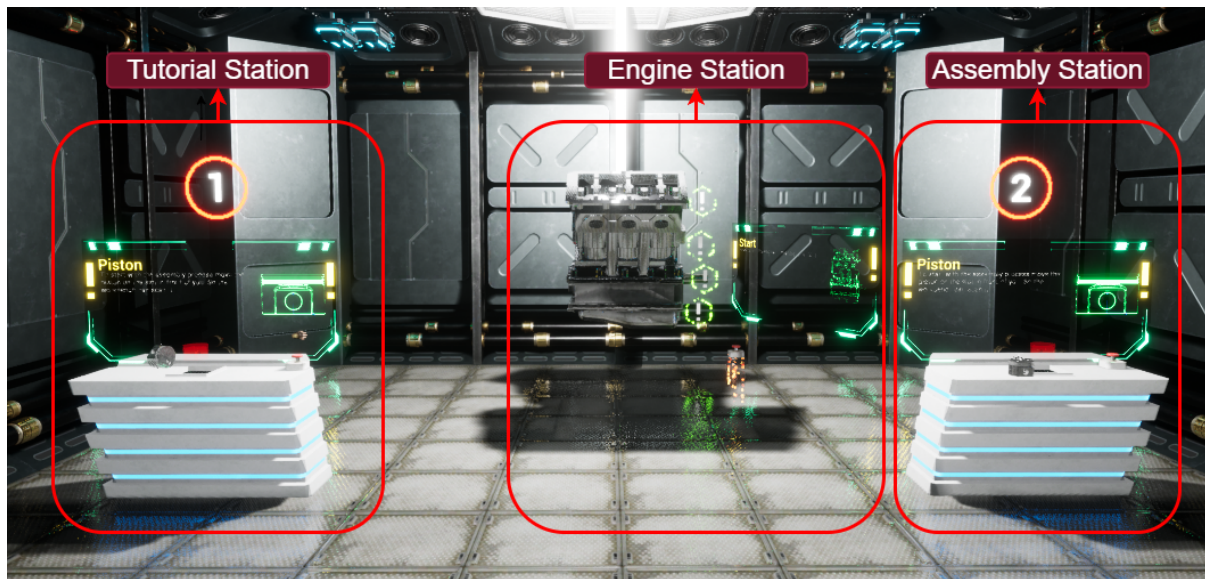


Fig. 1. Implementation of different stations in the VR environment.

Virtual Reality (VR) is a technology that holds the potential to bring the benefits of hands-on laboratory experiences into the realm of digital content. With the advent of consumer-based Head Mounted Displays (HMD), VR has entered a new era of development and application. It has expanded beyond its initial entertainment industry applications and found its way into various fields such as education, simulation, and medical treatment.

In the context of education, VR can create immersive and interactive experiences within a safe and controlled environment. By integrating VR and gamification as complementary approaches to achieve learning objectives, the intrinsic motivation of students can be significantly enhanced. Immersing students in the learning process through VR can have positive effects on their engagement and overall learning experience [9].

In the field of mechanical engineering, hands-on experience plays a crucial role in providing students with a deeper understanding of the subject matter. In this study, we sought to incorporate immersive Virtual Reality (VR) technology to simulate an educational scenario specifically focused on mechanical engineering. Our aim was to design and develop a VR environment that replicates a portion of the combustion engine assembly process. This allowed us to compare the effectiveness of the VR-based learning environment with the traditional teaching setup. Accordingly, an A/B study with 22 participants was conducted to achieve the following research goals:

- Explore whether VR is engaging enough to teach a learning concept in contrast to traditional learning.
- Compare whether teaching in VR is more effective than traditional learning.
- Investigate the influence of VR on different task load parameters in comparison to the traditional method.

The realization of these research objectives can contribute to a better understanding of the impact of VR on educational experiences, especially where hands-on training is essential.

2 Virtual Environment

Level Layout. To compare a VR learning environment with a traditional learning setup (classroom-based), we designed and developed a specific level in an immersive VR game. At this level, we provide instruction regarding the assembly of combustion engines as a topic in mechanical engineering. Accordingly, we provide a description and assembly order for each engine component that can be assembled in the application.

Our VR environment consists of three main stages: the tutorial workbench, the test workbench, and the engine assembly area, see Fig. 2. In the tutorial workbench, users are provided with detailed information and educational content for each part of the assembly process. This stage serves as a guided learning experience, where users can acquire knowledge about the assembly steps and gain a deeper understanding of each assembly part. The test workbench, on the other hand, challenges users to apply the knowledge they acquired in the tutorial workbench.

In this stage, there is no additional information provided about the assembly steps, and users are required to rely on their memory and understanding of the previous stage. This serves as a consolidation exercise to reinforce the learned concepts.

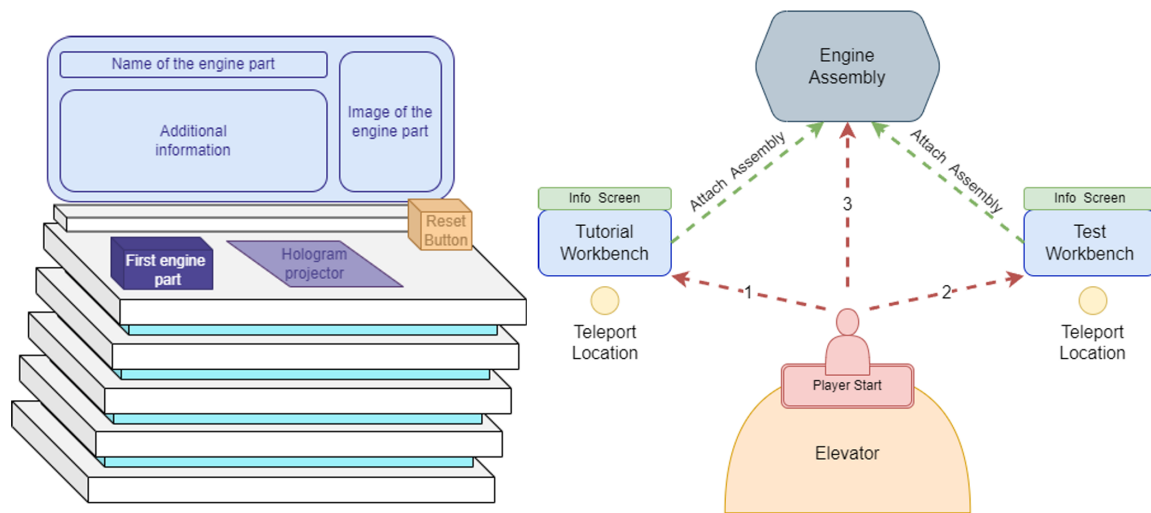


Fig. 2. (Left) The conceptual design of the workbench layout (Right) The conceptual design of the VR level layout.

Both the tutorial workbench and the test workbench share a similar structure, as depicted in Fig. 2. The interactive area and user interface (UI) remain consistent between the two workbenches. The central part of the workbenches features a hologram visualization of the assembly, aiding users in visualizing the progress of the assembly. Behind the workbench, a display provides information about the currently interacted part, including a simple 2D drawing of the object. Users also have the option to reset the assembly progress by pressing a reset button.

Finally, the parts that have been successfully assembled in the tutorial workbench and the test workbench can be further assembled in the engine assembly area. This allows users to witness the culmination of their learning journey by observing the completed combustion engine. Furthermore, this structure can be expanded in the future to accommodate different assembly scenarios by extending the workbenches to include additional learning steps.

The implementation of these concepts in VR scenario is visualized in Fig. 1. At its current stage, this VR experience is designed for individual use and does not support co-op or social interactions. In order to minimize the impact of users' prior experience with VR environments and ensure a consistent and user-friendly experience, we have simplified the interactions in the VR game. Users can grab and place the object by pressing/releasing the trigger button on the controller. The functionality of both controllers is similar to ensure the same experience for users with different dominant hands.

For locomotion in a virtual environment, there are several possibilities that can influence user experience and the possibility of cybersickness. In this study, we considered teleportation as a locomotion system to reduce the chance of cybersickness. In addition, users can also physically move in the virtual environment based on the provided physical area. These simplified interactions aim to create a user-friendly and accessible learning environment, enabling users to focus more on the learning content and the task of assembling the engine parts, rather than struggling with complex controls or experiencing discomfort in the VR environment.

The Assembly. The core element of the implementation is the assembly of the engine parts. In the tutorial workbench, each part is presented in two forms: a physical object and a hologram visualization. The physical objects are interactive and can be grabbed and manipulated by the user using the input controllers. This allows users to physically assemble the parts together, mimicking real-world assembly processes. The hologram visualizations, on the other hand, serve as a visual guide, showing a linear animation that demonstrates the correct assembly procedure. Although the holograms themselves are not interactable, they provide a clear visual reference for users to follow during the assembly process.

To aid in distinguishing between the different assembly parts, each part is assigned a distinct color, which may differ from their real-world counterparts. This color distinction helps users easily identify and differentiate the

various components during the assembly process. However, upon completion of the assembly, the assembled parts will adopt a metallic material, resembling their original real-world appearance.

All the parts involved in the assembly can be categorized into two main types: parent parts and child parts. For example, the piston serves as the parent part, while the piston rings are the child parts. The child parts need to be attached to the parent part in a specific order. When the correct collision occurs between the parts, the child part snaps into a predefined position on the parent part, indicating a successful attachment. Visual cues, audio cues, and haptic feedback are provided to the player to confirm if the parts are correctly assembled. Once all the parent parts in a workbench are assembled correctly, the holograms disappear, and the completed assembly product moves out of the workbench, allowing the player to grab it.

These design elements, such as the combination of physical and hologram objects, color coding, interactive assembly, and feedback mechanisms, are implemented to enhance the learning experience, facilitate the understanding of the assembly process, and provide users with a sense of achievement upon successful completion of the engine assembly.

3 Methodology

To evaluate usability and user response to the implemented VR level, we conducted a user study in comparison to the traditional class-based learning environment. Using this evaluation, we can investigate the research goals.

Material. In this study, the survey consisted of two main steps: a pre-questionnaire and post-questionnaires.

- Pre-questionnaire: All participants in the study completed a demographic questionnaire, which included questions about their experience with VR and mechanical engineering.
- Post-questionnaires: After VR experience or the traditional learning method, participants were asked to fill out the following four standard questionnaires: NASA TLX, System Usability Scale (SUS), Web-based Learning Tool (WBLT), and Game Engagement Questionnaire (GEQ).

In addition to the standard questionnaires, participants were also asked to provide qualitative feedback and share their learning experience and personal preferences through open questionnaires. The survey was conducted using the LimesSurvey web tool, which facilitated the collection of information online and streamlined the post-processing of the data.

Setup. The VR environment was implemented using Unreal Engine 5.0.3, considering OpenXR plugin for communications with VR devices. We used the Oculus Rift with base stations. This VR setup provided participants with the ability to move freely within an area of approximately four square meters. The Oculus Rift was connected to a PC with the following specifications: AMD Ryzen 9 3900X, NVIDIA GeForce GTX 1080, and 32 GB of RAM.

Participants. The study involved 22 participants with ages ranging from 18 to 58 years. Among the participants, 15 were female and 7 were male. At the time of the study, one participant was still attending high school, eight had completed their education but were not currently studying, and the remaining thirteen participants held a bachelor's degree or some other form of university diploma. All participants were recruited on-site and were not required to have any prior knowledge about the combustion engine. Eleven participants took part in the traditional classroom setting, while the other half tested the VR application. Fourteen participants had previous experience with a VR headset, but only three reported using it regularly. Four participants mentioned experiencing VR sickness in previous VR experiences. Half of the participants stated that they had no prior experience with the combustion engine.

Procedure. Participants were divided into two groups, with each group consisting of 11 people. Following the completion of the pre-questionnaire, the first group received traditional classroom-based content. The session began with an introduction to the experiment conducted in this study. A short lecture was then presented, providing an overview of the combustion engine. Participants had the opportunity to ask questions about the content presented.

The next step involves teaching the assembly process of the piston and connecting rod. To facilitate understanding, a real-life example was utilized. The parts were initially assembled and then disassembled by the instructor. Subsequently, the participants, working as a group, were tasked with reassembling the parts. In case

they encountered difficulties, they had the option to seek assistance, simulating a real classroom setting. The task was considered completed upon successful assembly.

The second group received a short verbal introduction to the VR application. They were familiar with the input system using motion controllers and provided an overview of the virtual environment and the purpose of the experiment. Each participant was instructed to read the additional information displayed on the station's widget.

Subsequently, the participants put on the Oculus Rift and performed a series of tasks, including:

- Learn basic manipulation in the VR environment by engaging in teleportation and grab/release interactions.
- Find the first workbench and start the tutorial assembly.
- Follow the instructions provided by the station to successfully assemble the piston and the connecting rod.
- Find the position where the assembly has to be attached to the engine.
- Go to the second workbench and repeat the assembly of piston and engine relying on their memory.
- Exit the virtual environment and examine the real part to compare it with the VR experience.

4 Results

The evaluation aimed to gather information about the participants' experience and compare the effectiveness of VR learning with traditional classroom-based learning. The comparative results of post-questionnaires are presented in Fig. 3 and 4.

4.1 NASA TLX

The results of the NASA TLX questionnaire indicated that, on average, the demand on the users was low in both the VR and traditional learning groups. Here are the specific findings:

Mental Demand (Q1): There was no significant difference found between the two groups ($p=0.87$), indicating that broader study group is needed to improve the statistical results.

Physical Demand (Q2): Both groups reported low physical demand, and There was no significant difference in physical demand between the two groups ($p=0.71$).

Temporal Demand (Q3): The VR group rated the pace of the task significantly lower ($p=0.039$) with an average score of 5.19 (SD=6.87) compared to the traditional group, which also had an average score of 5.19 (SD=18.64). This suggests that participants in the VR group perceived the task pace to be slower compared to the traditional group.

Performance (Q4): The performance ratings were not significantly different between the VR group (AVG=25.97, SD=17.03) and the traditional group (AVG=6.49, SD=12.72) ($p=0.48$). This indicates that participants' perceived performance in both groups was comparable.

Effort (Q5): The effort item for VR group (AVG=25.97, SD=17.03) is significantly higher in comparison to the traditional group (AVG=6.49, SD=12.72). It could be due to the additional interactions needed in VR condition.

Frustration (Q6): The VR group rated frustration with an average score of 12.99 (SD=12.86), while the traditional group rated no frustration at all (AVG=0.0, SD=0.0). The difference in frustration ratings between the two groups was significant ($p=0.019$), indicating that participants in the VR group experienced more frustration during the task.

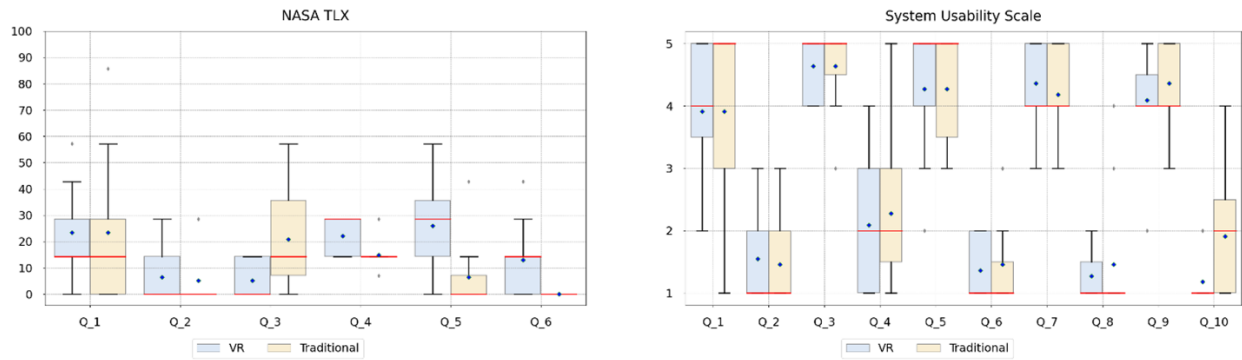


Fig. 3. Box plot of NASA TLX (left) and SUS (right) questionnaire.

4.2 System Usability Scale

The findings obtained from the System Usability Scale (SUS) questionnaire indicated no significant difference ($p = 0.267$) between the VR group and the traditional group. The average SUS score for the VR group was 84.55 (SD = 8.65), while the traditional group had an average of 82.05 (SD = 7.94). These scores indicate that the usability of both approaches is above average, based on [10]. On examining individual questions, all aspects were rated higher than average, except for the need for technical support, which received below average usability ratings. The VR group rated this aspect with an average of 2.09 (SD = 1.16), whereas the traditional group rated it slightly higher at 2.27 (SD = 1.14). However, this difference was not statistically significant ($p = 0.796$).

4.3 Web-based Learning Tool

The outcomes derived from the WBLT questionnaire revealed a significant difference ($p = 0.046$) in terms of organizational aspects between the two groups. Furthermore, there was also a border line significant difference ($p = 0.058$) observed in the level of engagement between the two studies. Questions two, three, and six were excluded from the analysis as they were not applicable to the traditional group.

Regarding the ease of product usage, the average rating was slightly lower for the VR application (AVG = 3.45, SD = 0.66) compared to the traditional lecture (AVG = 3.64, SD = 0.64). However, this difference was not statistically significant ($p = 0.414$). From a subjective perspective, participants in the VR group expressed that the learning objectives helped them marginally better (AVG = 3.73, SD = 0.62) compared to the traditional group (AVG = 3.64, SD = 0.64) with no statistical difference found between them ($p = 0.317$). The results indicate that the VR application (AVG = 3.55, SD = 0.66) was perceived as more entertaining and engaging than the traditional lecture (AVG = 2.82, SD = 1.47) on average but there was no statistical difference between them ($p = 0.1797$).

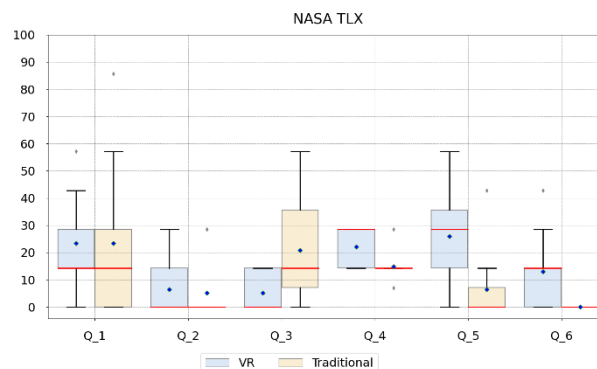


Fig. 4. Box plot of WBLT questionnaire.

4.4 Web-based Learning Tool

Participants who tested the VR application were also asked about its level of engagement. The results revealed that participants highly enjoyed the application (AVG = 3.45, SD = 0.66) and perceived the experience as realistic

(AVG = 2.55, SD = 0.99). However, they expressed a lack of interest in continuing to play beyond the necessary duration (AVG = 1.18, SD = 1.11). Some participants reported experiencing a loss of time perception (AVG = 1.64, SD = 1.87) and a decreased sense of spatial awareness (AVG = 1.73, SD = 1.21). These observations could be attributed, in part, to difficulties in reading information text and limitations of the application, such as the less realistic nature of grabbing engine parts.

5 Discussion and Conclusion

The demand for highly educated individuals is increasing, making it crucial to find effective teaching methods that keep students interested and engaged throughout their education. However, the lack of hands-on interaction with objects of interest often leads to student demotivation. To address this challenge, VR has emerged as a potential solution. By incorporating VR into education, students gain the opportunity to explore and interact with objects that would otherwise be inaccessible until after graduation or in their professional careers.

In this study, we developed a VR game that allows players to learn about a specific aspect of mechanical engineering. Through this immersive experience, users can physically manipulate engine parts, examine them in detail, and access additional information regarding their functions. To evaluate the effectiveness of VR as a learning tool, we conducted a comparative study between VR-based learning and traditional classroom-based learning. The results indicate that participants enjoyed and gained knowledge from both approaches.

Traditional lectures offer the advantage of direct social interaction, enabling students to ask questions and seek clarification from teachers. On the other hand, the VR application excels in engagement and entertainment, thereby fostering student motivation and interest in the subject matter.

Both groups of participants successfully completed their tasks of assembling the final piston and connection rod. On average, the VR group felt slightly more successful in accomplishing their task compared to the traditional group. Both groups rated their respective experiences as not mentally or physically demanding, and neither group considered the task to be hard work. However, the traditional teaching method received a lower score, while users of the VR application seemed to perceive an additional workload to feel accomplished. Participants from the traditional group did not mention feeling stressed or annoyed during the lecture, whereas some members of the VR group reported slight feelings of stress or annoyance. This can be partly attributed to the responses to the question "What parts did you not like, or could use improvements?" where five participants from the VR group mentioned issues related to the information text and user interface. Both groups had similar completion times for the study, with the task being significantly less temporal demanding for the VR group compared to the traditional group.

The user experience was perceived similarly by both groups. The VR group exhibited slightly less confidence when using the application compared to the traditional group. Both groups indicated that they did not need to learn additional topics beforehand to engage with the learning experience. The traditional group encountered slightly more initial difficulties before starting the lecture compared to the VR group. Neither group considered the execution of the task as complex; instead, they found it easy to use.

Among the VR group, several participants positively mentioned the animations when opening and closing the engine, and three participants appreciated the sound cues that signaled correct assembly of engine parts. Additionally, two participants expressed a desire for more sounds and had the information text read aloud to them. The information text received low ratings, with nine participants finding it partially helpful for completing the assembly, while most participants ignored it unless directly mentioned as a helpful feature. Five participants from the VR group suggested that the text could be improved or removed altogether.

Participants from the traditional group highlighted positive aspects such as personal explanations and the use of a real-life product. Similar to the VR group, multiple participants in the traditional group stated that the provided text (which was the same as that given to the VR group) was unnecessary as the teacher's explanation was more engaging. While both groups found the experiment engaging and fun, the VR group expressed greater enjoyment compared to the traditional group. Participants were also asked if they would like to use the learning objective again.

The results indicate that both traditional learning and the VR experience can be valid choices for educating people about new topics. The selection between the two methods may depend on the subject matter. According to participant responses, an important aspect of hands-on learning is the ability to physically interact with the objects being taught. Ideally, access to the real-life objects would be preferred, but VR can serve as a valuable tool to enhance learning outcomes when physical access is limited.

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