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ORIGINAL ARTICLE

Analysis of virtual reality teaching methods in engineering education: assessing educational effectiveness and understanding of 3D structures

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Abstract

Conventional digital learning with 2D videos or simulations on monitors and tablets has limitations in engineering education when covering complex concepts or complicated 3D structures. In response, virtual reality (VR) has been introduced as an immersive method that can enhance learning effectiveness. This study analyzed the impact of VR on overall learning outcomes and understanding of 3D structures in engineering education, comparing it with traditional digital learning approaches. We conducted a study with 40 participants who learned about LCD-related topics using two methods: VR-based learning and 2D video-based learning (2DLM). To evaluate their performance, we carried out a performance-based assessment consisting of a quiz and 3D reconstruction tasks, as well as a perception-based assessment using a questionnaire. As for the results, the VR-based learning showed a 12% improvement in post-test quiz scores and a 13% improvement in 3D reconstruction test scores compared to the 2DLM. Additionally, the questionnaire results confirmed that VR learning increased engagement by 11.9%, immersion by 18.6%, motivation by 10.3%, cognitive benefits by 9.3%, and perceived learning effectiveness by 8.7%. While VR showed better learning outcomes, these findings should be interpreted considering the small sample size, the specific learning topics addressed, and the partial integration of media and educational methods. Nevertheless, our results indicate that VR is more effective than conventional learning resources in supporting general memorization, understanding, and the specific comprehension of 3D structures.

Keywords Virtual reality · Augmented reality · Learning environment · Immersive learning · Spatial perception

1 Introduction

Engineering education using conventional digital learning tools has relied on basic 2D figures or animations to teach intricate structures (Miranda et al. 2021; Sharma et al. 2018; Magana and de Jong 2018). Typically, devices with displays, such as monitors, laptops, and tablets, are used to provide videos or simulations related to the learning topic. However, these tools often struggle to effectively convey complex 3D structures due to restrictive 3D representation, limited spatial information, and static participation (Astuti et al. 2020; Zacharia et al. 2014). The inherent constraints of these typical media fall short in accurately representing 3D real-world objects and spaces (El Beheiry et al. 2019), leading to a diminished visual perception among learners. This affects their grasp of shape properties, figure-ground relationships, and organizational principles due to limited visual engagement (Azarby and Rice 2022). These

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instruments may also hinder a comprehensive understanding of the overall structure, arrangement, and interrelations among components (George et al. 2017). Such limitations arise from presenting structures with confined spatial information from a fixed perspective on displays, relying heavily on the learners' spatial intelligence (Wang et al. 2018; Paes et al. 2017). Moreover, the understanding of 3D structures in engineering is often restricted by these approaches due to the passive participation and lack of interactions with learners (Soliman et al. 2021). This reduces the degree of freedom in learning and limits the potential to maximize learning outcomes (Hadgraft and Kolmos 2020).

In response, educators are exploring new technologies, such as 3D printing, augmented reality (AR), and virtual reality (VR) to enhance the learning experience (Pinger et al. 2019; Arulanand et al. 2020; Liu et al. 2017). 3D printing is a process of creating 3D solid objects from a digital file (Lipson and Kurman 2013; Shahrubudin et al. 2019). It works by laying down successive layers of material until the object is created. AR overlays digital information onto the real world, enhancing the user's perception of their surroundings without completely replacing them (Azuma 1997; Perez-Pachon et al. 2024). AR allows users to remain in contact with the real world while interacting with virtual objects (Carmigniani et al. 2011; Laera et al. 2023). Unlike AR, VR creates a completely digital environment that replaces the user's real-world surroundings (Biocca and Delaney 1995; Anthes et al. 2016; Tang et al. 2020). This technology immerses users in a simulated setting, which can be entirely different from the actual environment around them (Ladakis et al. 2024; Kwon 2021). In general, these technologies allow students to improve their understanding and retention of the learning material (Ford and Minshall 2019; Hu et al. 2021; Kavanagh et al. 2017).

In particular, these innovative learning media can enhance the understanding of 3D structures and overall learning effectiveness by strengthening the immersive learning experience (Kuhail et al. 2022). Immersive learning is an educational approach that provides learners with a fully immersive experience, deeply engaging them in the learning process (Makransky et al. 2021; Mystakidis and Lympouridis 2023; Fernandes et al. 2023). The goal of immersive learning is to maximize learner engagement and understanding (Mayrose 2012). Significantly, VR technology offers an enhanced learning experience in areas of 3D representation, spatial information, and participation, setting it apart from conventional digital learning methods.

Firstly, VR can improve 3D representation, a crucial aspect since visual language is the most dominant component in learning (Azarby and Rice 2022; Raiyn 2016). VR can visually express complex or abstract concepts and realistically depict objects through detailed 3D modeling (El Beheiry et al. 2019; Wang et al. 2018). In this way, VR can provide not only basic visual features such as the size, color, position, and shape of objects but also additional cues like rotation, occlusion, and shadow (Korkut and Surer 2023; Loyola 2018). Therefore, learners can acquire richer educational insight through VR's advanced 3D representation, thereby increasing their ability to understand 3D structures.

Secondly, VR can provide sufficient spatial information. Unlike a medium such as a monitor, VR's binocular system offers a true sense of depth perception and spatial relations (Korkut and Surer 2023). Through this information, learners can gain details about the length and depth of certain structures, as well as easily grasp their interrelations (George et al. 2017). Moreover, viewers are not confined to a fixed perspective; instead, they can freely explore the space from arbitrary angles and vantage points, similar to the real world. This flexibility enhances their ability to fully acquire spatial data, resulting in improved spatial perception (Roberts et al. 2022; Azarby and Rice. 2022).

Lastly, VR enhances comprehension of 3D structures by encouraging active learning engagement among learners. By providing a spatially immersive environment that makes participants feel as if they are present in the real world, VR enables learners to focus on the learning topic and actively involves them in the lecture (Gómez-Tone et al. 2021; Makransky et al. 2021). This environment facilitates the transformation of learning information and data into the learner's knowledge, thereby enhancing learning efficiency (Stevens and Kincaid 2015; Witmer and Singer 1998). Particularly, interactions in VR enable learners to explore the learning environment spontaneously and foster active participation, enhancing engagement and presence, both of which are closely related to immersion (Lindgren et al. 2016; Anjarichert et al. 2015; Ragan et al. 2015). As a result, such effects can increase learners' concentration on the educational content and strengthen their memory (Liu et al. 2020).

Building on the positive aspects of VR highlighted in previous research, our study aims to analyze VR's impact on learning effectiveness in engineering education by comparing it with traditional digital learning approaches. Specifically, we intend to demonstrate that VR-based learning can enhance students' learning abilities, including memory and comprehension of 3D structures, while also improving their overall learning experience. To achieve this, we selected liquid crystal displays (LCDs) as the learning subject and analyzed the outcomes between participants who learned through VR and those who used a video-based 2D learning method (2DLM). We conducted a quiz and a 3D reconstruction task for performance-based assessment and administered a questionnaire for perception-based assessment. The results of these assessments are expected to provide

justification for the implementation of VR in engineering education. Moreover, the findings could lead to the development of more immersive, interactive learning environments that foster deeper comprehension and better recall, suggesting the potential for wider adoption of VR-based learning across various fields of engineering education.

2 Literature review

2.1 3D printing and augmented reality in education

In many fields such as architecture, anatomy, and mechanical engineering, students must acquire understanding of 3D structures. In the past, education for this purpose used conventional methods such as drawing, photographs, and videos. However, these methods lack interaction and do not provide sufficient spatial understanding to learners. Recently, new technologies such as 3D printing and AR are being used to enhance educational effects (Álvarez Marín and Velazquez-Iturbide 2021; Martín et al. 2021).

3D printing is highly versatile and offers customized education on 3D structures, making it a valuable tool in engineering education for transforming concepts or structures of specific topics into physical models (Eslahi et al. 2020; Chiu et al. 2015; Ford and Minshall 2019). However, 3D printing's reliance on STL files that represent CAD models can confine students to only proportional models (Chua et al. 2022). Complementing 3D printing, AR further enhances students' comprehension and motivation in problem-solving activities by allowing them to interact with virtual objects and system interfaces (Cen et al. 2019; Christopoulos et al. 2022). In engineering education, AR provides additional learning information on specific frameworks or ideas through virtual images and offers guidance on experimental tools and procedures (Nesterov et al. 2017; Álvarez Marín and Velazquez-Iturbide 2021). Despite its benefits, AR faces its own limitations, including cognitive overload, design difficulties, and high costs (Ali et al. 2022).

Jarosław and colleagues reviewed the impact and potential of 3D printing in medicine (Meyer-Szary et al. 2022), highlighting its benefits in enhancing the understanding of patient-specific anatomy, improving pre-procedural planning, and increasing proficiency through simulation-based surgery. For instance, Valverde et al. found that 96% of surgeons using 3D printed models of 40 pediatric patients with congenital heart defects reported improved treatment outcomes (Valverde et al. 2017). They also emphasized the usefulness of 3D printing in the context of unusual or difficult procedures in medical education. Costello et al. used 3D printing to understand ventricular septal defect management, noting significant gains: 51.76% in knowledge acquisition ($p < 0.001$), 61.41% in knowledge reporting ($p = 0.01$), and 73.14% in structural conceptualization ($p < 0.001$) (Costello et al. 2015). Overall, the authors were convinced that 3D printing holds great promise for enhancing processes and outcomes in various medical fields.

Anđić et al. conducted a study to investigate the impact of 3D Modeling and Printing (3DMP) on the learning outcomes of students in cell-themed biology education (Anđić et al. 2022). Using 'Grounded Theory', they analyzed students' perspectives on the use of 3DMP in the learning process. The accuracy in describing cell parts and organelles improved by 38.5% in the post-test compared to the pre-test, and the level of confidence in their explanations also increased by 11.7%. The results showed that 3DMP was effective in enhancing students' understanding, spatial abilities, and visualization of the structure of cells, leading to improved learning outcomes. However, the authors noted certain limitations of 3DMP in education, such as difficulties in adjusting object positions and scales, inaccuracies in printing, and long printing times, which can potentially lead to new misconceptions among students.

Singh and Kaur highlighted the potential benefits of AR in education, such as increased engagement, motivation, and enhanced problem-solving skills by integrating virtual elements into real-world learning environments (Singh and Kaur 2022). Additionally, they described how game engines like Unity and Unreal are used to develop AR-based digital applications, which provide immersive and interactive learning experiences. Their review of prior studies on AR in education indicated that, despite its ability to improve learning outcomes, the adoption of AR is constrained by challenges like technological barriers and insufficient teacher training. Furthermore, the authors pointed out the limitations of conventional learning methods, such as the reliance on photos and videos that often lack engagement and adequate visual support, advocating for more interactive, technology-driven approaches. With effective implementation strategies, AR has the potential to transform education by offering real-time visualization, interactive 3D models, and contextual learning opportunities.

Han et al. conducted a study on the effectiveness of AR in improving students' learning efficiency in mechanical assembly classes (Han et al. 2022). They developed an AR-based assembly application and tested it with automotive engineering students. In the assembly process, the control group received handouts, while the experimental group used AR. In the basic assembly knowledge test, the experimental group scored significantly higher (Mean = 5.73, Standard Deviation = 0.98) than the control group ($M = 4.17$, $SD = 1.03$), according to the Mann–Whitney U test ($p < 0.001$). In the practical assembly test, the experimental group had better score and shorter completion

time (score: M = 11.65, SD = 1.67; time: M = 9.07 min, SD = 1.01) compared to the control group (score: M = 8.14, SD = 2.06; time: M = 14.19 min, SD = 1.27), with the Kruskal–Wallis test confirming that these differences were significant ($p < 0.001$). Additionally, the AR group showed higher scores in learning interest, task difficulty, academic achievement, confidence, and satisfaction, all with statistically significant differences ($p < 0.001$). The study found that AR significantly improved conceptual retention, assembly quality, speed, and overall student engagement.

2.2 Virtual reality in education

VR provides a highly interactive and spatially immersive simulation environment, enabling users to experience a realistic virtual space that offers enhanced engagement and interest (Makransky et al. 2020). The development of head-mounted displays (HMDs) has accelerated the adoption of VR technology. Available VR HMDs range from low-cost devices compatible with smartphones to high-end HMDs specifically designed for fields such as medicine and computer science. Similar to AR, VR is employed in engineering education to provide additional learning experiences on lecture topics through virtual objects (di Lanzo et al. 2020; Soliman et al. 2021). Specifically, VR's ability to freely create virtual environments and objects not only facilitates the study of micro or macro structures but also offers virtual experiments, enabling the safe conduct of experiments that would otherwise be dangerous and costly (Pietikäinen et al. 2021; Loures Brandão et al. 2018). It is regarded as an effective method to provide education about 3D structures, because it can efficiently develop students' theoretical knowledge by faithfully reproducing immersive simulations (Greuter et al. 2021).

Dalgarno and Lee examined the educational benefits of 3D virtual learning environments (VLEs) by identifying their learning affordances (Dalgarno and Lee 2010). These affordances include enhanced spatial knowledge representation, increased opportunities for experiential learning, and heightened motivation and engagement through immersive experiences. Notably, closely mimicking real-world scenarios facilitates contextualized learning, which helps apply acquired knowledge practically. Furthermore, allowing multiple users to interact within the same virtual space supports richer collaborative learning, enhancing communication and teamwork. The authors concluded that these affordances provide a strong foundation for the use of 3D VLEs in educational settings.

Rojas-Sánchez et al. conducted a literature analysis to examine the various areas where VR is utilized in education (Rojas-Sánchez et al. 2023). They used bibliometric analysis to identify the key topics, authors, papers, countries, and publications with the highest citation frequency. They presented VR educational methods, such as learning environments, simulations, and games. Notably, they observed that the use of VR in education increased during the COVID-19 pandemic, with students quickly adapting to it. This was due to a significant shift in educational methods resulting from remote learning. Particularly in 2020, the number of articles related to VR more than doubled compared to the previous year. Furthermore, they argued that active learning using VR, which allows interaction with the learning environment, can improve the speed and quality of learning by enhancing students' motivation and engagement.

Tan et al. conducted a systematic review of the use of AR and VR technologies in education and training within the Architecture, Engineering, and Construction (AEC) industry (Tan et al. 2022). They analyzed 82 studies, finding that approximately 80.49% of those published between 1997 and 2021 appeared after 2013, reflecting a growing interest in exploring new educational methods using AR/VR technologies. Specifically, 55 studies related to education were categorized into four application areas: 40% for Immersive AR/VR Learning, 27% for AR/VR Structure Analysis, 15% for Visual-Aided Design Tools, and 18% for AR/VR-Based Teaching Aids, highlighting immersive learning as the most actively researched area. A meta-analysis of 17 studies using the 'Random Effect Model' revealed an overall effect value of 0.44 (Standardized Mean Difference = 0.39, 95% Confidence Interval: 0.16–0.62), indicating that AR/VR technologies positively impact education and training effectiveness in the AEC industry. They concluded that AR and VR hold significant potential to enhance educational strategies, offering more diverse learning environments and added value for the AEC industry.

Kim et al. conducted a study on the impact of immersive VR content using 360-degree video on undergraduate education (Kim et al. 2022). They compared 360-degree video and 2D video with a group of 33 college students and performed a paired-sample t-test to analyze the mean test scores. In the evaluation using a 7-point Likert scale, the learning effectiveness between 360-degree VR and 2D video content showed differences of 1.25 in Engagement, 2.64 in Immersion, 1.27 in Motivation, 1.11 in Cognitive Benefits, and 1.00 in Perceived Learning. The probability values for all items related to effectiveness were less than 0.001 ($p < 0.001$). The results suggested that 360-degree VR content can improve students' concentration, interest, and learning environment compared to the 2D learning method. However, Matovu et al. argued that using simple 360-degree videos without interactions may hinder fully immersive learning (Matovu et al. 2023). This is because 360-degree video lacks interactions, which may reduce its ability to construct empirical knowledge.

Balzerkiewitz et al. studied the effectiveness of VR-based teaching methods in engineering education (Balzerkiewitz et al. 2022). They tested educational scenarios using VR with a group of students and assessed the learning effect through a survey. Approximately 89% of participants found VR-based education interesting, and 67% responded that VR helped them better understand the learning topic. The results showed that VR can effectively connect theoretical knowledge with practical experience, and interaction with 3D objects significantly improved understanding. Furthermore, VR training boosted student engagement and motivation, as most participants found the VR experience enjoyable and valuable for learning. However, the study's limitations include a small set of evaluation criteria and insufficient detailed analysis.

In summary, VR enhances student interest and fosters active participation by providing high spatial immersion and various interactions. This ultimately leads to improved learning outcomes, which is why it is widely used in the field of engineering education. Previous studies in the field of engineering education have attempted to verify the educational impact of VR, but many either lack an evaluation of the actual learning performance abilities or have limited evaluation items in their questionnaires. Furthermore, the effect of VR on education regarding 3D structures has not been thoroughly considered. To address these gaps, we conducted both performance-based and perception-based assessments, providing a dual approach to evaluate different aspects of learning. Our comprehensive approach not only provides a more detailed analysis of both performance and learning experiences but also rigorously evaluates learners' practical understanding of 3D structures, supplementing areas that previous research may not have fully addressed. This offers new insights and strengthens the rationale for VR in engineering education, particularly in spatial learning contexts.

3 Method

3.1 Research design

We conducted a detailed comparison and analysis of learning outcomes for LCDs, which possess inherent structural complexity (Gärtner and Hanappi-Egger 1999). These complex structures include various intricate sub-components, such as glass (GLASS), liquid crystals (LC), polarizers (POL), color filters (CF), thin-film transistors (TFT), and backlight units (BLUs). Understanding these components and their functions, as well as structural changes like the rearrangement of liquid crystals under voltage, can be challenging for learners, especially when they study the topic through 2DLM. These learning topics were developed into VR content and pre-rendered videos, with more detailed information provided in the following section.

Our evaluation of the learning outcomes was conducted with a rigorous approach, using both performance-based and perception-based assessments. For the performance-based assessment, we used a quiz and a 3D reconstruction task. The quiz, consisting of a pre-test and a post-test, assessed learners' pre-existing knowledge of the LCD topic and their retention of this knowledge after the learning process. It includes items that assess the identification of LCD components, operational principles, and characteristics of each LCD mode. To further evaluate learners' understanding of the 3D structure, we conducted a 3D reconstruction task. Participants were required to physically assemble LCD components produced by a 3D printer, and we assessed the accuracy of their assembly. This step determined the impact of the learning medium on their comprehension of the 3D structure. For the perception-based assessment, we administered a questionnaire to compare the perceptual learning effectiveness of VR and 2DLM. The purpose of this process was to determine the subjective learning effect that students feel in each learning method. Detailed information about each assessment can be found in Sects. 3.4 and 3.5.

Participants in our study were randomly divided into two groups. One group participated in learning via VR, while the other group utilized a 2DLM. Both groups underwent the same five-step experimental procedure (Fig. 1). The pedagogical approach and curriculum design were identical for both VR-based learning and 2DLM, with the only difference being the 3D immersive experience provided in the VR group, whereas the 2DLM group received a flat 2D video recording. In the first step of the experiment, students in both groups took a pre-test quiz for 10 min. In the second step, the participants learned about LCDs using VR or 2DLM, with each group studying the same topic for 10 min using VR devices or laptops. In the third step, the students were given a post-test quiz that had the same content as the pre-test quiz, which was also conducted for 10 min. In the fourth step, students were given 5 min to reconstruct a general LCD in 3D, representing the common structure shared across all modes. In the fifth step, the students completed a questionnaire to evaluate the learning method that they had used. They were allowed 15 min for this step.

To ensure consistency and effective process control in our study, we implemented several key measures. First, we maintained a uniform experimental environment. All experiments for both groups were conducted in the same undisturbed location, following identical steps and durations, with the learning medium as the only variable. To avoid bias, we did not share expected outcomes with participants or provide any educational enhancements to either

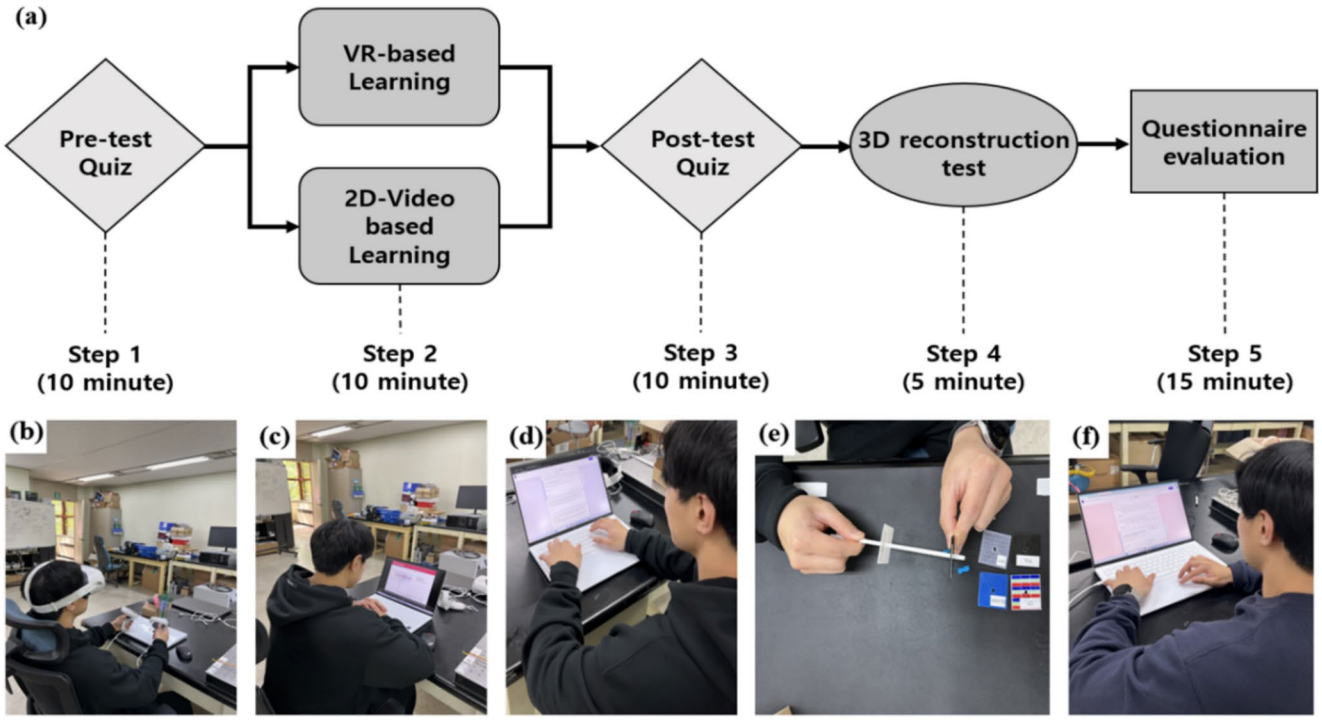


Fig. 1 Overview of the experimental process. **a** experimental design diagram. **b** VR-based learning. **c** Video-based learning. **d** quiz. **e** 3D reconstruction. **f** questionnaire evaluation

group. Additionally, both learning contents included audio instructions and visual UIs to guide participants, helping to prevent unexpected behaviors and minimize potential errors. Finally, the entire experiment was closely monitored to ensure that participants engaged consistently and stayed focused on the tasks, thus maintaining uniform experimental conditions.

3.2 LCD contents creation

We created the VR LCD content using 3dsMax and the Unity 2020.3.14 engine. In 3dsMax, we modeled LCD components and structures that use liquid crystal driving methods (TN mode, IPS mode, VA mode). The mesh, size, and animation of the 3D object were adjusted and optimized to ensure compatibility with Unity, making content development easier. In Unity, we imported these 3D models and arranged them according to each learning topic to design the educational environment. We also integrated audio instructions and created visual UI elements to provide a cohesive educational experience. Lastly, we scripted interactions and animations to allow users to explore LCD features dynamically, emphasizing key educational aspects. The produced content was built on the Oculus Quest 2 device for an experiment.

The VR content is divided into five sessions (Fig. 2). In Session A, learners who are wearing VR headsets enter the virtual classroom. During this time, they familiarize themselves with how to operate the controllers to move freely in the virtual space and interact with virtual objects. In Session B, they learn about the basic structure of LCDs, its components, and their arrangement. In Session C, instructions focus on the TN mode, where students learn about the initial arrangement of liquid crystals, the movement of liquid crystals in response to applied voltage, and the polarization state of light. They also learn about the characteristics, strengths, and weaknesses of TN mode LCD. Sessions D and E are similar to Session C, with the LCD mode changed to IPS and VA, respectively. Figure 3 shows the detailed configuration scene for each section of the content. In this content, all learning was conducted following the lecturer's audio instructions, and subjects had the freedom to move around the virtual space. Subjects could immerse themselves in the learning experience by using the controller of the Oculus Quest 2 to interact with the virtual objects.

To create the pre-rendered video for the 2DLM, we used Adobe Premiere Pro 2023. The video includes the same topics, explanations, and audio as the VR content but is presented with 2D figures, animations, and a brief text. Through narrated explanations by the instructor, students watched 2D video-based lectures that covered the learning topics in sequence: the basic structure and components of LCDs and the characteristics and operating principles of TN, IPS, and VA modes. The learning process was also designed to mirror

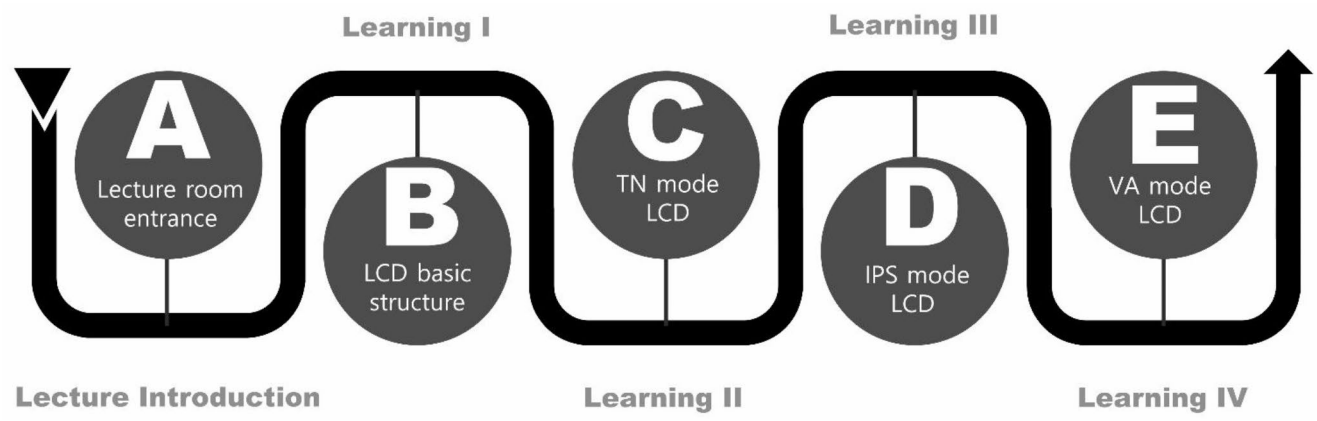


Fig. 2 Composition of VR-based learning content: LCD learning process

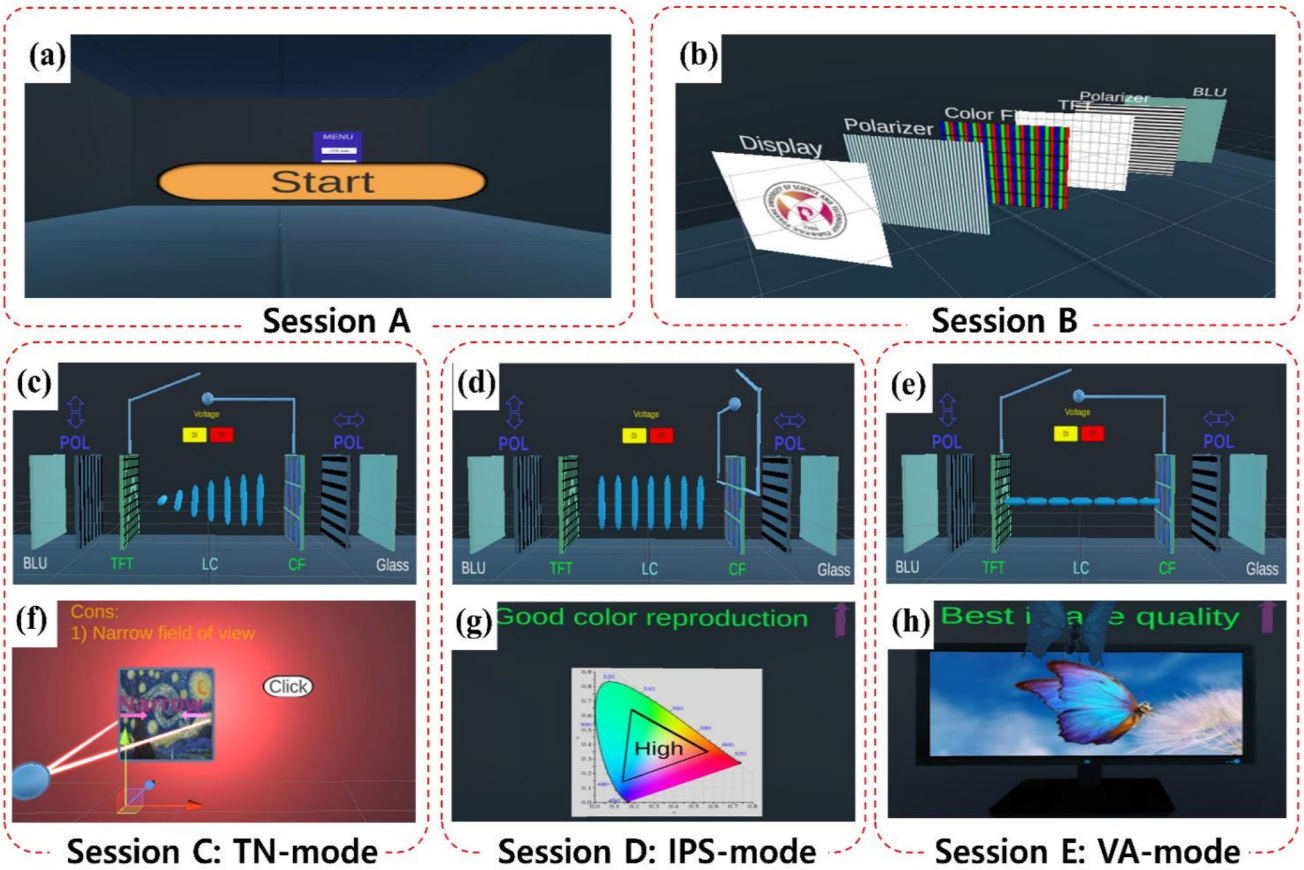


Fig. 3 Scene view that composes VR-based learning content. **a** Lecture introduction. **b** Basic structure of the LCD. **c** Structure of the TN mode LCD. **d** Structure of the IPS mode LCD. **e** Structure of the VA mode LCD. **f** Property of TN mode LCD. **g** Property of IPS mode LCD. **h** Property of VA mode LCD

the content and sequence of the VR sessions (Fig. 2). Unlike the VR environment, which allowed learners to navigate and interact with virtual objects, the 2DLM offered a more observational learning experience, focusing solely on pre-rendered recordings without interaction.

3.3 Participants

This experiment involved 40 participants (31 male, nine female, ages 20–26); all were students at Pohang University of Science and Technology. They voluntarily participated as subjects when we recruited participants for our study, and we obtained their consent to protect their privacy and use

the experimental data. The experiment was conducted under the assumption that the participant's gender would not affect learning ability. Prior to the experiment, participants were surveyed about their experience with VR technologies. Among the participants, 25 had prior experience with VR, and 15 had no such experience. The participants were randomly divided into two groups regardless of their gender or age: one was instructed using VR, while the other was instructed using video. In detailing the distribution, the VR group comprised 13 participants with prior VR experience and seven newcomers to VR. Conversely, the video group included 12 participants with VR experience and eight without. This distribution aimed to mitigate any potential bias that prior experience with VR could introduce to the learning outcomes. It was also explicitly ensured that participants were unaware of the instructional methods employed in the parallel group to prevent any bias or preconceived notions from influencing their learning experience or feedback. After the learning session, all participants completed the post-test quiz, 3D structure reconstruction, and questionnaire evaluation sequentially.

3.4 Performance-based assessment

3.4.1 Quiz

We prepared a quiz to assess the subjects' prior knowledge of the content covered in the lecture and the information retention achieved through each learning medium. The quiz consists of 13 short-answer subjective questions created based on the key concepts of LCDs learned through VR and 2DLM. Specifically, it covers the components of LCDs and the distinguishing characteristics of each LCD mode. Each question is crafted to match the difficulty level presented in each learning method, ensuring students can effectively address them with careful study. All of the questions in the quiz were validated by display engineering experts and then pre-tested in a small group. Each question was worth 1 point, and subjects who answered all the questions correctly got 13 points. The pre-test and post-test quizzes comprised the same questions. Both tests have a time limit of 10 min. Based on the results of all tests, we calculated the mean, standard deviation, standard error, and Gain. Gain refers to the extent of the increase in post-test scores compared to pre-test scores. Through these statistical analyses, we can quantitatively assess the impact of the VR learning method and 2DLM on subject comprehension.

3.4.2 3D reconstruction

We performed a 3D reconstruction of the LCD structure to assess the effect of VR learning on the comprehension of 3D structures. This also serves as an assessment to measure the retention of structural and spatial information. Subjects were asked to reconstruct the basic structure of LCDs, which they had learned either in VR or 2DLM. They assembled the basic structure by inserting each component into the appropriate location on a bar, all within a 5-min time limit. The LCD is composed of seven components, arranged in the following order: GLASS, POL, CF, LC, TFT, POL, BLU (Fig. 4). The total score for the 3D reconstruction was seven points, with one point awarded for each correctly placed component.

Inspired by assembly tests, our method allows for the assessment of a specific structure's characteristics and spatial understanding (Abidi et al. 2019; Gavish et al. 2015; Carlson et al. 2015). Prior to the actual assessment, we conducted a pilot test with a small group to ensure the experiment's clarity and feasibility. Regarding the analysis of 3D reconstruction data, we implemented a systematic approach to quantify the learning outcomes associated with VR and 2DLM. Utilizing the data from the test results, we calculated the mean, standard deviation, standard error, and normalized scores. These statistical measures serve as indicators for evaluating the participants' spatial intelligibility. We crafted each component using a 3D printer, based on models designed in 3dsMax. The components used in the reconstruction task were identical to those depicted in the 3D models and images presented in both the VR and 2DLM.

3.5 Perception-based assessment

To evaluate the educational effect of VR-based learning, we created a user evaluation questionnaire consisting of five categories: 'Engagement', 'Immersion', 'Motivation', 'Cognitive Benefits', and 'Perceived Learning Effectiveness'. 'Engagement' measures the level of interest and involvement that users experience while engaging with the content (Cheng et al. 2015). It was evaluated using 12 questions, with items such as Attraction, Time Investment, and Usability (Georgiou and Kyza 2017). 'Immersion' assesses the extent to which users feel present and engaged in the virtual environment. It was evaluated using 15 questions with emotional attachment, focus of attention, sense of presence, and flow (Jennett et al. 2008; Brown and Cairns 2004). 'Motivation' measures the user's level of interest, enthusiasm, and willingness to engage with the content.

This category was evaluated using 12 questions related to psychological factors affecting learning outcomes (Lee et al. 2010). 'Cognitive Benefits' refers to improvements in cognitive processes such as attention, memory, and spatial reasoning (Antonietti et al. 2000) and was assessed with five questions. 'Perceived Learning Effectiveness' measures how much users feel they have learned based on changes in

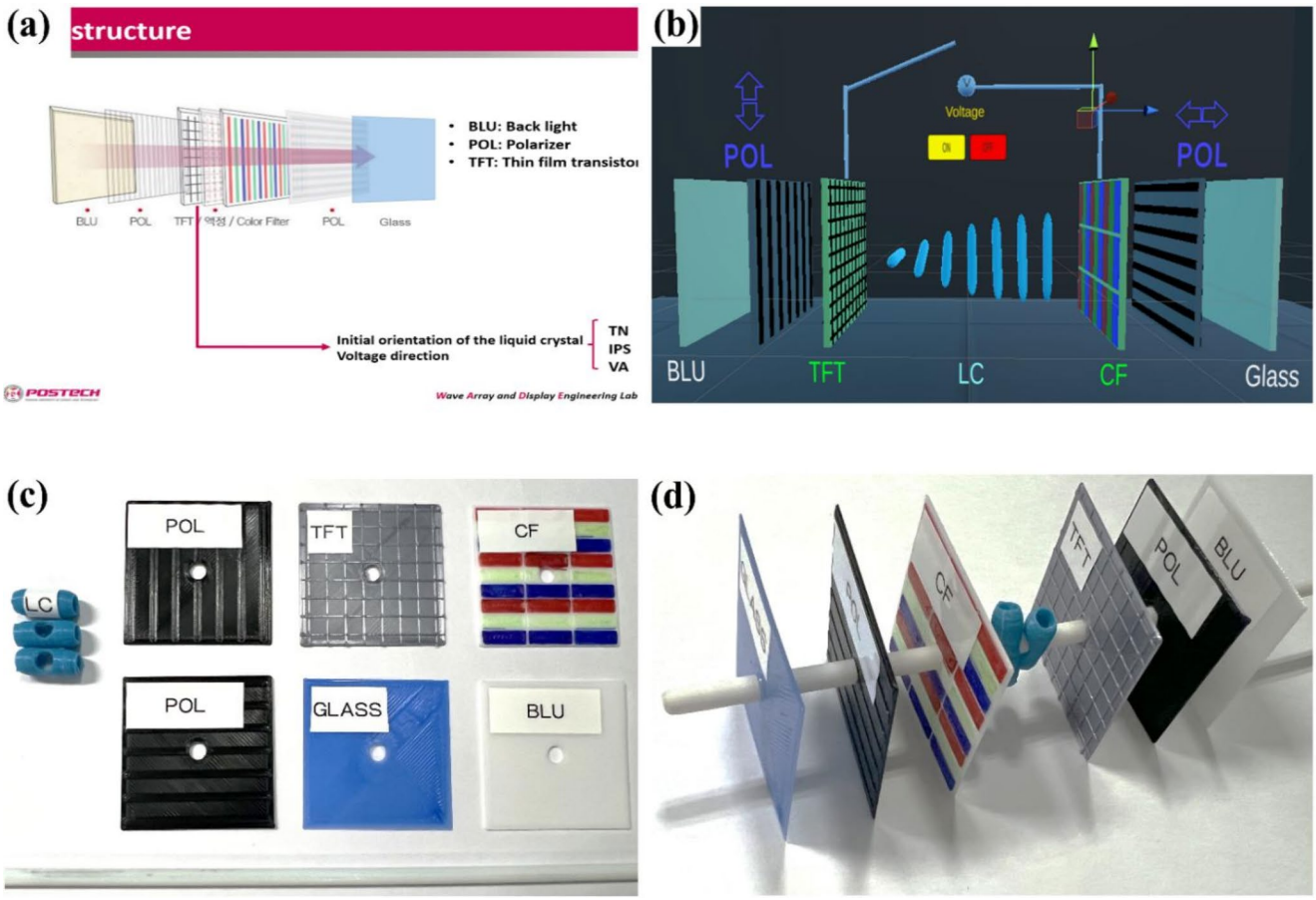


Fig. 4 Supplementary for 3D reconstruction evaluation. **a** Lecture materials of 2D e-learning. **b** Lecture contents of VR learning. **c** LCD physical component for 3D reconstruction evaluation made from 3D printing. **d** Complete example of 3D reconstruction

their understanding and knowledge (Alavi et al. 2002) and was evaluated using eight questions to assess the effectiveness of new learning environments or tools.

All questionnaires used in this study were inspired by various literature in educational methodology (Georgiou and Kyza 2017; Cheng et al. 2015; Jennett et al. 2008; Qin et al. 2009; Lee et al. 2010; McAuley et al. 1989; Antonietti et al. 2000; Benbunan-Fich and Hiltz 2003; Martens et al. 2007). Before applying them in this study, a preliminary test with a small group was conducted to gather feedback on objectives, clarity, and length. Based on this feedback, we revised ambiguous questions and refined the overall structure. Ultimately, we confirmed that the questionnaires, as used in previous studies (Kim et al. 2022; Kim et al. 2023), were sufficient to verify the educational outcomes. To assess reliability, we employed Cronbach's alpha, which measures whether items consistently evaluate the same concept. The Cronbach's alpha ranges from 0 to 1, with values above 0.8 indicating high consistency.

Mean, total mean, and total mean difference were calculated to compare the learning effects of VR and 2DLM across five educational categories. For a detailed comparison, mean differences were also calculated for specific items within each category. We utilized the independent t-test, a statistical method designed to compare the means of two independent groups in order to determine whether there is a statistically significant difference between them (Mair and Wilcox 2020). The significance level was set at 0.05, indicating that if the p-value fell below this threshold, we concluded there was a significant difference between the two learning methods. Meeting this condition would indicate that VR offers superior learning effectiveness compared to 2DLM. The statistical analysis was conducted using Jamovi v. 2.3.2 (The jamovi project, Sidney, Australia).

4 Result

4.1 Performance-based assessment

Both instruction modes increased the participants' understanding of LCD structure (Table 1). In the pre-test quiz, the mean scores of each group were close to zero ($M_{\text{2D-Pre}} = 0.35$, $M_{\text{VR-Pre}} = 0.48$), which indicates that the students had little

Table 1 Mean *M*, and standard deviation *SD* and standard error *SE* of points (/13) earned during the quiz (n = 20 for both media)

Learning method	Pre-test [Points]			Post-test [Points]			Normalized Post-test	Gain
	M	*SD*	*SE*	*M*	*SD*	*SE*	$M_{XX-Post}/13$	$(M_{XX-Post} - M_{XX}$
2DLM	0.35	1.56	0.35	6.93	0.75	0.17	0.53	18.80
VR	0.48	1.73	0.39	8.47	0.60	0.14	0.65	16.65

Table 2 Mean *M*, standard deviation *SD* and standard error *SE* of the score (/7) on 3D reconstruction (n = 20 for both media)

Learning method	*N*	Score [Points]			Normalized Score
		M	*SD*	*SE*	$M_{XX}/7$
2DLM	20	3.65	2.08	0.47	0.52
VR	20	4.35	1.98	0.44	0.65

Table 3 The composition of research variable and Cronbach's alpha values for questionnaire

Research variable	Number of Items	Cronbach's Alpha (α)
Engagement	12	0.91
Immersion	15	0.958
Motivation	12	0.918
Cognitive benefits	5	0.954
Perceived learning effectiveness	8	0.898

prior knowledge about LCDs. Thus, we expected that it would be suitable for comparing learning effects depending on learning media with students who had little prior knowledge. On the post-test quiz, participants who learned in the VR environment scored 1.54 points higher than those who learned in the 2D environment ($M_{\text{2D-Post}} = 6.93$, $M_{\text{VR-Post}} = 8.47$). Considering the results of the normalized post-test, the score was 12% higher in the VR learning environment than in the 2D environments.

In the 3D reconstruction experiment (Table 2), the score of participants who learned in the VR environment was 0.7 points higher than that of those who learned in the 2D environment ($M_{\text{2D}} = 3.65$, $M_{\text{VR}} = 4.35$). The normalized test showed a difference of 0.13 ($M_{\text{2D}} = 0.52$, $M_{\text{VR}} = 0.65$). This means that the score in the VR learning environment was about 13% higher when considering normalized score.

4.2 Perception-based assessment

The questionnaire that we used revealed that all categories exhibited Cronbach's alpha values greater than 0.8 (Table 3), indicating that the questions were both reliable and internally consistent. Building on this reliability, Table 4 summarizes the statistical results across the five educational evaluation categories, highlighting the overall trends and differences observed in the responses. Furthermore, Table 5 offers a more detailed comparison of the results for specific items within each category.

In 'Engagement', most responses were more positive for learning with VR than with 2DLM (Total $M_{\text{2D}} = 4.32$, $M_{\text{VR}} = 5.15$), which represents a difference of 11.9%. 'Attraction' showed the most significant difference in the A2 item ($M_{\text{2D}} = 3.85$, $M_{\text{VR}} = 5.45$) and the lowest in A1 ($M_{\text{2D}} = 4.55$, $M_{\text{VR}} = 5.75$). 'Time investment' was also confirmed to be higher in VR than in 2DLM ($M_{\text{2D}} = 4.11$, $M_{\text{VR}} = 5.34$). The most significant difference was in T3 ($M_{\text{2D}} = 4.35$, $M_{\text{VR}} = 5.70$). Finally, 'Usability' was evaluated as slightly easier for 2DLM than for VR ($M_{\text{2D}} = 4.83$, $M_{\text{VR}} = 4.69$), but the difference was not significant.

Table 4 Mean, total mean, total mean difference between VR-based learning and 2DLM in each educational evaluation category

Category	Subcategory	Mean		p-value	Total mean		p-value (One-sided)	Total mean difference	Total mean difference
		2DLM	VR		2DLM	VR		[Points]	[%]
Engagement	Attraction	4.03	5.44	< 0.001	4.32	5.15	< 0.001	0.83	11.9
	Time investment	4.11	5.34	< 0.001					
	Usability	4.83	4.69	0.260					
Immersion	Emotional attachment	3.28	4.98	< 0.001	3.18	4.49	< 0.001	1.31	18.6
	Focus of attention	3.70	4.94	< 0.001					
	Presence	2.55	3.33	0.055					
	Flow	3.20	4.70	< 0.001					
Motivation		3.98	4.70	< 0.001	3.98	4.70	< 0.001	0.72	10.3
Cognitive benefits		4.44	5.09	0.007	4.44	5.09	0.003	0.65	9.3
Perceived learning effectiveness		4.82	5.43	< 0.001	4.82	5.43	< 0.001	0.61	8.7

Table 5 Mean difference between VR-based learning and 2DLM

Category	Questionnaire	2DLM		VR		t	p-value (One-sided)
		M	SD	M	SD		
Engagement (Attraction)	(A1) The contents we employed captured my attention Strongly	4.55	1.67	5.75	1.89	2.13	0.02
	(A2) I liked the contents because it was novel	3.85	1.90	5.45	1.57	2.90	0.003
	(A3) The topic of the contents made me want to find out more about it	3.90	1.37	5.30	1.69	2.88	0.0035
	(A4) The space in which the contents took place was interesting	3.80	1.58	5.25	1.97	2.57	0.007
	Total	4.03	1.64	5.44	1.76	5.25	< 0.001
Engagement (Time investment)	(T1) I wanted to spend the time to complete the contents successfully	4.00	1.49	5.50	1.49	2.97	0.0025
	(T2) I wanted to spend time to participate in the contents	3.95	1.32	5.50	1.32	3.05	0.002
	(T3) I wanted to spend time collecting the information provided	4.35	1.42	5.70	1.42	3.56	0.0005
	(T4) I think that participating in this content was a waste of my time. *	4.15	1.31	4.55	1.31	0.82	0.2075
	Total	4.11	1.37	5.34	1.63	5.05	< 0.001
Engagement (Usability)	(U1) It was easy for me to use the contents	5.65	1.50	5.70	1.50	0.11	0.4585
	(U2) I found the contents confusing. *	3.60	1.60	3.40	1.60	0.35	0.364
	(U3) I felt confident since I knew how to use the contents	5.65	1.63	5.50	1.63	0.31	0.3795
	(U4) The content was unnecessarily complex. *	4.40	1.60	3.95	1.60	0.80	0.214
	Total	4.83	1.78	4.69	1.97	0.63	0.2645
Immersion (Emotional attachment)	(E1) I was curious about how the content would progress	3.25	1.92	5.90	1.25	5.18	< 0.001
	(E2) I was often excited since I felt as being part of the contents	2.60	1.82	5.05	1.57	4.56	< 0.001
	(E3) I often felt interested in the content	2.90	1.89	4.35	1.23	2.88	0.0035
	(E4) If interrupted, I looked forward to returning to the content	4.35	1.90	4.60	1.79	0.43	0.3355
	Total	3.28	1.96	4.98	1.57	6.06	< 0.001
Immersion (Focus on attention)	(FA1) I was more involved with the content than with any other thoughts	4.10	1.48	5.10	1.80	1.92	0.0315
	(FA2) I often forgot the passage of time in the environment	3.55	1.85	4.95	1.82	2.41	0.0105
	(FA3) I was more focused on the content rather than on any external distraction	3.85	1.63	4.70	1.84	1.55	0.065
	(FA4) During the session, hardly anything could distract me	3.20	1.54	4.65	1.76	2.78	0.0045
	(FA5) Time went by quickly during the sessions	3.80	1.61	5.30	1.53	3.03	0.002
	Total	3.70	1.62	4.94	1.73	5.22	< 0.001
Immersion (Presence)	(P1) I felt that I was in a realistic environment, in which I could hardly separate what was virtual or real	2.25	1.55	2.85	1.73	1.16	0.1275
	(P2) The content felt so authentic that it made me think that the virtual characters/objects existed in reality	2.85	2.01	3.80	1.7	1.61	0.0575
	Total	2.55	1.80	3.33	1.76	1.95	0.0275
Immersion (Flow)	(F1) I did not have any irrelevant thoughts or external distractions during the session	3.00	1.34	4.60	1.73	3.27	0.001
	(F2) The content became the only thought occupying my mind	3.45	1.50	4.80	1.64	2.71	0.005
	(F3) I lost track of time as if everything stopped, and the only thing that I could think about was the content	2.95	1.47	4.25	1.94	2.39	0.011
	(F4) All of my senses were concentrated on the content	3.40	1.60	5.15	1.63	3.42	0.0005
	Total	3.20	1.47	4.70	1.74	5.89	< 0.001
Motivation	(M1) I enjoyed this type of content very much	4.20	1.44	5.20	1.94	1.86	0.036
	(M2) Learning in this type of environment was fun	3.90	1.62	5.50	1.93	2.84	0.0035
	(M3) I would describe this type of content as interesting	3.70	1.63	5.65	1.76	3.65	< 0.001
	(M4) I was satisfied with my performance in this type of content-based learning environment	4.45	1.50	4.90	1.83	0.85	0.2005
	(M5) I felt pressured while learning in this type of environment. *	3.70	1.56	4.10	1.80	0.75	0.229
	(M6) I did not try very hard while learning in this type of environment. *	3.10	1.65	3.65	1.81	1.00	0.161
	(M7) I was thinking how much I enjoyed learning in this type of environment	3.60	1.60	4.50	1.73	1.71	0.048
	(M8) I felt competent after trying this type of tool for a while	4.15	1.42	4.75	1.52	1.29	0.1025
	(M9) I was very relaxed while learning with this type of (VR/2D) tool	4.30	1.17	3.95	1.64	0.78	0.2215
	(M10) I am very skilled at this type of content	5.05	1.57	5.05	1.73	0.00	0.5
	(M11) This type of environment did not hold my attention. *	3.55	1.79	4.45	1.73	1.62	0.057
	(M12) I could not learn much using this type of tool. *	4.05	1.54	4.65	1.84	1.12	0.1355
	Total	3.98	1.59	4.70	1.83	4.58	< 0.001

Table 5 (continued)

Category	Questionnaire	2DLM		VR		t	p-value (One-sided)
		M	SD	M	SD		
Cognitive benefits	(C1) This type of content makes comprehension easier	4.80	1.36	5.30	1.69	1.03	0.1545
	(C2) This type of content makes memorization easier	3.95	1.47	4.90	1.80	1.83	0.038
	(C3) This type of content helps me to better apply what was learned	4.25	1.68	5.35	1.79	2.01	0.026
	(C4) This type of content helps me to better analyze the problem	4.50	1.61	4.65	1.76	0.28	0.39
	(C5) This type of content helps me to have a better overview of the content learned	4.70	1.66	5.25	1.94	0.96	0.171
	Total	4.44	1.56	5.09	1.78	2.75	0.0035
Perceived learning effectiveness	(PL1) I was more interested to learn the topics	4.50	1.32	5.40	1.43	2.07	0.0225
	(PL2) I learned a lot of information in the topics	5.20	1.10	5.45	1.28	0.66	0.256
	(PL3) I gained a good understanding of the basic concepts of the (VR/2D) content	5.20	1.15	5.50	1.32	0.77	0.224
	(PL4) I learned to identify the main and important issues of the topics	5.35	0.99	5.40	1.19	0.15	0.443
	(PL5) I was interested and stimulated to learn more	3.75	1.55	5.50	1.64	3.47	0.0005
	(PL6) I was able to summarize and conclude what I learned	5.10	1.41	5.35	1.46	0.55	0.2925
	(PL7) The learning activities were meaningful	5.05	1.23	5.65	1.35	1.47	0.075
	(PL8) What I learned; I can apply in real context	4.40	1.76	5.20	1.44	1.58	0.062
	Total	4.82	1.4	5.43	1.37	3.95	<0.001

*These questions are measured with reverse scores, and measure negative items

In 'Immersion', as well as 'Engagement', it was confirmed that the total mean was higher in VR than in 2DLM (Total $M_{2D}=3.18$, $M_{VR}=4.49$), which represents a difference of 18.6%. Among the items of 'Immersion', 'Emotional attachment' showed the largest difference in the immersion category ($M_{2D}=3.28$, $M_{VR}=4.98$). Especially, in 'Emotional attachment' the largest difference was in E1 ($M_{2D}=3.25$, $M_{VR}=5.90$), and the smallest difference was in E4 ($M_{2D}=4.35$, $M_{VR}=4.60$). In 'Focus on attention', the largest difference was in FA5 ($M_{2D}=3.80$, $M_{VR}=5.30$), and the smallest difference was in FA3 ($M_{2D}=3.85$, $M_{VR}=4.70$). Although FA3 items individually had $p>0.05$, total sum of 'Focus on attention' had $p<0.05$. 'Presence' consisted of two items, and both had $M_{2D}<M_{VR}$, but $p>0.05$. For 'Flow', the largest difference was in F4 ($M_{2D}=3.40$, $M_{VR}=5.15$), and the item that showed the smallest difference was F3 ($M_{2D}=2.95$, $M_{VR}=4.25$). All items in 'Flow' had $p<0.05$.

For 'Motivation', the mean values were higher in VR than in 2DLM in all items except M9 and M10. The total mean was approximately 10.3% higher in VR compared to 2DLM (Total $M_{2D}=3.98$, $M_{VR}=4.70$). Each item individually had $p>0.05$, except M1, M2, M3, and M7 but the sums of all items had $p<0.05$. The most significant difference was in M3 ($M_{2D}=3.70$, $M_{VR}=5.65$), and the most negligible difference was in M10 ($M_{2D}=5.05$, $M_{VR}=5.05$).

For 'Cognitive benefit' the means of all items were higher for M_{VR} than for M_{2D}, and the total mean was also 9.3% higher in VR compared to 2DLM (Total $M_{2D}=4.44$, $M_{VR}=5.09$). All individual items had $p>0.05$ except C2 and C3, but when pooled, they had $p<0.05$. The item with the most significant difference was C3 ($M_{2D}=4.25$, $M_{VR}=5.35$), and the item with the most negligible difference was C4 ($M_{2D}=4.50$, $M_{VR}=4.65$).

Finally, for 'Perceived learning effectiveness' total means were 8.7% higher for M_{VR} than for M_{2D} (Total $M_{2D}=4.82$, $M_{VR}=5.43$), exhibiting higher mean with VR in all of individual sub-items. Each individual item, except PL1 and PL5, had $p>0.05$, but the total scores of all items had $p<0.05$. The item with the most significant difference was PL5 ($M_{2D}=3.75$, $M_{VR}=5.50$), and the item with the most negligible difference was PL4 ($M_{2D}=5.35$, $M_{VR}=5.40$).

5 Discussion

5.1 Performance-based assessment

Overall, we confirmed that use of VR learning can improve quantified learning outcomes compared to the traditional 2DLM. The comparison of mean post-test scores $M_{XX\text{-}Post}$ to mean pre-test score $M_{XX\text{-}Pre}$ was used to quantify the gain in knowledge (Table 1). The gain $M_{XX\text{-}Post}-M_{XX\text{-}Pre}$ / $M_{XX\text{-}Pre}$ was higher by 2DLM (18.80) than by VR (16.65), but the difference was a result of the (non-significantly) lower pre-test scores achieved by the 2DLM than by the VR. When considering the post-test means, students exposed to 2DLM achieved scores of 6.93 points, while those in VR-based learning environments scored 8.47 points, representing an approximately 12% higher score. The results indicated that students were more interested in VR-based teaching methods, better understood the knowledge, and focused on learning through steady thinking based on immersion and motivation.

We also verified that VR learning is more helpful than 2DLM in improving comprehension of 3D structure and spatial-perception ability. When considering the mean scores of the 3D reconstruction test, students who experienced 2DLM achieved scores of 3.65 points, while those who experienced VR-based learning scored 4.35 points, representing an approximately 13% higher score (Table 2). VR learning enables learners to freely adjust their point of view within a virtual space, so they can actively observe 3D structures from various angles and distances, and thereby increase their spatial understanding. Moreover, the various possible interactions and visual effects available in VR can improve learners' concentration and strengthen their memory for specific structures. Additionally, VR courses are conducted in a safe environment, so users can effectively learn about structures and spaces without any burden, particularly in engineering classes that involve dangerous content. These effects were reflected in result of the 3D reconstruction.

5.2 Perception-based assessment

In 'Perception-based assessment,' we confirmed that VR is a more effective learning method than 2DLM across five categories that evaluate learning effectiveness. Notably, each category offers a crucial link in enhancing the understanding of complex 3D structures. We also confirmed that the results of 'Perception-based assessment' were consistent with the 'Performance-based assessment'.

Total mean for 'Engagement' was much higher with VR than with 2DLM. 'Engagement' consists of 'Attraction', 'Time Investment', and 'Usability', and these are the primary indicators that can be initially observed when engaging with content. The three sub-categories respectively signify the learner's interest in the content, the time they are willing to invest, and the convenience of using the content (Georgiou and Kyza 2017). Among the specific categories, the item that showed the most significant difference was 'Attraction' (A1-A4). Ensuring full immersion of users in the learning environment requires prioritizing the overcoming of preference barriers, which tend to favor certain instructional modes (Cheng 2015). In this context, 'Attraction' is defined as the process that users must navigate to advance to the participation stage. The experimental results show that the educational approach using VR can increase students' preference for learning and stimulate their interest. However, the 'Usability' results showed that 2DLM was easier to use than VR for all items. 'Usability' (U1-U4) measures the ease of participation for students in the teaching method. This result may be a consequence of the participants' having higher level of manipulation with traditional 2DLM than with VR. Students may encounter some difficulties when exposed to VR teaching methods. The limited 10-min duration of the experiment and the students' lack of experience in manipulating VR content may explain the comparatively low assessment for 'Usability' of VR. However, we can expect improved assessment of 'Usability' as students fain familiarity with VR methods. Nevertheless, it is shown that the total mean of 'Engagement' for VR is higher compared to 2DLM. The superior engagement of VR demonstrates its ability to elicit positive reactions from students and lower the entry barriers to learning immersion. This, in turn, leads to increased active participation, ultimately enhancing the learning effectiveness of 3D structures.

Total mean for 'Immersion' was much higher with VR than with 2DLM. Specially, 'Emotional attachment' (E1-E3) showed the most significant difference among measures of immersion. 'Emotional attachment' is the reaction that occurs when a user feels an emotional connection and ownership of the educational environment, i.e., the extent to which the user finds the process of self-learning enjoyable, and is consistently interested in the teaching method. The experimental results confirmed that teaching using VR could help students develop an emotional connection to learning, as students enjoy and show interest in learning on their own. Additionally, 'focus on attention' (FA1-FA2, FA4-FA5) also showed a significant difference in mean values. 'Focus on attention' measures the level of concentration and awareness towards the learning content as a result of selective perception and reactions. The responses to FA4 and FA5 suggest that the teaching using VR effectively isolates students from the real world by presenting a fully-virtual environment and eliminating distracting external elements. This state of immersive isolation can create a psychological arousal that facilitates deep engagement with the learning content. Consequently, VR can enhance immersion, including emotional bonding and concentration, through realistic 3D representation and intuitive interaction. This enhances learners' spatial perception by reducing distractions to the learning subject, maintaining focus, and increasing understanding.

Total mean for 'Motivation' were also higher for VR than 2DLM. Many previous studies in education have shown that motivation strongly affects learning (Yaman et al. 2008). Previous research on educational psychology has demonstrated a positive correlation between intrinsic motivation and learning outcomes (McAuley et al. 1989). Adequate motivation enables learners to engage more actively in their studies, investing more time and effort in exploring and understanding new information. Additionally, it facilitates continuous learning, contributing to the achievement of educational goals, and fostering a positive attitude towards learning. These results were represented in various items of motivation, including M1, M2, M3, and M7, which are all directly related to 'Engagement' and 'Immersion', showing

similar trends. Ultimately, the 'Motivation' enhanced by VR learning is linked to 'Engagement' and 'Immersion', leading to improved understanding of 3D structures. However, some items related 'Engagement', such as M10, which indicated that VR was less usable than 2DLM, suggest that students may need time to adapt to the VR teaching method.

Total mean for 'Cognitive benefits' was higher for students that used VR than that used 2DLM. 'Cognitive Benefits' include improved memorization, comprehension, application ability of the content learned in the provided environment. VR enhances cognitive benefits by providing lifelike experiences; making learning vivid and enabling intuitive understanding of 3D objects and environments, thus directly improving learning effectiveness. However, when evaluating individual sub-items of 'Cognitive Benefits', no significant differences were observed in items PL2, PL3, PL4, and PL6. This could be attributed to the participants using 2DLM being more accustomed to conventional digital learning methods, thus assigning relatively higher scores to specific items.

Total mean for 'Perceived learning effectiveness' was higher for VR learning than for 2DLM. 'Perceived learning effectiveness' describes change in the learner's awareness as the student develops knowledge and skills by participating in a new learning environment. The features of VR such as high 3D representation and facilitation of intuitive understanding enhance 'Perceived Learning Effectiveness', making complex learning more manageable. However, similar to 'Cognitive benefits' when each item was considered individually, the differences were not significant. The small mean difference between the learning methods in PL2, PL3, PL4, and PL6 can be attributed to the dominant influence of 'Cognitive benefits' on these items, and to the students' familiarity with existing learning methods. Therefore, an experiment should be designed such that participants familiarize themselves with the VR device.

6 Limitation

This study has some limitations. Firstly, a sample size of 40 is relatively small and may not be sufficient to determine the actual educational effect of teaching using VR. Previous studies have suggested that, to enable statistically significant results, experiments comparing educational methods require hundreds of participants (Lund 2023). We plan to conduct further research with a larger sample to validate and expand our conclusions. Furthermore, the influence of a few outliers may have inflated the standard deviation, thereby increasing the p-values. This effect would limit the educational significance of our findings. To overcome these limitations, we will use biometric data to quantify the level of immersion and concentration during the learning process, thereby enabling a more comprehensive evaluation of the educational impact of teaching with VR.

Additionally, our study was limited to the use of LCD topic as the educational content. Consequently, the results of this study are specific to this subject and may not be directly applicable to learning in other domains. To broaden the application of VR in educational contexts, there is a need for versatile content-authoring tools and an evaluation system that is specifically designed for educational VR content. In future research, we advocate for the development of VR content-authoring tools that can be employed across a variety of educational fields and the enhancement of evaluation systems specialized for education utilizing VR.

Finally, the design of our study focused on specific media such as VR and 2D video, but failed to thoroughly integrate the educational methodologies applied with these media. Therefore, our results might represent limited outcomes regarding the differences in learning effects between the two groups, and there could be limitations in fully elucidating the impact of the learning effects between the two media. Recognizing these points, future research needs to more systematically analyze the learning effectiveness of various media along with their corresponding educational methodologies.

7 Conclusion

In this study, we confirmed the educational effectiveness of VR in enhancing overall comprehension of learning topics and spatial awareness of 3D structures compared 2DLM. To assess the effectiveness of the method, we developed VR and video-based learning content and conducted a questionnaire evaluation of educational categories using a Likert 7-point scale. Additionally, pre-test and post-test quizzes, along with a 3D-reconstruction test, were administered to evaluate learning outcomes. The VR learning method was found to be superior to the conventional digital learning method for 'Engagement', 'Immersion', 'Motivation', 'Cognitive benefits', and 'Perceived learning effectiveness'. Likewise, The VR learning method have higher learning outcomes then the 2DLM by about 12% higher on the post-quiz and about 13% for the 3D reconstruction test. We conclude that the use of VR for learning can offer better outcomes for students compared to traditional video-based learning, particularly by enhancing the understanding of 3D structures in complex and challenging fields like engineering. Therefore, employing VR in engineering education has the potential to provide an innovative and immersive learning experience for students.

With the advancement of VR education, educators can maximize the potential of learning by applying some considerations. Specially, in complex learning scenarios like understanding 3D structures, it's crucial to consider setting specific educational goals, enhancing the quality of learning content, and continuously evaluating and improving the developed VR learning methods. Firstly, educators must establish clear and specific learning objectives for VR-based education. The level, characteristics, and components of VR content will vary depending on the learning objectives, directly impacting students' learning outcomes. Therefore, after a detailed analysis of learners' current abilities, knowledge levels, and motivations, learning objectives should be established based on these findings and incorporated into the VR content design. Moreover, these established learning objectives will later serve as critical benchmarks for evaluating learning outcomes and determining the effectiveness of the educational process. Additionally, the development of high-quality content with enhanced immersion is paramount for deeper understanding of complex concepts. According to our research, immersive VR education enhance learning effectiveness by providing users with active participation and motivation. To improve immersion, it's essential to create virtual environments and objects that maximize realism and simulate physical effects as closely as possible to the real world. Also, facilitating maximum interaction within the content to encourage active learning can further increase immersion. Lastly, continuous evaluation and improvement of the developed VR learning methods are essential. A systematic approach is required to evaluate students' learning outcomes and collect their feedback on the learning experience. This process can identify both strengths and areas for improvement within the VR learning environment. By adjusting and applying the components of VR content based on collected data, educators can provide learners with a richer and more effective learning experience.

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Author contribution Jonghyeon Ka wrote the main manuscript and prepared all figures and tables. Haryun Kim conducted the literature research for the introduction and literature review. Jihyung Kim assisted in designing the methodology and analyzed the experimental results. Wooksung Kim provided guidance on the overall management of the paper.

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Data availability The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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