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Examining the impact of head-mounted augmented reality on learning engineering drawings: A case study for three-view drawing

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Abstract

As the cornerstone of spatial geometry and engineering drawings, three-view drawing lays the necessary foundation for students to learn geography, graphics, industrial design, geographic information science, and so forth. However, teaching three-view drawing can be challenging due to its abstraction. Currently, desktop and handheld augmented reality (AR) systems are widely applied to three-view teaching. However, existing systems suffer from visuo-tactile inconsistency and contain unfriendly interactions, resulting in a poor learning experience. In this paper, head-mounted AR is introduced for the first time in the teaching of three-view drawing. A system was designed for learning three-view drawing to facilitate students' free exploration and learning in lessons. Additionally, a comparative experiment was designed and conducted to investigate whether multimodal interaction and head-mounted AR help students to better understand the relationship between concrete three-dimensional (3D) objects and abstract two-dimensional planes and the impact on subjective perceptions. The results demonstrated that the proposed system significantly improved learning performance. Furthermore, the proposed system heightened students' interest in learning, made reproducing 3D structures more intuitive, and students were more willing to use such systems in their future studies.

KEYWORDS

augmented reality, comparative study, head-mounted display, learning system, three-view drawing

1 | INTRODUCTION

Spatial ability, the fundamental cognitive ability of human beings, refers to the ability to understand, reason, and remember the spatial relationship between objects [61]. Good spatial ability is beneficial for understanding the spatial geometry of the real world [27] and expanding logical thinking to analyze and solve problems [57]. Fortunately, spatial ability and geometric intuition can be trained by observing associations between three-dimensional (3D) space geometry and its corresponding two-dimensional (2D) views [3, 21], and three-view drawing is one of the most widely used training methods, and is crucial for mathematics [29], geography [16], and engineering drawing-based majors, such as industrial design [40]. Three-view drawing is the foundation of engineering drawing. It describes the 2D orthographic projections of the spatial geometry under light rays from three separate directions (top, left, and front). Proficiency in three-view drawing is essential for students to fully grasp spatial geometry. However, since projection and view are abstract and nonintuitive concepts that require more profound understanding through one's imagination, it is difficult for students with insufficient spatial imagination to acquire knowledge of three-view drawing. Therefore, how to educate becomes a challenging subject in secondary mathematics lessons and a hot topic in the realm of education to assist students in the comprehension and mastery of abstract knowledge.

An essential theoretical foundation for supporting students' acquisition of abstract view knowledge is provided by experiential learning theory [32]. According to the theory, learning is the process of converting experience into knowledge. However, a good experience requires a natural way of interacting [58], which has a lower cognitive load and is not distracting [20, 41]. By ensuring enhanced communication between humans and systems, multimodal interaction is a natural way of interacting and is widely used in the field of education. It also improves students' interest in learning. Students' interest in the classroom can significantly affect the learning process and can be considered an essential factor in designing reinforcement learning strategies [49]. However, it is still a challenge to teach three-view drawing based on more natural interaction.

Previous three-view drawing learning systems can be categorized into three groups: (a) handheld AR systems, (b) desktop systems, and (c) head-mounted virtual reality (VR) systems. For handheld augmented reality (AR) [71], although virtual 3D structures can be superimposed on real scenes, 3D structures displayed by handheld AR applications can only be observed, and the virtual spatial structure cannot be adjusted. It limits the scope of three-view drawing knowledge exploration. Desktop systems [13, 68] are developed to help students grasp the relationship between 2D planes and 3D objects. However, the nonstereoscopic presentation of 3D objects affects students' perception and understanding of 3D information [62]. In pursuit of greater immersion in learning, Hong et al. [25] employed VR head-mounted displays (HMDs) to create an immersive learning environment. Immersion is a subjective phenomenological experience of partaking in an all-inclusive experience [43], and forms the basis of immersive learning, emphasizing complete engagement in the learning process [4, 5]. An immersive learning environment comprises a technology system, narrative content, and challenging tasks, collectively designed to offer learners a rich and engaging experience [5]. Students interact with virtual objects using 3D controllers and navigate a virtual space with a heightened sense of immersion and spatial awareness. This immersive approach contributes to an improved understanding of three-view drawing. However, it's noteworthy that the study lacks an assessment of students' learning performances and their interest in the learning process. In addition, 3D controller operations are usually different from real environments. Training in advance is needed, which incurs more cognitive load [70]. Despite these considerations, the utilization of immersive technology holds promise for fostering a more immersive and engaging learning experience.

In this paper, an experiential system is developed as the first three-view drawing learning system based on AR HMD and multimodal interaction. The hardware includes a Microsoft HoloLens2 AR HMD and a tablet personal computer (PC). The HMD, as the student platform, allows students to construct 3D structures and answer questions with multimodal interactions, including gestures, voice, and gaze interactions. It presents 3D virtual objects stereoscopically, allowing students to observe 3D structures more intuitively and immersively. The tablet PC, as the teacher platform, enables teachers to design and publish teaching resources while viewing students' learning progress in real-time. Furthermore, the first comparative study is conducted among various learning systems on the students' learning performance and subjective perceptions, which answers the following questions:

RQ1: *Whether the learning performance of the proposed system is better than desktop and handheld AR systems?*

RQ2: *Whether the perceived usefulness of the proposed system is better than desktop and handheld AR systems?*

RQ3: *Whether the perceived ease of use of the proposed system is better than desktop and handheld AR systems?*

RQ4: *Whether the willingness to continue to use of the proposed system is better than desktop and handheld AR systems?*

Our research objective is to establish an immersive and highly interactive learning environment for students to enhance learning performances (RQ1) and improve user experience (RQ2, RQ3, and RQ4). The structure of the rest of this paper is as follows. The related work is discussed in Section 2. Following that, Section 3 introduces the system' design framework. The method is presented in Section 4. The results of the experimental data are presented in Section 5. The experimental data is analyzed in Section 6. Finally, conclusions are provided in Section 7.

2 | RELATED WORK

2.1 | Spatial geometry learning systems

Since three-view drawing is an important concept of spatial geometry and there are few in-depth studies on three-view learning systems, we extend the literature review to spatial geometry learning systems.

2.1.1 | Handheld AR-based spatial geometry learning systems

In handheld AR-based systems for learning spatial geometry, virtual geometric objects can be overlaid onto the real world using identified markers.

Kang et al. [71] and Mambu et al. [42] developed handheld AR systems using a tablet PC to display 3D virtual objects by scanning markers. However, these objects cannot be interacted with. Some works attached markers to real cubes. For instance, in the system developed by Yu et al. [72], students used a tablet PC to scan a 3D structure made of labeled cubes to see the cross-sectional view of each layer. This method helped them practice spatial cognitive skills and count cubes. Lin et al. [37] designed a three-view drawing system where the tablet PC displays a corresponding 3D structure based on the the views by the student. Additionally, students could use the tablet PC to scan real 3D structures and view their corresponding three views. However, this study did not assess students' learning performance or interest in learning. Lin et al. [36] created a learning system to assist junior high school students in learning solid geometry. They explored the relationship between mathematical achievement and spatial perception and whether the learning system could improve students' spatial perception skills.

Students observe 3D structures using AR to naturally superimpose virtual 3D objects on the real scene [33, 47]. Nevertheless, the existing AR learning system, with its unfriendly interaction, requires students to hold the tablet PC with one hand and operate the marker with the other. Thus, a natural interaction will be used in the proposed system to manipulate virtual objects.

2.1.2 | Desktop-based spatial geometry learning systems

In desktop-based systems for learning spatial geometry, users manipulate virtual geometric objects via keyboards and mice.

Nesbitt et al. [44] developed a learning system aimed at enhancing students' mental rotation and translation abilities between 3D and 2D representations. The system incorporated a freely rotatable 3D perspective map and three-view drawing. Christou et al. [13] designed a system for teaching spatial geometry and visual thinking, allowing students to construct and observe 3D structures, as well as explore the process of rotation of a 3D object along different axes by manipulating 2D planes. However, these researchers did not conduct experimental evaluations. Xiao et al. [68] created the Cubicle platform for teaching spatial visualization abilities and performed an evaluation experiment. Based on the three-view drawing shown by the system, users construct a 3D structure to match the drawing. Nurjanah et al. [46] utilized Cabri 3D software to assist students in learning spatial geometry and fostering the development of their spatial skills. After using the software, students showed significantly improved learning independence compared to traditional teaching methods.

Students interact with desktop systems using keyboards and mice. Due to the familiarity with keyboards and mice, desktop systems do not cause a burden of learning how to use new interaction devices. However, 3D objects presented on computer screens do not have spatial depth, and therefore do not fully provide the 3D perception necessary to solve spatial problems in the real world, which can hinder the learning of visualization skills [9, 30], which refer to the ability to understand the visual and spatial relationship among objects. Therefore, an AR HMD with immersion will be used to present 3D objects to help students learn about spatial geometry.

2.1.3 | VR HMD-based spatial geometry learning systems

In VR systems for learning spatial geometry, users wear headsets and use 3D controllers to observe and manipulate virtual geometric objects.

Chao et al. [10] leveraged VR technology to transform 2D graphics into 3D spaces, aiming to effectively solve the problem of learning abstract 3D spaces. The study demonstrated that interactive VR learning materials significantly enhanced students' spatial abilities, leading to increased learning efficiency and motivation, especially among students who initially scored lower in mathematics. In the system developed by Hong et al. [25], users freely construct 3D structures using 3D controllers. During the construction, the system presents a three-view drawing of the 3D structures in real time. However, for complex 3D objects, it is still difficult for students to relate three-view drawings to 3D objects. To solve the problem, Rodríguez et al. [51] employed color differentiation to distinguish the parts of the 3D object projected into the three-view drawing, enhancing clarity for users while transforming 2D planes into 3D objects. Additionally, the system improves students' 3D visualization abilities, aiding their understanding of geometric and topological properties. Su et al. [55] designed a learning system for geometry topics, aiming to investigate the impact of immersive VR on students' technology acceptance, learning motivations, and performance.

VR devices facilitate the display of 3D objects. Immersion brought by HMDs helps students to understand spatial geometry and increases their motivation to learn. However, existing VR HMDs mostly require a user to hold a 3D controller and press a trigger to achieve interaction, which is an unnatural and high cognitive load for students. As a result, a more natural gesture will be used in the proposed system.

2.2 | Effectiveness evaluation of learning systems

Learning systems, from traditional desktop systems to the current AR and VR learning systems, provide abundant opportunities for leveraging technology to enhance learning [2].

Some studies focus on the effectiveness of desktop systems in assisting students. Yahiaoui et al. [69] analyzed the impact of desktop e-learning systems on student motivation and performance and found that both students' motivation and performance were significantly influenced by desktop e-learning systems. Perez et al. [48] evaluated the NEO learning management system and found that the system met the international quality standards for management systems. Moreover, they examined its potential to improve students' motivation and English language skills and found that it was effective in enhancing students' motivation and English language skills.

The use of VR in training and education is growing, particularly in light of the COVID-19 pandemic. As a result, it is becoming more crucial to understand how personality traits and VR technology acceptance affect learning performances [65]. Chen et al. [11] investigated learners' attitudes and perceived utility in L2 learning. The results indicated that learning the target language in a VR environment was a practical intervention for developing autonomous motivation and L2 students had better attitudes towards their learning experiences. Li et al. [35] evaluated the effectiveness of VR tools for students to learn 3D vectors in an introductory university physics course and students praised the value of VR tools in enhancing their learning experience and understanding of knowledge.

AR sparks interest, boosts motivation, and enhances engagement in the learning process. Its interactive style fosters learner initiative and curiosity, significantly enriching the overall learning experience. Wyss et al. [67] surveyed 18 student teachers specializing in science and technology for lower secondary schools at a teacher education university. The findings highlighted the students' strong positive attitude towards AR technology and their high motivation to use it for learning. Belda-Medina et al. [6] conducted a study on the impact of AR on cognition, vocabulary learning, and student motivation. The research findings demonstrated that using AR for language learning sparked positive attitudes and strong interest among students. Yuan et al. [73] designed a Chinese chess system based on spatial AR and their experiments demonstrated that most participants experienced better user satisfaction, learning performance, and player motivation using the proposed chess compared to conventional chess and mouse-interaction-based chess.

Therefore, although people are more familiar with the keyboard and mouse interaction of desktop systems, they are relatively lacking in providing an immersive experience and interactivity. This is not conducive to learning knowledge that requires spatial ability. In contrast, AR and VR systems offer an immersive digital experience that traditional teaching methods cannot replicate [74], enabling students to better engage with complex learning materials beyond lectures and textbooks [56]. Furthermore, compared to VR, AR is generally more user-friendly in terms of physiological sensations. Because AR retains a part of the real world, users typically don't easily feel dizzy or experience motion discomfort when using AR, which is more advantageous for prolonged learning and training. We hope to use AR technology to create a learning environment that assists students in learning three-view drawings.

2.3 | Multimodal interaction

Multimodal interaction integrates various interaction channels, including physical objects, gestures, voice, and gaze. This enhances the authenticity, naturalness, and efficiency of the user interaction process.

Shou et al. [53] proposed a multimodal natural interaction technology based on gestures, tangible objects, and natural walking, designed for patients with limb impairments. User research indicated that compared to controller interaction, natural multimodal interaction is more engaging, provides a stronger sense of realism, and enhances participants' enthusiasm and motivation. Doumanis et al. [17] constructed a multimodal virtual reality environment and compared it with a nonmultimodal control group. The results showed that the multimodal collaborative virtual environment improved certain aspects of student learning performance and subjective experience. However, Shou et al. and Doumanis et al. have applied multimodal interactions in a VR environment. This may not be conducive to students exploring the real environment. Wang et al. [63] proposed a multimodal interaction system that integrated gaze, gesture, and speech into a flexibly configurable AR system. They evaluated the system in a scenario involving table lamps and compared the performance of different interaction techniques. The experimental results showed that the Gaze + Gesture + Speech was superior in terms of performance. However, their multimodal systems require sitting in front of a computer, preventing free body movement and limiting students' ability to explore freely.

Multimodal interaction is expected to take advantage of each modality and provide better usability [63]. However, currently no one has applied multimodal interaction in the three-view drawing learning system, which could potentially improve learning performance and user experience.

H1 The three-view learning system based on AR HMD and multimodal interaction can positively and significantly affect the learning performance.

H2 The three-view learning system based on AR HMD and multimodal interaction can positively and significantly affect subjective perceptions.

3 | DESIGN FRAMEWORK

The system aims to establish an engaging and immersive learning environment by enhancing students' learning experiences through the process of constructing 3D structures and acquiring knowledge related to three-view drawing concepts. Our design is inspired by the constructivist theory [54] as it is one of the most common learning theories. Constructivist theory posits that learning is a process of constructing knowledge, with students actively engaging, exploring, and solving problems to develop an understanding of the world. According to the constructivist theory, we develop our system and it consists of two platforms, namely the teacher platform and the student platform, which are run on a tablet PC and Hololens2, respectively. The former is used for designing teaching resources and monitoring students' learning progress while the latter is used for interactive learning and exercises. Figure 1 depicts the schematic diagram of the system, which comprises

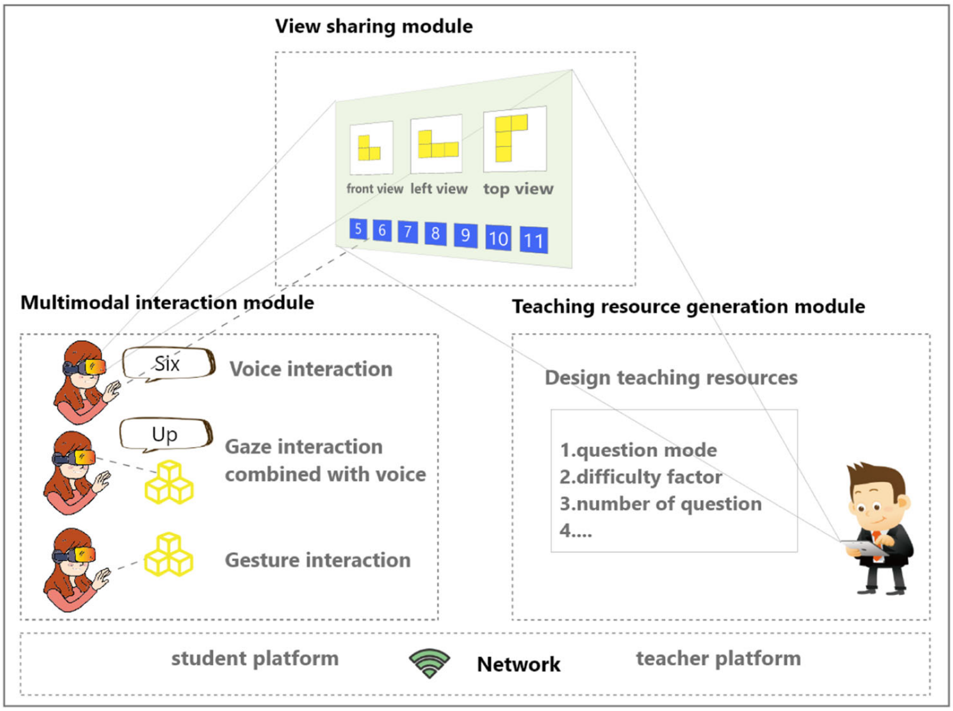

FIGURE 1 System schematic diagram.

multimodal interaction, view sharing, and teaching resource generation. In the multimodal interaction module (RQ1, RQ3), we offer a multisensory experience to enable students to comprehensively understand the learning content. The view-sharing module (RQ1 and RQ2) allows students to share their viewpoints, facilitating collaborative learning and interaction. The teaching resource generation module (RQ2) is responsible for creating educational materials related to 3D structures, providing support for the learning process. In addition, two learning modes (RQ2 and RQ4) are designed to cater to diverse learning needs and preferences. These modules collectively contribute to the creation of an immersive learning environment, offering students opportunities for active participation and social interaction during the knowledge-building process.

3.1 | Multimodal interaction module

The multimodal interaction module processes input requests, including gesture, voice, and gaze. Given that having a strong learning motivation affects learners' performance [59], learning motivation is considered a crucial factor in the learning process [19]. When considering how to enhance learning motivation, multimodal interaction becomes a noteworthy direction. By fully incorporating experiential teaching theory, we design multimodal interactions to establish a vivid and innovative educational system. This approach generates a more engaging and enriching learning experience by integrating various senses, such as vision and hearing. Applying multimodal interaction enhances the usability of the system (RQ3) and improving learning performance (RQ1).

Gesture, regarded as a natural method to interact with surroundings [60], is selected for constructing and manipulating 3D structures. To allow users to interact quickly and directly and make interaction easy [24], voice interaction is selected for answering questions. Gaze interaction enables a natural gaze at the object of attention. Moreover, gaze and voice work more effectively together, which does not distract the user spatially, as voice and gaze may be directed at the same information recipient, suitable for quickly indicating where or on which object an action should be applied [75]. These three interaction modalities work together since students are more likely to develop meaningful learning in environments with multimodal interaction [50], contributing to heightened user enthusiasm [53].

(1) **Gesture interaction**

In the system, gesture dominates most inputs. Students use custom gestures to generate virtual cubes with their own hands to construct 3D structures. Figure 2 shows the gesture operations. In addition, students use the gesture in Figure 2a to grab the virtual cube and move it. When students grab the virtual cube, the color of the cube will change, as shown in Figure 6. If students make a mistake when constructing 3D structures, they can trigger a "revoke" or "delete" action by using a customized gesture. They can also "press" virtual buttons in the command menu shown in Figure 3.

The command menu contains four basic commands for constructing 3D structures: create, next and revoke. It can be either user-fixed (by default) or world-fixed to adapt to different operating habits. The user-fixed menu can be in a consistent position in the display view, while the world-fixed option

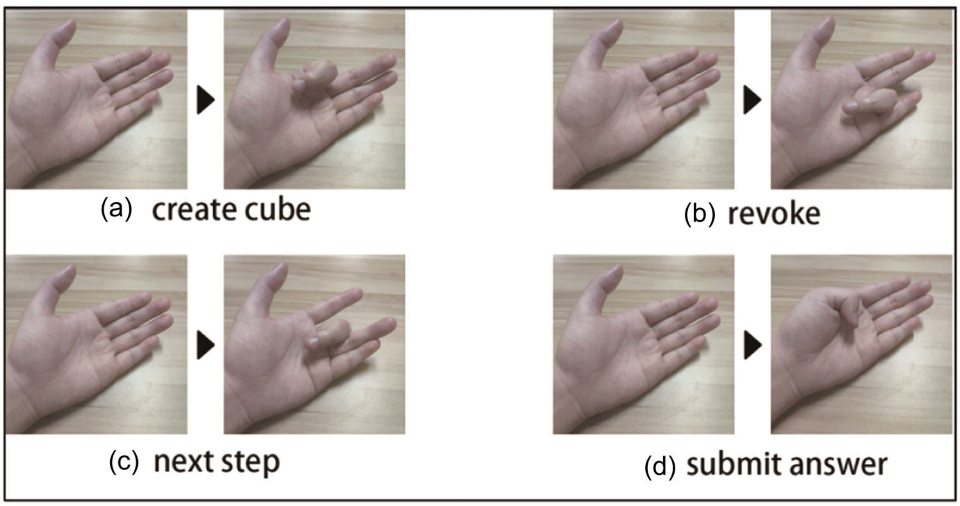

FIGURE 2 Gesture operations. (a) create a cube. (b) undo actions. (c) advance the system to the next step. (d) submit the 3D structure.

provides the illusion of seamlessly integrating virtual objects with the real world. Students have the flexibility to grab and place the menu to adjust its position and can tap the pin button to lock/unlock it.

The system provides an intuitive display of the left, front, and top views. For the left and front views, users position the 3D structure directly in front of them and physically move to transition between these views. However, the top view requires the 3D structure to be placed lower, so the system designed for adjustment of the vertical position of the 3D structure using a slider bar, as shown in Figure 3. When users move the 3D structure lower, they can see the top view of the 3D structure. After seeing the top view, users can adjust the 3D structure up again if they still want to see the left and front view.

(2) **Voice interaction**

Because voice interaction frees up hands [22, 34] and uses fewer senses and less energy, it is becoming a major form of interaction in immersive applications.

The system monitors voice keywords and processes events via MRTK (Mixed Reality Toolkit). Voice interactions are applied to identify the number of cubes in a 3D structure. Students just need to say a number and the system will make the decision. In addition, students can choose to use voice commands to delete, add, undo, and submit instead of using the menu when constructing a 3D structure.

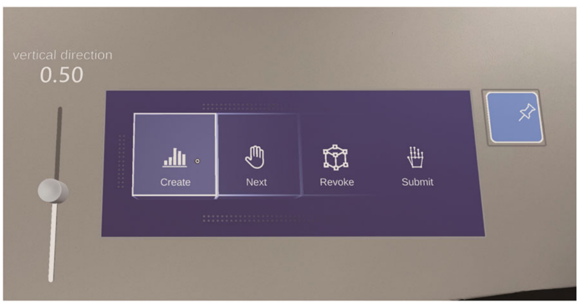

FIGURE 3 Menu panel.

(3) **Gaze interaction combined with voice**

Gaze interaction is one of the most natural forms of human–computer interaction, with the direction of gaze showing the user the area of interest [26]. In daily communication, gaze is often used in conjunction with voice. However, this combined technique has not been widely used in systems to date [75].

To quickly and accurately select virtual objects and perform the corresponding actions, a combination of gaze and voice interaction is applied. When a student is gazing at a virtual object for more than 1 s, it will be selected automatically. Then, the student says "down" to adjust the vertical position. The interaction makes it simple and intuitive for students to see the top view. When a student has finished looking at the top view, if he wants to see the left and front views, he can gaze at the 3D structure and say "up."

(4) **The use of multimodal interaction**

The application of multimodal interaction in the system can be found in to Table 1. After receiving three-view drawing questions from the teacher on their tablets, students can create new small cubes using voice keywords or gestures. Subsequently, through gestures, students can move the small cubes and assemble them into a structure consistent with the three views provided by the teacher. Using gaze and voice keywords, students can select the entire 3D structure and adjust its vertical height, facilitating easy inspection of the top view of the constructed structure for self-assessment. After completing the construction of the 3D structure, students can submit the object to the system using voice keywords or gestures, and the system will assess its correctness.

3.2 | View sharing module

In HMD-based learning scenarios, the inability of teachers to observe the learning process directly impacts their understanding of students' learning statuses. Research suggests that offering shared views not only

TABLE 1 The use of multimodal interaction.

Interaction mode	Functionality	Usage method
Gesture	Users can create cubes, undo the previous step, move to the next step, and submit answers.	Specific gestures, refer to Figure 2.
Voice	Users can create cubes, undo the previous step, move to the next step, and submit answers. Furthermore, they can also use voice keywords to determine the number of cubes in the three views, for example, saying "six."	Speak the corresponding voice keywords.
Gaze	Move the 3D structure up or down.	Gaze at the 3D structure and speak the voice keyword "up" or "down."

enhances task performance but also improves the overall user experience during collaboration [12]. It is essential to consider the viewpoints of collaborators when selecting a perspective [64]. Moreover, teachers play a crucial role in guiding and supporting students throughout their learning journey by gaining insights into their perspectives. This mutual understanding and exchange of viewpoints fosters a closer teacher-student relationship (RQ2), ultimately boosting the effectiveness of teaching and enhancing learning performances (RQ1). The view-sharing module addresses this by capturing the first-person view of students and transmitting the video stream back to the teacher platform, improving the usability of the system. The PV (photo video) camera initially captures raw graphical data, which is then converted into JPG format. Subsequently, lossless compression is applied to further reduce the data size.

3.3 | Teaching resource generation module

The teaching resource generation module automates the creation of 3D structures using the generation algorithm, aiming to alleviate the burden on teachers in designing teaching resources and increase the number of test questions. The automatic generation of teaching resources ensures that students have access to a broader array of learning materials and information, thereby enriching their learning experience and improving their comprehension abilities. Furthermore, these resources can meet students' personalized learning needs and can enhance the utility of the system (RQ2).

The algorithm takes inputs such as the number of cubes, difficulty level, and suspension mode (whether suspension is allowed), set by the teacher on the tablet PC. During the generation process, the nonsuspension mode requires that (1) the non-bottom cube must be supported from below to prevent it from falling due to gravity, and (2) a newly generated cube should be adjacent to existing cubes. In suspension mode, only the second point needs to be satisfied. The detailed generation process is illustrated in Figure 4.

In the non-suspension mode, the system randomly generates 3D structures with different numbers of cubes according to the difficulty factor set by the teacher. At first, a cube is generated on the first layer of the 3D structure and the corresponding position matrix is set, which is used to mark whether a cube is generated at a particular position or not. Then, a cube is randomly generated adjacent to the existing cube and it is determined whether the generated cube is located in the first layer of the 3D structure. Finally, as a three-view drawing cannot uniquely determine a 3D object, the system excludes cases where the three-view drawing correspond to multiple 3D objects. For example, removing the white cube in Figure 5 doesn't change the final three-view drawing.

3.4 | Two learning modes

The system supports two learning modes: constructing a 3D structure to satisfy a given three-view drawing, and expressing the minimum number of cubes for a given three-view drawing. The former aims to enhance the ability to transition between 2D drawings and 3D structures, while the latter is used to test the consolidation of knowledge. Using different learning modes helps students with a range of learning needs and tastes (RQ2). Through hands-on building, students can apply theoretical knowledge in practical contexts, deepen their understanding, cultivate practical skills, and foster creative thinking. Furthermore, abundant exercise content aids students in reinforcing learned knowledge and enhancing problem-solving abilities. This learning approach sparks students' interest and enhances their willingness to continue using the system (RQ4).

(1) **Constructing a 3D structure to satisfy a given three-view drawing**

Students construct 3D structures according to a given three-view drawing. As there will be multiple results for one three-view drawing, students are asked to construct the structure with the minimum number of cubes. Once construction is completed, the system will determine whether it is correct. If the submission is incorrect, the system will display the correct one to help students find out their mistakes.

The generated virtual cubes are anchored in the real environment and do not change position due to the movement of students. When two cubes come close to each other, they will automatically be attached with voice feedback. Once a held cube is released, the system will find the nearest face to attach it using sphere detection as shown in Figure 6. Any extra cubes can be put in the green bin on the right after the 3D construction has been completed

(2) **Expressing the minimum number of cubes for a given three-view drawing**

In this mode, the teacher is able to set the degree of difficulty, question mode (whether suspension is allowed or not), and question number on the tablet PC, and then sends them to students, as shown in Figure 7. First,

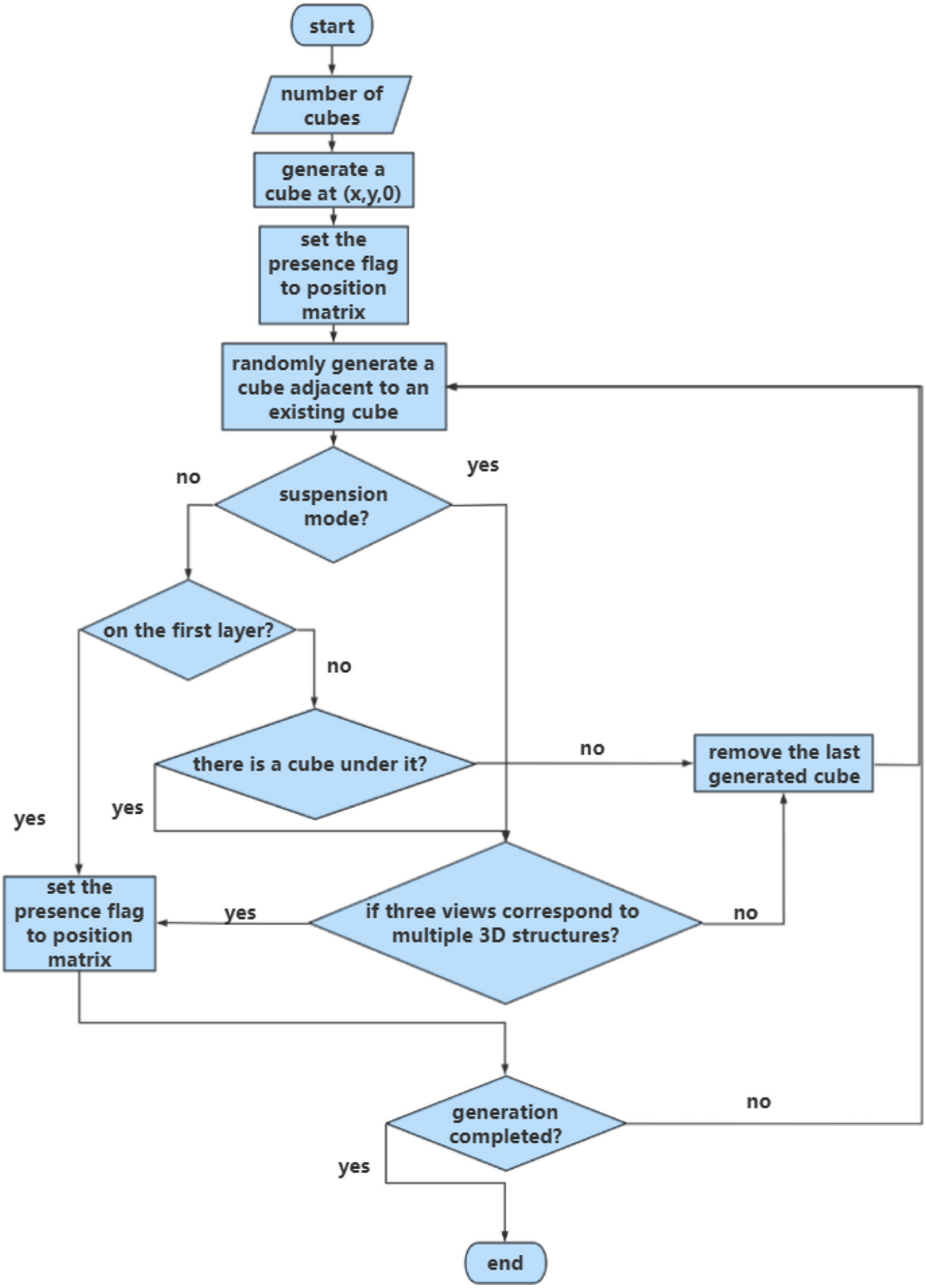

FIGURE 4 The processes of generating a three-dimensional structure.

HoloLens2 presents the three-view drawing designed by the teacher and asks students to express the minimum number of cubes in the 3D structure, as shown in Figure 8. Second, students can complete the questions through voice or gesture interaction. If an incorrect answer is submitted, the system will display the correct 3D structure. Students can move, rotate, and observe the 3D structure, as shown in Figure 9.

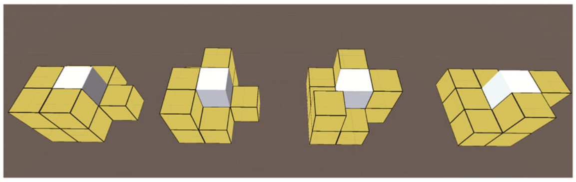

FIGURE 5 Deleting a cube does not change the three-view drawing in this case.

FIGURE 6 Construct a three-dimensional structure.

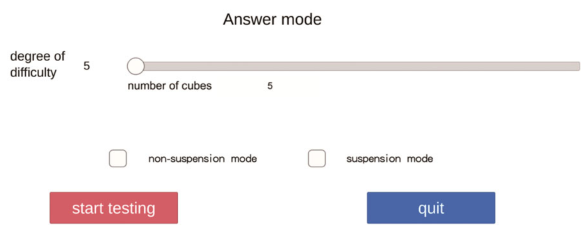

FIGURE 7 Answer mode.

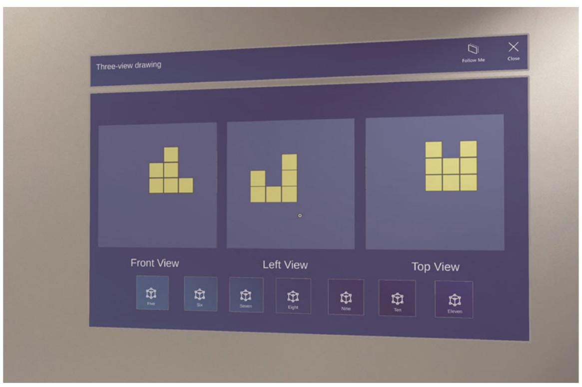

FIGURE 8 Answer panel.

4 | METHOD

To evaluate the performance of the system in terms of learning performance and subjective perception (including perceived usefulness, perceived ease of use, and willingness to continue to use) of a three-view drawing-related knowledge in secondary schools and universities,

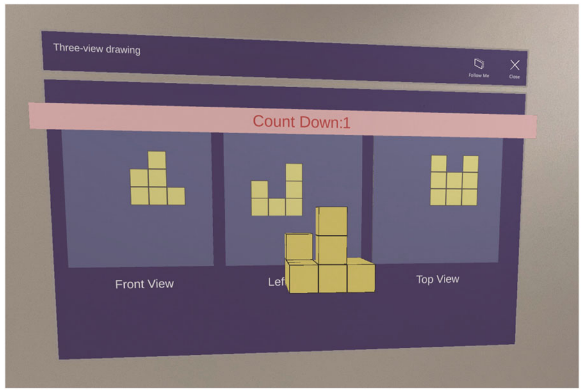

FIGURE 9 Three-dimensional model display.

a comparative study was designed and conducted to compare the HoloLens2 system (HL2) with two state-of-the-art systems: a desktop system (DES) [13] and a handheld AR system (HAR) [37].

4.1 | Participants

The experiment was conducted in a laboratory at a university in China, and 45 participants were recruited through advertising posters at the laboratory. The participants (22 males and 23 females, aged between 20 and 25) were composed of 29 undergraduate and 16 graduate students, majoring in various research fields related to space geometry, including computer graphics, virtual reality, 3D CAD modeling, data visualization, industrial design, and so forth. In particular, they learned three-view drawing in secondary school mainly based on traditional teaching methods. None of them had a history of traumatic brain injury or mental illness.

4.2 | Experiment procedure

To evaluate learning performance and subjective perception of HL2 (Figure 10), HAR (Figure 11), and DES (Figure 13) from both objective and subjective perspectives, we designed and conducted a mixed investigation method combining the pretest and posttest design, and subjective questionnaires. First, the pretest and posttest design was performed to quantitatively evaluate students' learning performance on the three systems from an objective perspective. Then, the subjective questionnaires were conducted to quantitatively and qualitatively compare them in terms of perceived usefulness, perceived ease of use, and willingness to continue to use from a subjective perspective. The whole experimental process is shown in Figure 15 and the whole experiment

FIGURE 10 A student experiencing our system on HoloLens 2.

FIGURE 11 A student experiencing the handheld augmented reality system on a tablet.

lasted 80–110 min. For this experiment, the learning outcomes refer to cultivating students' ability to reconstruct 3D shapes from given three-view drawings.

(1) **Pretest and Posttest design**

The pretest and Posttest design consists of four steps: pretest, familiarization with learning systems, task completion, and Posttest.

Pretest. Participants complete an online pretest questionnaire to assess their understanding of the knowledge related to three-view drawings in mathematics. The pretest questionnaire consists of 10 questions, each worth 10 points, sourced from 9th-grade mathematics final exams from the past decade in China. These questions cover determining the minimum and maximum number of small cubes in two or three views, as well as identifying different types of 3D structure combinations in two or three views. The design of these questions is aimed at effectively enhancing students' spatial abilities. The maximum score on the pretest questionnaire is 100. The detailed content of the pretest questionnaire is provided in Appendix A. Forty-five participants are then equally divided into three groups based on pretest scores with no statistical difference from each other. This step takes 20 min.

Familiarization with learning systems. Each group is randomly assigned one of the three learning systems (HL2, HAR, and DES). Each group is asked to be familiar with the basic operations of the corresponding system before the experiment, and then experience the system for a few minutes. This step is to prevent innovative benefits from using the system for the first time. It takes 10 min.

Task completion. The task of each group is to reconstruct the 3D geometry based on the given three-view drawings. However, due to different operations of different systems, the specific task completion processes are slightly different. Specifically, in HL2 group, students first construct a 3D structure step-by-step based on the three-view drawing shown. Second, students express the minimum number of cubes needed to satisfy the three-view drawing, as shown in Figure 10. In HAR group, students explore the relationship between the 2D three-view drawing and the 3D structure and are asked to judge whether additional cube(s) can be added while maintaining the same three-view drawing. Ten groups of markers are used for 10 questions. Each group has three markers which stand for front, left, and top view in one 3D structure. A sheet of A4 paper is given for the experiment, with main marker printed on the top and three blanks on the bottom. Firstly, students place three markers in one group on the three blanks and scan with a tablet PC. Then, the corresponding 3D structure will be displayed on the main marker. Students can adjust the viewing angle by moving either the tablet PC or the paper, as shown in Figures 10 and 12. In DES group, students first use the keyboard and mouse to construct a 3D structure on a checkerboard grid based on the three-

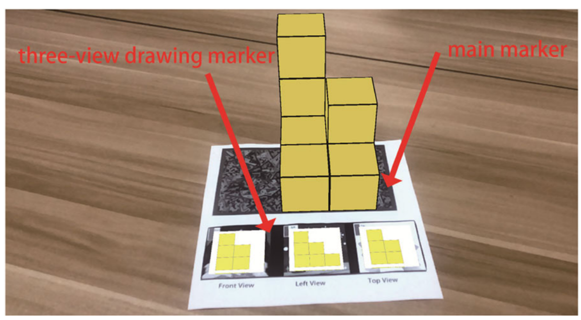

FIGURE 12 A screenshot of the handheld augmented reality system.

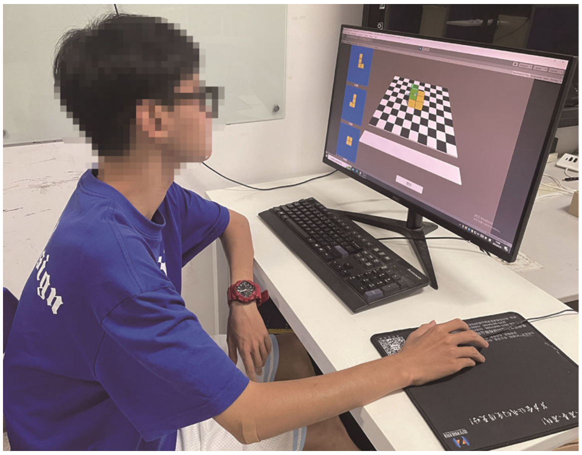

FIGURE 13 A student experiencing the desktop system.

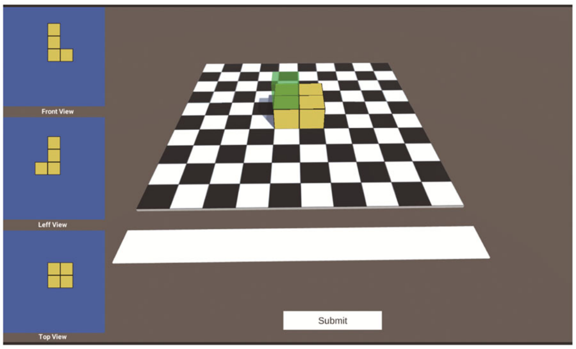

FIGURE 14 A screenshot of the desktop system.

view drawing displayed on the left. When students left click, a cube will be created at the that position. They can also undo the operation by right clicking. Second, students can also use the arrow keys to adjust the viewing angle, as shown in Figures 13 and 14. It takes 30 min.

Posttest. Each group takes an online posttest, which includes the same questions as the pretest but in a different order. This design aims to minimize order effects and enhance the reliability and validity of the research results. This step takes 20 min.

A pretest can assess the starting level of students before using the learning system, while a posttest can be used to evaluate the progress students have made after using the learning system. By comparing the scores of the pretest and posttest, we can quantify the students' learning outcomes to evaluate the learning performance of the system.

(2) **Subjective questionnaire**

After a 5-min break, each participant uses the other two systems for approximately 15 min each. Following the completion of all three system

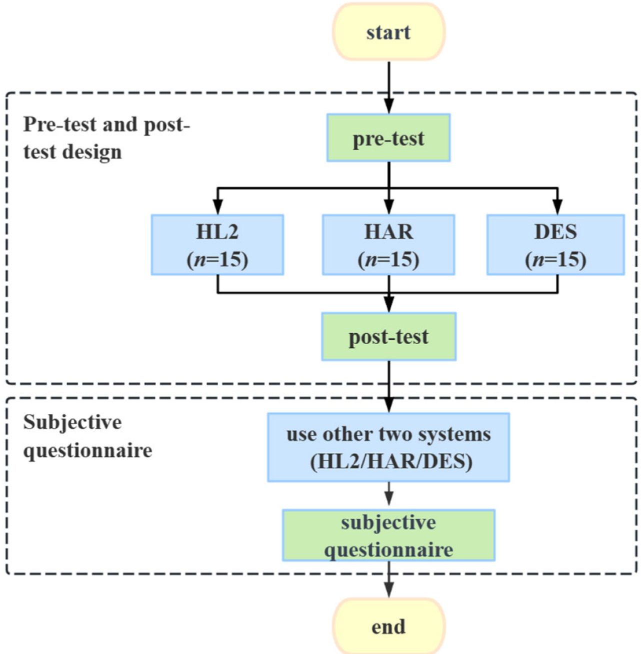

FIGURE 15 Experimental processes. DES, desktop system; HAR, handheld AR system.

experiences, participants are asked to complete the subjective perception questionnaire (Appendix B). The subjective perception questionnaire is adapted from the scale proposed by Davis [14] and Bhattacherjee [7]. Among them, perceived usefulness is designed to measure students' subjective feelings and satisfaction with the technology. Perceived ease of use is designed to measure the ease or difficulty with which students can use the system. Continuous usage intention aims to measure students' willingness for the ongoing use of the information system. All items on these scales were scored using a 5-point Likert scale. It was proposed by American social psychologist Likert in 1932 and includes a series of statements [28]. Each statement has five answers: "strongly disagree," "disagree," "neutral," "agree," and "strongly agree" on a scale of 1, 2, 3, 4, and 5, respectively. All questions are drawn from validated questionnaires, though some have been reworded to better suit this study (e.g., "It can intuitively restore the 3D structure of the three-view drawing."). Additionally, to enhance reliability, the order of certain questions has been reversed to prevent participants from consistently providing the same answers. It is estimated to take approximately 5 min to complete the questionnaires. After users complete the subjective perception questionnaire, we will engage in a brief exchange and interview to understand their feedbacks and gather suggestions about our system.

4.3 | Data collection and analysis

Learning performance and subjective perception (including perceived usefulness, perceived ease of use, and willingness to continue to use) were evaluated with quantitative and qualitative methods based on the pretest and posttest questionnaires and subjective questionnaires. Both pretest and posttest questionnaires and subjective questionnaires were analyzed using IBM SPSS Statistics version 26, and the scale reliability of subjective questionnaires was verified by Cronbach's α test.

Learning performance was mainly objectively and quantitatively assessed based on the posttest questionnaires and the brief interview data about learning performance is used as a supplement to subjective assessment. Since participants were grouped according to their pretest scores, the single-factor analysis of variance (ANOVA) [52] test was performed on the posttest questionnaires to determine the intergroup differences in posttest scores, which could capture the objective differences in learning performance among the three types of systems.

To evaluate the subjective perception, we first collected data from subjective questionnaires on questions related to the perceived usefulness, perceived ease of use, and willingness to continue to use (Tables 5–7), and then applied descriptive analysis and the Wilcoxon signed-rank test to compare the differences between HL2 and the other two regarding subjective perception.

5 | RESULT

5.1 | Learning performance

The statistical analysis on the pretest and posttest questionnaires reveals the differences in students' learning performance between three groups.

(1) **The pretest and posttest score results**

Based on the pretest scores, the students were divided into three groups. Figure 16 displays the mean values of these three groups, with the mean values being around 58. Through ANOVA, the value of p is 0.998, suggesting no statistically significant difference among three groups. This implies that students in each group had similar baseline levels, facilitating the comparison and analysis of learning performances in subsequent stages. From the posttest scores, it can be observed that H1 holds true.

The single-factor ANOVA was used to analyze the intergroup differences in scores, as shown in Table 2. It can be observed that the scores of the three groups have significant differences ($p < .05$). The average score of HAR group is 61.00, which is much lower than that of HL2 group (71.33) and DES group (70.0). To explore potential small differences between groups in more detail, Least Significant Difference (LSD) post hoc tests were conducted pairwise. As shown in Table 3, there is a significant difference between DES group and HAR group, as well as between HAR group and HL2 group. However, no significant difference is observed between HL2 group and DES group.

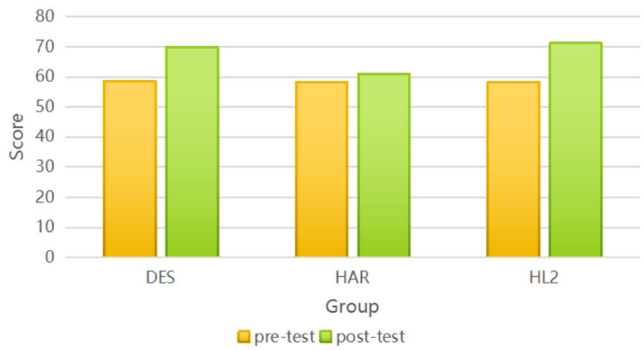

FIGURE 16 The scores of the pretest and posttest questionnaires. DES, desktop system; HAR, handheld AR system.

TABLE 2 Posttest questionnaire result.

Group (mean ± SD)				
HL2 ($n = 15$)	HAR ($n = 15$)	DES ($n = 15$)	f	p
71.33 ± 11.72	61.00 ± 14.42	70.00 ± 9.45	3.272	.048*

Abbreviations: DES, desktop system; HAR, handheld AR system.
*$p < .05$.

TABLE 3 Post hoc of posttest scores.

	(I) Group	(J) Group	(I) Mean	(J) Mean	Difference (I–J)	p
Score	DES	HAR	70	61	9	.047*
	DES	HL2	70	71.333	−1.333	.763
	HAR	HL2	61	71.333	−10.333	.023*

Abbreviations: DES, desktop system; HAR, handheld AR system.
*$p < .05$.

TABLE 4 Analysis of pretest and posttest scores for three groups.

	Pre-post test comparison (mean ± SD)			
	Pretest ($n = 15$)	Posttest ($n = 15$)	t	p
HL2	62.353 ± 20.087	70.588 ± 18.865	3.775	.002**
HAR	58.33 ± 16.97	61.00 ± 14.42	0.759	.461
DES	58.67 ± 15.75	70 ± 9.45	2.963	.010*

Abbreviations: DES, desktop system; HAR, handheld AR system.
$^{*}p < .05$; $^{**}p < .01$.

This study further analyzed the pretest and posttest scores of the three groups using paired samples t-test [31]. Table 4 shows that except for the HAR group, all other values of p are less than 0.05, indicating a significant difference between the pretest and posttest scores. In HL2 group, students' average score also increases by 13 points after using the proposed system, with the standard deviation decreasing from 16.44 to 11.72, indicating a significant improvement in students' learning performance and stability.

(2) **Results grouped by score intervals in the pretest and Posttest**

We categorized the pretest and posttest scores into intervals, with group names on the x-axis. "pre-test DES" represents the pretest scores for DES group, and percentages are on the y-axis, ensuring that the total number of individuals in each score interval adds up to 100%. As shown in Figure 17, it can be observed that for the HL2 group, compared to the pretest, the number of failing students (0–59) decreased from 8 to 3. In the 80–89 score range, the count increased from 2 to 6. The number of high-scoring individuals (≥80) for the HL2 group is consistently higher than those for the HAR group and DES group.

Subsequently, we conducted a statistical analysis of the improvement in scores. The formula used to calculate the improvement in scores is the posttest score minus the pretest score. Figure 18 displays the box plot depicting the grade improvement. It can be observed that the average grade improvement for HL2 group is greater than that for DES group and HAR group. Additionally, in terms of the highest improvement score, HL2 group surpasses both DES group and HAR group.

The pretest and posttest results were compared for every student in the experimental group, as shown in Figure 19. Most students improved

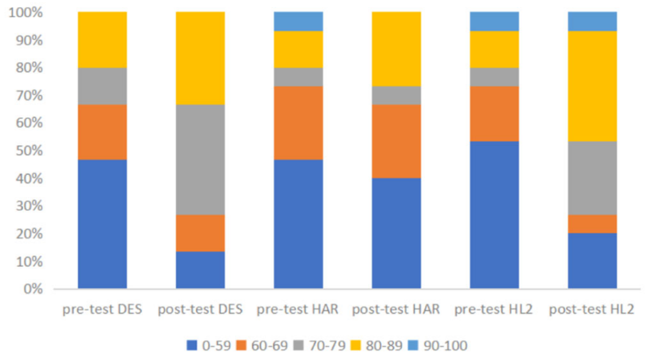

FIGURE 17 Pretest and posttest score range number. DES, desktop system; HAR, handheld AR system.

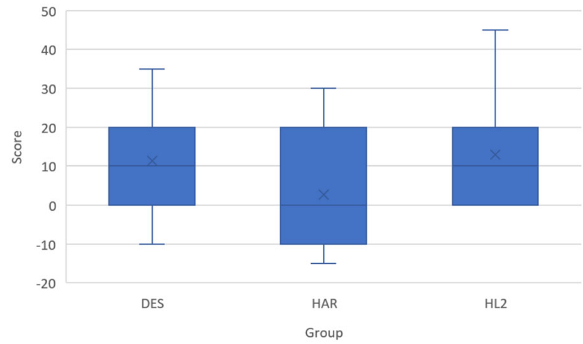

FIGURE 18 Box plot for improving scores. DES, desktop system; HAR, handheld AR system.

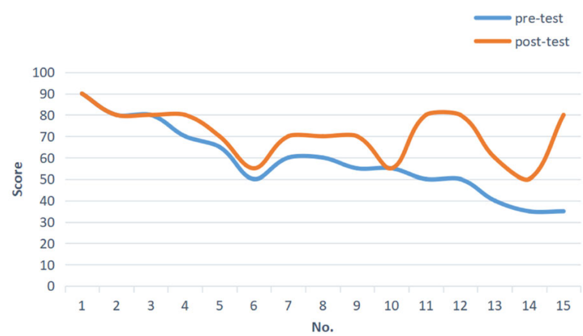

FIGURE 19 Comparison of changes pretest and posttest in the experimental group.

their scores, however, students with higher scores have less improvements than those with lower scores.

(3) **Interview**

When studying the topic of learning performance, most participants mentioned that HL2 was able to stimulate their curiosity about learning the knowledge points of three-view drawing, thereby generating a stronger interest in learning. Here are some specific comments:

User A: "I find that HAR's current design hinders my ability to interact and learn. I'm familiar with the keyboard and mouse interaction of DES, but I need to learn the interaction of HL2 in advance. However, HL2 provides a stronger sense of immersion. I feel that it provides the most significant assistance to my learning."

User B: "I think manually constructing 3D structures is helpful for spatial ability and learning three-view drawing. HL2 provides me with a stronger sense of immersion. With HL2's help, I learned the three-view drawing more effectively, and I'm more interested. The other two seem a bit monotonous."

Based on users' feedback, HL2 is considered to enhance the learning effectiveness of three-view drawing. This immersive learning system and natural interaction are positively beneficial for users.

5.2 | Perceived usefulness

Cronbach's α for 5.2 perceived usefulness is 0.816, demonstrated a high level of internal consistency.

In comparison with DES group and HAR group, HL2 group exhibits notably higher median and mean values for perceived usefulness (5 items), as shown in Table 5. Furthermore, the standard deviation of HL2 group is lower than that of DES group and HAR group, indicating greater stability in the system's perceived usefulness. Additionally, the intergroup differences in scores were analyzed by the Wilcoxon signed-rank test, and significant differences in usefulness (5 items) were found. The mean score of the perceived usefulness is shown in Figure 20 (Questions No.1 to 5).

In the topic of perceived usefulness. Most participants mentioned that HL2 provided them with a better sense of immersion, making the process of learning and playing three-view drawing more enjoyable. Here is a specific comment:

User C: "I feel that HL2 can better reproduce 3D structures, as if it is overlaid in real space. However, the 3D reproduction of DES is not high. Although HAR reproduces the 3D structure, the sense of immersion is not as good as HL2."

5.3 | Perceived ease of use

Cronbach's α for perceived ease of use is .815, demonstrated a high level of internal consistency.

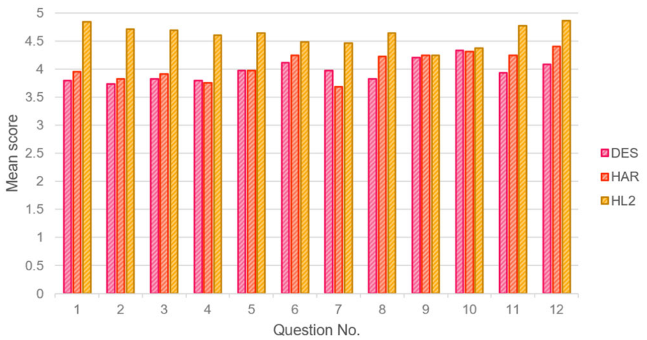

FIGURE 20 Mean score of subjective questionnaire. DES, desktop system; HAR, handheld AR system.

TABLE 5 Perceived usefulness results.

Questions	Mean (SD) HL2	DES	HAR	Wilcoxon signed-rank test HLEN-DES z	p	HLEN-HAR z	p
It can intuitively restore the 3D structure of the three-view drawing.	4.844 (0.367)	3.800 (0.842)	3.956 (0.767)	5.120	.000**	4.651	.000**
It can improve my interest in learning three-view drawing and solid geometry.	4.711 (0.458)	3.733 (0.780)	3.822 (0.747)	4.868	.000**	4.888	.000**
It helps me learning about three-view drawing more effectively.	4.689 (0.468)	3.822 (0.936)	3.911 (0.733)	4.256	.000**	4.486	.000**
It has improved my learning performance more significantly.	4.600 (0.580)	3.800 (0.726)	3.756 (0.743)	4.198	.000**	4.590	.000**
It is useful for the learning of three-view drawing and solid geometry knowledge.	4.644 (0.484)	3.978 (0.723)	3.978 (0.621)	4.039	.000**	4.210	.000**

Abbreviations: DES, desktop system; HAR, handheld AR system.

**$p < .01$.

TABLE 6 Perceived ease of use results.

Questions	Mean (SD) HL2	DES	HAR	Wilcoxon signed-rank test HLEN-DES z	p	HLEN-HAR z	p
It is easy for me to learning use it.	4.489 (0.626)	4.111 (0.910)	4.244 (0.712)	2.191	.028*	2.043	.041*
It has clear instructions and user-friendly interface that doesn't distract me.	4.467 (0.757)	3.978 (0.812)	3.689 (0.733)	2.595	.009**	4.429	.000**
I think the interaction of it is very flexible.	4.644 (0.529)	3.822 (1.029)	4.222 (0.795)	3.976	.000**	2.909	.004**
I hardly ever encounter problems when I use it.	4.244 (0.679)	4.200 (0.944)	4.244 (0.883)	0.302	.763	0.016	.987
It's easy for me to operate with it.	4.378 (0.716)	4.333 (0.853)	4.311 (0.668)	0.204	.838	0.570	.568

Abbreviations: DES, desktop system; HAR, handheld AR system.

*$p < .05$; **$p < .01$.

TABLE 7 Willingness to continue to use results.

Questions	Mean (SD) HL2	DES	HAR	Wilcoxon signed-rank test HL2-DES z	p	HL2-HAR z	p
I would like to use it in my future studies.	4.778 (0.471)	3.933 (0.939)	4.244 (0.743)	4.263	.000**	3.735	.000**
I would like to introduce it to my friends.	4.867 (0.344)	4.089 (0.996)	4.400 (0.780)	4.183	.000**	3.749	.000**

Abbreviations: DES, desktop system; HAR, handheld AR system.

**$p < .01$.

In comparison with DES group and HAR group, HL2 group demonstrated significantly higher median and mean values for perceived ease of use (5 items), as shown in Table 6. Additionally, the intergroup differences in scores were analyzed using the Wilcoxon signed-rank test, and significant differences in perceived ease of use (3 items) were found.

Regarding perceived ease of use, the majority of students expressed that the proposed system is easy to use, highlighting its user-friendly nature, greater naturalness, reduced distraction, and clearer instructions compared to the other systems. The mean score of the perceived ease of use is shown in Figure 20 (Question No. 6 to 10).

In the topic of ease of use. Most participants mentioned that the interactive methods in HL2 is more flexible. Here is a specific comment:

User D: “I find learning HL2 relatively easy. Its interactive methods are quite flexible. I prefer gesture interaction the most, as it allows me to grab virtual cubes.”

5.4 | Willingness to continue to use

Cronbach's α for willingness to continue to use is .807, demonstrated a high level of internal consistency.

In comparison with DES group and HAR group, HL2 group obtained significantly higher median and mean values for willingness to continue using the system (2 items), as shown in Table 7. Additionally, the intergroup differences in scores were analyzed using the Wilcoxon signed-rank test and significant differences in willingness to continue to use (2 items) were found. The mean score of the willingness to continue to use is shown in Figure 20 (Questions No. 11 to 12).

In the topic of willingness to continue to use. Most participants mentioned that they would prefer to use HL2 in the future. Here is a specific comment:

User E: “I am very willing to use HL2 in future learning because it provides a magical learning experience.”

6 | DISCUSSION

6.1 | Effectiveness of the system

In terms of posttest scores, HL2 group scored much higher than HAR group, which may be attributed to different learning modes between the groups. In HAR, students are limited to observing the relationship between 2D views and automatically generated 3D structures, lacking hands-on manipulation. While in HL2, students are empowered to actively explore and construct various 3D structures, and this hands-on learning significantly improves their learning performance [18]. In addition, although HL2 group scored slightly higher than DES group, the difference was not statistically significant. This may be attributed to similar learning patterns in both groups, where students acquire knowledge by actively constructing 3D structures, and the relatively short duration of time learners used the systems. According to user interviews, users generally believe that HL2 can better enhance their self-perceived learning performance with longer use. Previous studies have also indicated that long-term learning tends to lead to more noticeable improvements in learning performance compared to short-term learning [38].

In terms of score grouping results, the number of individuals in the 80–89 score range showed the most significant change in the HL2 group, increasing from 2 to 6. Whereas in the DES group, it increased from 3 to 5. Improved learning performance may be attributed to the more natural interactive methods and immersive learning environment provided by HL2. This rich interaction combines various sensory inputs and gamified learning experiences, possibly more actively guiding students to participate in the learning process and improve learning performance [17]. HL2 offers an AR experience that does not require handheld mobile devices, reducing cognitive burden and enhancing the learning experience. Overall, HL2 provides students with a captivating and effective learning platform, fostering their interest and skills in 3D learning. However, for high-scoring students, the improvement is not significant, possibly because these students already have strong spatial abilities, allowing them to easily grasp relevant knowledge and achieve high pretest scores even with traditional teaching methods. Therefore, the system may face challenges in providing significant assistance to these students to further improve their proficiency. However, students with weaker spatial abilities, indicated by slightly lower pretest scores, may benefit more from the system's assistance. This is because the system provides real learning opportunities, enabling students with poor spatial abilities to actively participate and enhance their understanding and application skills. The application of immersive AR increases students' enthusiasm and engagement, leading to better academic performance [15, 63].

In terms of subjective perception, students are more satisfied with the proposed system. A majority of students believe that the system can more realistically reproduce the 3D structure, thereby increasing their interest in acquiring three-view knowledge. This is attributed to the immersive experience facilitated by HoloLens2's holographic projection [1]. Furthermore, students unanimously believe that HL2 can enhance their interest in learning three-view drawing. This is possibly because this diverse learning approach helps stimulate their curiosity and desire for exploration, thus strengthening their interest in the learning content. An interest in learning can promote an increase in user motivation [23].

6.2 | Rationality of the system

Constructivist theory emphasizes students' active exploration of knowledge [54]. With an emphasis on students' active engagement in the learning process, this theory puts the student at the centre and highlights how they construct meaning and understanding from new information. In our system, we encourage students to actively construct 3D structures rather than passively accepting system-generated ones. Compared to HAR that passively deliver information, active participation in the learning process is more conducive to problem-solving [66]. Furthermore, our system operates in an immersive learning environment, allowing students to interact with the environment in a more immersive way, thereby increasing engagement and deepening understanding of concepts [39].

According to flow theory, in a Head-Mounted Display Augmented Reality (HMD AR) environment, users can enter a state of flow closely linked to the concept of intrinsic motivation [8]. In this state, comprehension of three-view drawing is enhanced, leading to improved learning performance. Additionally, in the context of continuous usage of information systems, perceived usefulness holds significant importance, as it is a proven and persistent belief influencing users' intent at various stages of information system use [15]. Due to the strong perceived usefulness of our system, users are more inclined to use it in their future learning activities, resulting in better-sustained usage intentions. Therefore, other systems should also aim to construct an immersive learning environment where users can actively explore, putting them in a state of flow.

Based on Norman's design principles [45], clear visibility and adequate feedback contribute to understanding the system guidance [73]. The proposed system enhances the learning experience by providing students with an effective interactive interface through visual guidance and voice keywords. Furthermore, the support of multimodal interaction technology makes students perceive the system's interaction as flexible, with relatively lower learning costs. In our system, we have enhanced the learning performance and user experience by offering clear and visible guidance and utilizing multimodal interaction to assist users in learning three-view drawings. Other systems should also consider these aspects in their system design.

6.3 | Limitation and future work

First, our system does not show a significant improvement for students with better spatial abilities, but it exhibits notable enhancements for those with weaker spatial abilities. To address this, we plan to optimize the system's content and introduce additional learning modes to help improve academic performance for students with stronger spatial abilities.

Second, our experiments didn't differentiate students based on age, gender, or major. Consequently, we were unable to delve into potential differences related to age, gender, or major. In future data collection, we intend to incorporate this information and conduct detailed analyses in subsequent experiments.

Finally, our current system only supports individual users, whereas collaborative learning is often essential in educational settings. To address this, we plan to introduce AR technology in future developments to support collaborative learning, aiming to facilitate the collective growth of multiple users in the collaborative process and better meet the learning needs of students.

7 | CONCLUSION

This paper proposes an AR HMD multimodal system to facilitate comprehension of spatial geometry and mastery of engineering drawing, and an application for three-view drawing learning is implemented and used as a case study. Students observe and construct 3D structures in an immersive environment. Teachers design and send teaching resources to students and identify how each student is learning in real-time. The system fully assists in teaching abstract three-view drawing via providing an immersive environment for students and advanced teaching methods for teachers. The experimental results demonstrate that, in terms of learning performance, the system is far better than the handheld AR system and slightly better than the desktop system. In terms of subjective perception, the system significantly outperforms other two systems. Furthermore, the system can greatly assist students who struggle with spatial imagination in improving their abilities.

The main contribution of this paper is the development of a first three-view drawing learning system based on HMD AR and a comparative study with desktop and handheld AR systems. The system fully integrates experiential teaching theory to design multimodal interactions to provide a vivid and innovative education system.

In the future, we will expand the system to teach other abstract concepts in engineering drawings and implement collaborative learning to enable multiple users from different places to learn together on a given task through multiple devices, for example, tablets PC, phones, AR HMDs, and VR HMDs.

AUTHOR CONTRIBUTIONS

Qingshu Yuan wrote Sections 1, 2, and 3, and developed the PC system. Kailiang Shou wrote Sections 4 and 5 of the manuscript and developed the HoloLens2 system. Jin Xu wrote Sections 6 and 7 of the manuscript and developed the handheld AR system. Zhengwei Yao and Zhigeng Pan designed the experiment and made the user study. All authors reviewed the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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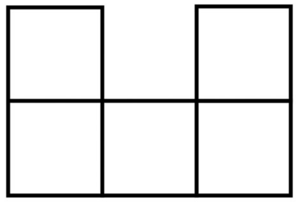
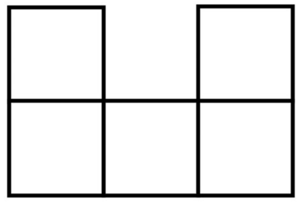
APPENDIX A

Unless specified otherwise, the cubes cannot be suspended.

1. A geometric shape is composed of several identical cubes. If its front view and left view are as shown in the diagram, what is the maximum number of such cubes that can form this geometric shape? ()

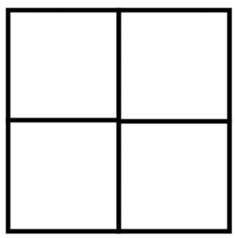


front-view

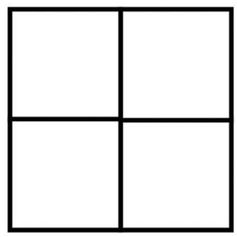


left-view

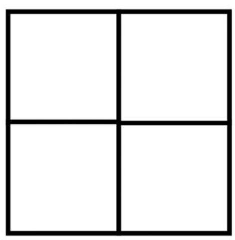
2. A certain three-dimensional geometric figure is composed of several cubes with edge lengths of 1, as shown in the three views in the diagram. Assuming the cubes can be suspended, what is the minimum number of cubes needed ()?



front-view

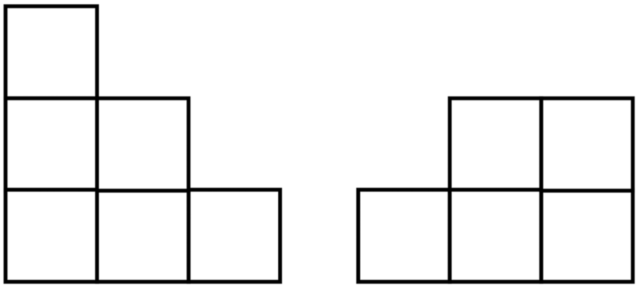


left-view



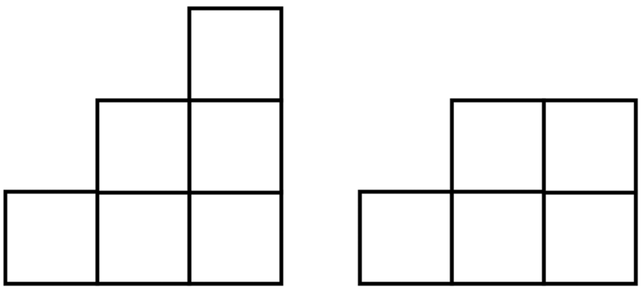
top-view

3. On the table, there is a geometric shape composed of several identical small cubes. Its front view and top view are as shown in the diagram. The number of small cubes forming this geometric shape could be (). (If there are multiple possible answers, please use "or" to separate them, e.g., 1 or 2 or 3.)



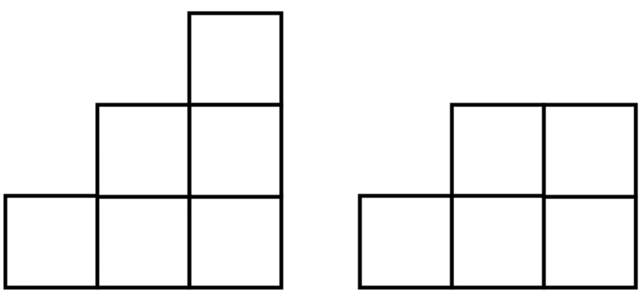
front-view top-view

4. The front view and top view of a simple geometric shape composed of small identical cubes are shown in the diagram below. If the number of small cubes used to construct this geometric shape is denoted by "n," how many different arrangements are there when n equals 10? ()



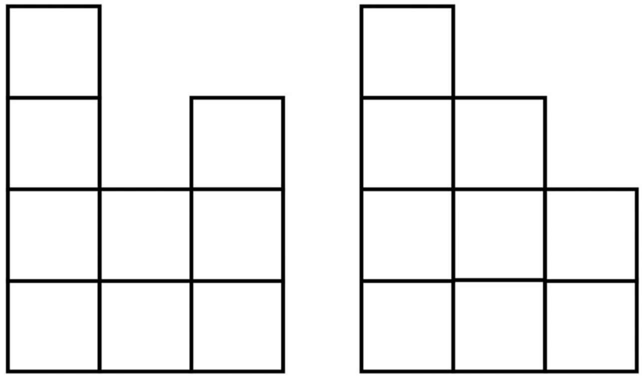
front-view top-view

5. The front view and top view of a simple geometric shape composed of small identical cubes are shown in the diagram below. If the number of small cubes used to construct this geometric shape is denoted by "n," how many different arrangements are there when n equals 8? ()



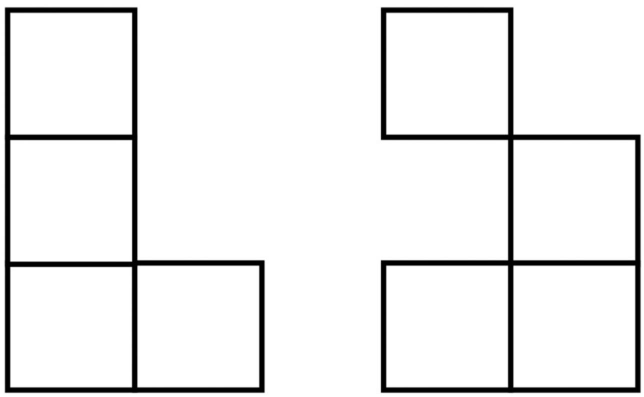
front-view top-view

6. A geometric shape constructed from 16 identical small cubes, with the bottom layer arranged with 9 small cubes. Its front view and left view are as shown in the diagram. Therefore, there are ________ different ways to assemble this geometric shape.



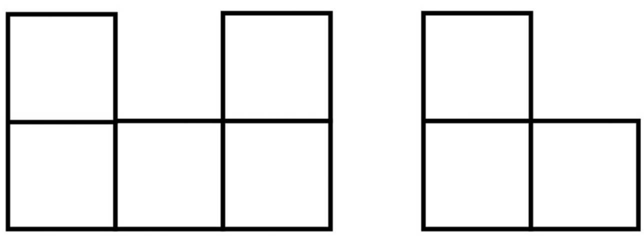
front-view left-view

7. If the front view and top view of the geometric figure formed by several identical small cubes, as shown in the diagram, then this geometric figure may be composed of __ small cubes (If there are multiple answers, please use "or" to separate, e.g., 1 or 2 or 3).



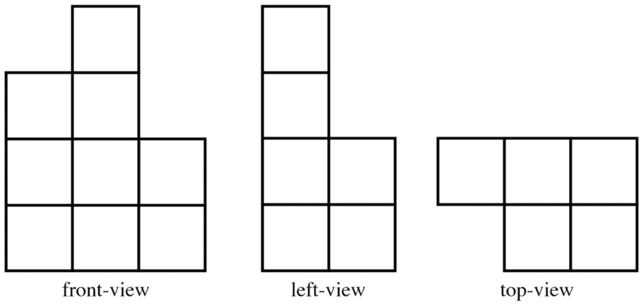
front-view top-view

8. A geometric shape is composed of several small identical cubes. If cubes can be suspended, the front view and left view are as shown in the diagram. In this case, the minimum number of small cubes required to construct this geometric shape is ().

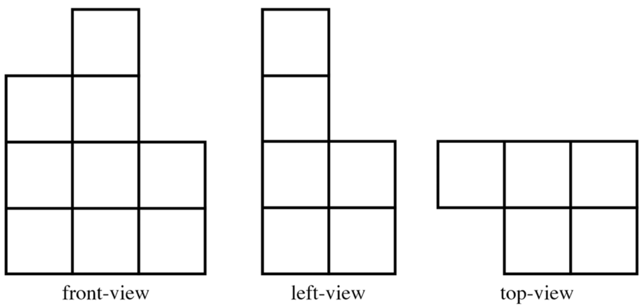


front-view left-view

9. If the three views of a geometric shape constructed from several small cubes are as shown in the diagram, is it possible to build this shape with a minimum of () small cubes? At most, () small cubes are needed.



10. If the three views of a geometric shape constructed from several small cubes are as shown in the diagram, then there are a total of () possible ways to assemble this shape.



APPENDIX B

Perceived usefulness
1. It can intuitively restore the 3D structure of the three-view drawing.
2. It can improve my interest in learning three-view drawing and solid geometry.
3. It helps me learning about three-view drawing more effectively.
4. It has improved my learning performance more significantly.
5. It is useful for the learning of three-view drawing and solid geometry knowledge.
Perceived ease of use
6. It is easy for me to learning use it.
7. It has clear instructions and user-friendly interface that doesn't distract me.
8. I think the interaction of it is very flexible.
9. I hardly ever encounter problems when I use it.
10. It's easy for me to operate with it.
Willingness to continue to use
11. I would like to use it in my future studies.
12. I would like to introduce it to my friends.

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