IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received March 8, 2020, accepted March 30, 2020, date of publication April 20, 2020, date of current version May 1, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2988678

Identifying the Optimal 3D Display Technology for Hands-On Virtual Experiential Learning: A Comparison Study

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This work was supported in part by the National Natural Science Foundation of China under Grant 61802232.

ABSTRACT The purpose of this study was to test different 3D display technologies in a hands-on virtual experiential learning environment (VELE) and determine the optimal 3D display technology. A conceptual framework was firstly proposed to explain the mechanism of how VR display features affect virtual experiential learning. Then, a single-factor within-subject experimental design was adopted for testing. The within-subject factor was three types of 3D display technology: fully immersive virtual reality (VR) mode [VR head-mounted display (HMD)], partially immersive VR mode (3D projection), and augmented reality (AR) mode (AR HMD). The dependent variables were visual comfort, interaction experience, learning experience, and outcome. A virtual math learning environment was established, and the aforementioned display technologies were tested in two hands-on virtual experiential learning scenarios. Results showed that different display technologies significantly affected users' visual comfort, interaction experience, learning experience, and outcome in experiential learning ($ps < 0.05$). User ratings on these aspects for the VR HMD were significantly higher than those for the 3D projection and AR HMD. Thus, the VR HMD contributes to a best viewing experience and learning experience in terms of hands-on virtual experiential learning in the scenarios tested. Whether the study results still hold reliably in terms of more complex learning activities and long-term learning needs to be further studied.

INDEX TERMS Experiential learning, hands-on learning, virtual reality, augmented reality, visual comfort.

I. INTRODUCTION

Experiential learning can be an effective way to promote learning interest. In contrast to teacher-centered didactic instruction, it emphasizes free thinking and firsthand experience as a source of learning and development [1]. Through interactive and hands-on experiences, students gain an understanding of core knowledge from learning tasks and explore the relation between concepts and implications. Learners not only transfer the experience gained through learning activities into the construction of knowledge but also develop positive intrinsic interest and extrinsic behaviors [2].

Traditional experiential teaching and learning have some limitations [3]. First, it needs appropriate corresponding learning environments (such as tools, places, and equipment), some of which are difficult to create (e.g., different ecosystems) or experience (e.g., surgeries). Second, traditional experiential learning is limited to fixed locations (e.g., mechanical assembly), and moving to other locations is difficult. With the development of computational information technologies, such as digital media, real-time virtual reality (VR), and augmented reality (AR), various new types of experiential learning can be designed. Compared with traditional methods, these novel technologies provide new opportunities to create a vivid, lifelike virtual experiential learning environment (VELE), eliminating the simplicity and boredom of traditional learning models [4]. Integrating new technologies into learning helps transform learning materials from textbook-oriented or two-dimensional multimedia content into more interactive multimedia material. The integration has helped to overcome time and space constraints in traditional learning models, thereby moving learners from

The associate editor coordinating the review of this manuscript and approving it for publication was Lei Wei.

the passive reception of knowledge to more active learning approaches [5], [6]. Some advantages of VR learning over traditional learning have been reported by numerous studies [7], [8].

In VELEs, an embodied interaction design is a way to achieve "embodied cognition," which postulates that human cognition can be shaped by aspects of bodily interaction with the world [9]. It is related to the way people interact mentally and physically with information technology and has been considered a novel approach in human–computer interaction for improving interaction efficiency and interaction experience [9], [10] [11]. Through interaction in a VELE, learners can acquire intuitive embodied experiences that may reduce their cognitive load and contribute to the internalization of knowledge. A learner is mentally and physically fully mobilized, making learning easier, more interesting, and more efficient [7]. Different VR technologies have been applied in experiential learning and training. Different display technologies have their own unique characteristics, and thus can be a key factor in influencing user experience in VELEs, especially for an embodied interaction design.

The main purpose of this study is to identify the optimal 3D display technology (among three current mainstream types of 3D display technologies) for hands-on virtual experiential learning, and understand the underlying mechanism. The exploration on these issues will help clarify the relationship between 3D display features and experiential learning, and then find the way of using the most appropriate 3D display form to effectively enhance users' experience and efficiency in experiential learning. This paper makes the following contributions:

(1) proposes a conceptual framework based on an existing framework, which attempts to explain the mechanism of how different 3D display features affect hands-on virtual experiential learning;

(2) constructs a hands-on virtual experiential learning environment with three immersive display technologies, which can be used to test how they affect learner's experience (viewing, interaction and learning experience) and outcome;

(3) conducts an empirical comparison study to identify the optimal 3D display technology for hands-on virtual experiential Learning. Results show that users' visual comfort, interaction experience, learning experience, and outcome for the VR HMD are significantly better than those for the 3D projection and AR HMD.

II. RELATED WORK

Integrating new technologies into education could transform teaching from a fixed combination of text and graphics into interactive multimedia. These new technologies can contribute to hands-on virtual experiential learning.

A. VR IN HANDS-ON LEARNING

VR offers possibilities to accurately simulate interactive disciplinary scenarios to be enacted by learners. Fully immersive VR (such as a head-mounted display, HMD) and non-immersive VR (such as a desktop VR display and VR projection) are two common modes that have been used in disciplines such as medical [12] and engineering education [13]. By employing two-handed interaction within the virtual environment, learners can perform learning activities that require similar two-handed operations in real world.

Various VELEs have been applied to the learning of complex manual tasks. A VR HMD or VR glasses with stereoscopic display have been used to provide a fully immersive VR mode, and a screen-based interface or 3D projection have been used to provide a partially immersive VR mode in application areas such as industrial training, medical training, and classroom education. In an earlier study, for instance, Assfalg *et al.* [14] aimed to test the suitability of a 3D virtual environment (VE) as a complementary tool supporting education and training for construction workers' safety. They built a VE which showing 3D graphics with 3D stereo glasses for construction workers in a safety training system. Results showed that participants showed an increased interest in the 3D environment and expected to see such solutions be systematically used for their training application. In later studies, Parmar *et al.* [13] examined the effect of two VR viewing condition (i.e. HMD-based VR viewing metaphor and desktop-based VR viewing metaphor) on experiential education of psychophysical skills. They created an interactive 3D virtual circuitry simulation to train learners on the operations of electrical circuitry measurement achieving combined physical and cognitive skill learning. Results suggested that there was a significant increase in cognition in both VR viewing conditions in levels of knowledge, application, analysis and evaluation. There are also studies which examined experiential learning with CAVE as the VR environment. Learning process of engaging with 3D CAVE immersive platform for VR improved spatial cognition [2]. However, although VR can provide an immersive learning environment, perform hands-on experiential learning tasks in natural way is difficult due to limitations in interaction. In 2016, two sets of high-end headsets with hand controllers (Oculus Touch and HTC VIVE) came to the market, and embodied interaction in VR are slowly coming to light. The new generation of hand controllers induces embodiment and agency via meaningful and congruent movements with the content to be learned. For example, Tamaddon and Stiefs [15] created a visually and physically simulated whole-body interactive VR environment where learners can intuitively explore physics of microgravity. Oculus Rift HMD and Kinect were used to provide immersive and body-interactive VR learning environment. Their purpose was to see if the system could improve the participants view experience and performance. The results of this study show that the simulation was beneficial for participants and improved their ability to make better predictions about some interactions in microgravity. In another recent study, Zhou *et al.* [16] designed and implemented an educational application of computer assembly under virtual reality using HTC Vive to explore the influence on user's learning performance and experience. They found the use of the immersive VR and natural interaction not only makes the learning interesting and fosters the engagement, but also improves the construction of knowledge in practice.

In conclusion, VR is an effective display technology to promote experiential learning. However, there are some potential problems in the application of VR to hands-on experiential learning. Firstly, although full-immersive VR (i.e. VR HMD) can provide an immersive learning environment, it easily produces feelings of visual fatigue or motion sickness [17]. In contrast, although non-immersive VRs bring lower degree of visual discomfort, visual experience and immersions from them are far from ideal.

B. AR IN HANDS-ON LEARNING

AR technology is another novel technology being increasingly applied to learning and training in many fields. It allows users to view and interact with virtual objects in ''augmented'' real-world environments [18]. Observers in AR can digitize information in the surrounding real world and make them operable virtually.

Existing studies have shown that AR can be an effective pedagogical tool with large educational potential in various learning and training environments [19]–[22], helping promote learning outcomes [23]–[25]. For instance, to examine the impact of learner emotion using the AR learning system on experiential learning and learning performance, Huang *et al.* developed an AR action ecological learning system which provided a rich learning experience in field learning and eco-education [2]. Results showed that the system successfully stimulated students' positive emotions and improved learning willingness and outcomes. Recently, Hsu [26] developed two AR educational game systems for third graders to learn English words. They found that the AR educational game systems had a positive effect on learning effectiveness and flow experience [26]. Furió *et al.* [7] used an iPhone AR game for children to learn the water cycle. Their results revealed significantly better learning gains about the water cycle in the AR lesson than in the traditional classroom lesson. The emergence of AR glasses (or AR HMD) gives AR a more advanced form (also known as mixed reality). Unlike mobile AR, AR HMD are not designed to isolate its user from the surrounding reality, but to superpose synthetic information on a transparent glass, such as Microsoft's Hololens [27]. In a recent study, to investigate the effectiveness of the AR application in teaching Geometric relationships, a practicable application was developed on the HoloLens system [28]. It allows students to visualize the geometry of 3-D objects as well as the exploded diagrams of selected components. The students can command the system through the command manual. Results show that the AR application positively improves students' understanding in geometric relationships and creativity [28].

However, AR also has some shortcomings: (1) Its visual field is often limited, especially in the AR HMD, and (2) Natural embodied interaction is difficult to achieve. Mobile AR lacks an effective interactive form based on body movement; although AR glasses support gesture interaction, the naturalness and fluency are still not ideal. (3) Although AR HMD is less prone to cause motion sickness than VR HMD, the virtual contents displayed with AR HMD are easily disturbed by the real environment.

C. COMPARISON OF DIFFERENT DISPLAY TECHNOLOGIES

Different 3D display technologies have respective characteristics that make them more suitable for some applications than others. Some empirical studies have compared the effects of various display technologies and viewing conditions on learning experience and performance.

Most studies comparing immersive and non-immersive VR systems have shown that systems with a more novel and immersive display lead to a better learning experience and performance. For instance, Alhalabi [8] conducted a study to evaluate the impact of VR systems on the students' achievements in engineering colleges. The research compared the Corner Cave System to HMD and examined the effect of different methods on students' scores after each test. Results showed that using any VR system dramatically improves the students' performance, and revealed a significant advantage of using HMD compared with Cave. However, there have been studies with different conclusions.

Demiralp *et al.* [29] performed a qualitative and quantitative comparison between Cave and desktop VR displays for scientific visualization. The qualitative results showed that users preferred desktop VR displays over Cave. The quantitative results showed that users performed a visual search task significantly more quickly and more accurately in the desktop VR display than in Cave. They concluded that desktop VR displays are more effective than Cave systems for applications in which the task occurs outside the user's reference frame (where the user views and manipulates the virtual world from the outside). Aoki *et al.* [30] studied trainees' orientation and navigation performance during simulated space station emergency egress tasks using either immersive HMD or desktop VR. Although their analyses showed that the HMD group was significantly faster than the desktop VR group in navigation performance, this difference may be attributed to differences in the input device used. All other 3D navigation performance measures suggested that the simpler desktop VR system may be useful for the specific astronaut 3D navigation training [13]. Generally, the outcomes are mixed.

These three 3D display technologies have been widely concerned so far in many papers, and now they are not very novel technologies. However, they might have potentials in creating VELEs and promoting hands-on experiential learning. These VELEs are of novelty which is the main reason why we consider the three technologies. From the previous review, it can be concluded that different forms of 3D display technologies have their own advantages and disadvantages in terms of hands-on VELE, so the most suitable display for hands-on experiential learning is still need to be tested. In existing studies, the comparisons of different display modes were not pure effect of the 3D display technologies, because some

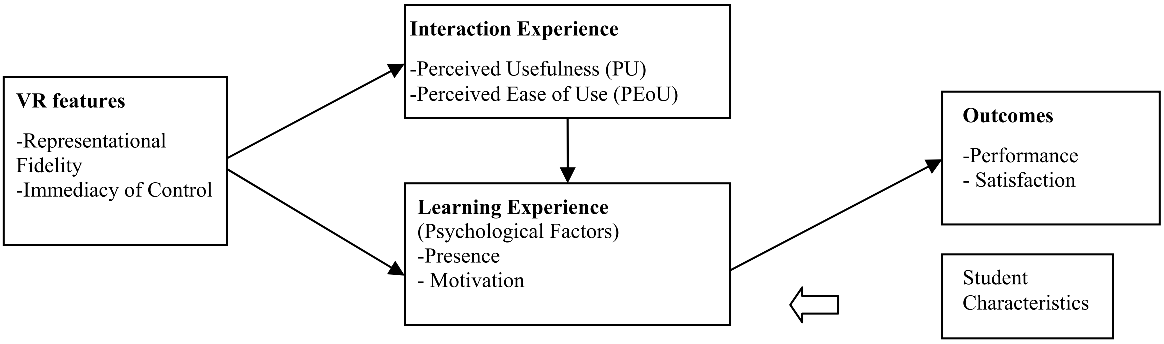


FIGURE 1. Lee *et al.*'s conceptual framework [31].

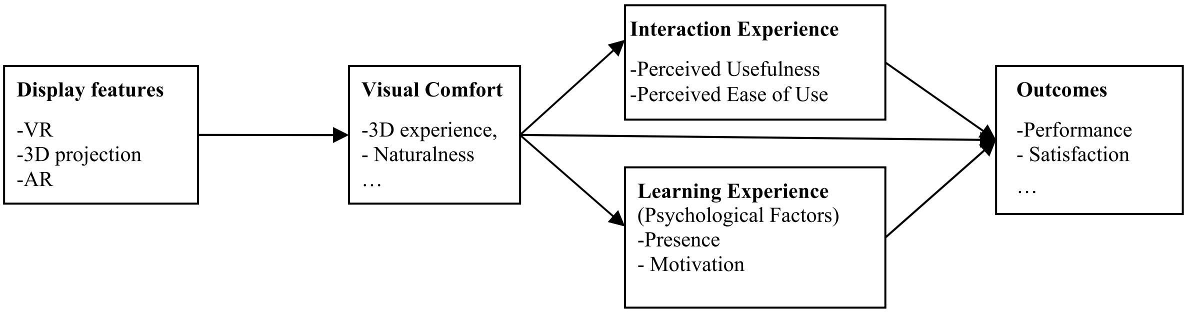


FIGURE 2. Conceptual framework of the effect of display features in hands-on virtual experiential learning.

factors such as the input device and interaction methods were not well controlled. Moreover, the genres of virtual learning activities were also different.

In addition, studies have consistently claimed that AR-enabled learning environments can enhance learning motivation and effectiveness, but few studies have compared the effect of VR with AR in virtual experiential learning. The present study compares the effect of different 3D display technologies on embodied interaction-based experiential learning experience while the interaction condition is well controlled amongst the three 3D display technologies: VR HMD, 3D projection, and AR HMD.

III. HYPOTHESIS

Lee, Wong, and Fung [31] proposed a conceptual framework of learning outcomes and their causal relationships in a desktop VR-based learning environment (Figure 1). In this framework, VR features do not directly influence learning outcome, but indirectly influence it through the quality of the interaction and learning experiences. It provided a suitable framework for this study. The current study focuses on learning in a specific feature (i.e., display technology) and a specific context (embodied interaction-based hands-on virtual experiential learning). In this context, the quality of visual comfort is an antecedent factor, which will further influence the interaction experience, learning experience, and even the outcome. Therefore, based on the work of Lee *et al.* [31], the current study proposed a framework (Figure 2).

The characteristics of the three display technologies were analyzed. In the AR mode, the user wears glasses that do not occlude the real world but display holographic images onto the real world for the user to interact with. Since the user still visualizes the real world, the surroundings easily interfere with the observation of virtual objects. Moreover, compared with VR displays that can provide a large visual field, an AR display (e.g., HoloLens) can only provide a small virtual window that cannot fill the user's visual field [12]. Regarding different VR displays, the VR HMD can create a more immersive experience than a VR projection. In addition, the VR HMD may contribute to a better experience by providing proper distance from virtual objects and by avoiding visual interference of objects in the real world. To sum up, the characteristics of the three display technologies involve the size of visual field, distance between display screen and hands or eyes, visual interference from physical world, etc. Based on our conceptual framework and analysis, these characteristics may directly affect the quality of visual comfort in hands-on VELE (a mediation variable), and then further influence the interaction experience, learning experience, and even the outcome.

Based on the above analysis, four hypotheses are proposed.

Hypothesis 1 (H1): The display technology will significantly affect visual comfort, and the VR HMD mode will lead to the best visual comfort.

Hypothesis 2 (H2): The display technology will significantly affect interaction experience, and the VR HMD mode will lead to the best perceived usefulness and ease of use.

Hypothesis 3 (H3): The display technology will significantly affect learning experience, and the VR HMD mode will lead to the best flow experience and other learning experiences.

Hypothesis 4 (H4): The display technology will significantly affect learning outcome, and the VR HMD mode will lead to the best performance and satisfaction.

The test of these hypotheses will help to clarify the effects of different 3D display technologies on hands-on virtual experiential learning, as well as the underlying mechanism. Finally, the result will help identify the optimal 3D display technology with most advantages in improving experiential learning experience and outcome.

IV. METHOD

A. EXPERIMENTAL DESIGN

A single-factor within-subject experimental design was adopted. The within-subject factor was three types of 3D display technology: fully immersive VR Mode (VR HMD), partially immersive VR Mode (3D projection), and AR mode (AR HMD). Except for the display technology, other factors were well controlled among the three conditions, that is, the experiential learning scenes, contents, and interactions were all kept the same across the three modes. Dependent variables included visual comfort, interaction experience, learning experience, and outcome. The potential ordering effects of the different display technologies were counterbalanced using a Latin square approach. Three conditions (VR HMD=a, 3D projection=b, VR HMD=c) organized into 6 orders of experience: ① a-c-b; ② b-a-c; ③ c-b-a; ④ b-c-a; ⑤ c-a-b; ⑥ a-b-c. Each order was experienced by 6 participants who were randomly assigned. The main objective of this study was to investigate the effect of different display technologies on user experience in VELE, thus complex learning tasks were not selected and learning gain was not measured.

B. PARTICIPANTS

A total of 36 volunteers (15 males and 21 females; mean age, 20.00 ± 3.34) were recruited to participate in the experiment. They were all college students and were recruited by giving notice in their classes. For those initially willing to participate (185 volunteers), they were asked to fill out a simple questionnaire, including their demographic information and their familiarity with VR and AR system. Only those who hadn't experienced VR and AR were chosen to participate in the formal study. The reason for this was to avoid their previous experience interfering the experiment results. As a result of this criterion, the selection rate of the final participants was relatively low at 19.5% (one of the reasons for the small sample size), because most today's students have some or even very rich VR experience. They each experienced the three display technologies in VELEs in a counterbalanced order. There was no money for the test, but each participant received some small gifts as rewards.

C. EXPERIMENTTAL TASK AND APPARATUS

In order to test the hypotheses, it was necessary to construct a virtual experiential learning environment based on hands-on tasks. According to the existing research, there are many examples of experiential learning in the fields of medicine, engineering, geography, mathematics and so on. This study focused on identifying the optimal 3D display technology for hands-on VELE (by testing the impact of different 3D displays on visual comfort, interactive experience and interactive efficiency in hands-on experiential learning), rather than focused on specific subject area or learning content. Hands-on learning scenarios of any subject would be available to be the testing scenario. Although there were many optional learning scenarios, two simple experiential learning scenarios of mathematical knowledge were finally adopted and constructed as the experimental scenarios. Scenario 1 was the "calculation of cone volume", and scenario 2 was the "Tower of Hanoi problem". The reason for these choices are as follows: (1) When learning these mathematical knowledge, getting hands-on operation and experience is necessary to help learner achieve an intuitive understanding of knowledge; (2) compared with other virtual learning scene where the scene modeling is very complex (such as medicine and biology), the construction of mathematical knowledge scene is relatively typical, and the hands-on task is relatively easy to understand. After all, the two simple hands-on experiential scenarios are enough to examine the research questions of this study.

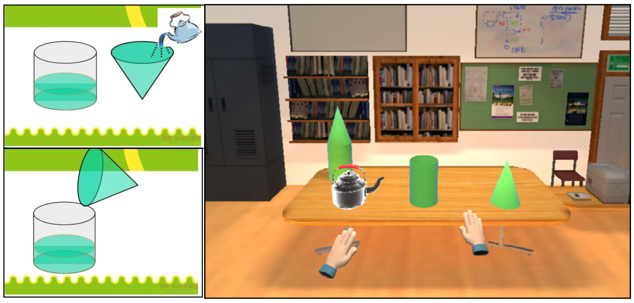


FIGURE 3. The virtual mathematic learning scene 1.

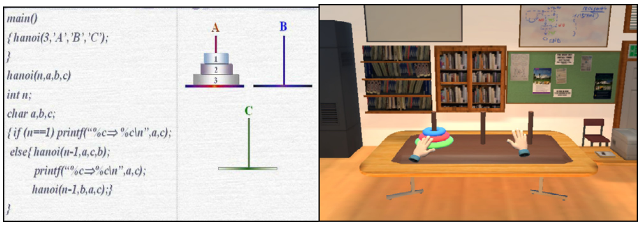
1) SCENARIO 1: CALCULATION OF CONE VOLUME

A basic lesson in mathematical geometry is the volume of a cone, which is one-third of the volume of a cylinder with the same radius and height. Thus, the formula for the volume of a cone is:

$$V_{\text{cone}} = \frac{1}{3}\pi \mathrm{r}^2\mathrm{h}$$

Physical experimentation can make it easier for students to intuitively understand this concept. As shown in Figure 3, a virtual classroom was created with an experiment table containing a few virtual math teaching aids, including a virtual conical container, a virtual cylindrical container, and a virtual kettle full of water. Users were able to manipulate virtual props to directly experiment the mathematical relationship.

Users could operate these virtual objects with virtual hands, which were manipulated by handle controllers. Users were able to pick up virtual teaching aids to observe and compare them. They could also hold the kettle in one hand and



```
main()
{hanoi(3,'A','B','C');
}
hanoi(n,a,b,c)
int n;
char a,b,c;
{if (n==1) printf("%c⇒%c\n",a,c);
 else{hanoi(n-1,a,c,b);
       printf("%c⇒%c\n",a,c);
      hanoi(n-1,b,a,c);}
}
```

FIGURE 4. The virtual mathematic learning scene 2.

the conical container in the other and then pour water to fill the container. They were able to transfer the water from the conical container into the cylindrical container. By repeating this procedure three times, the cylindrical container would be filled with water to the brim. Through this type of hands-on and intuitive experience, it was easy to understand that the volume of a cone is one-third of the volume of a cylinder with the same radius and height.

In this scenario, the goal was to fill the cylinder container with a virtual conical container and a virtual kettle full of water. Repeat this process three times, so that the learner can experience the relationship between cylinder and cone volume and then better understand the volume calculation formula.

2) SCENARIO 2: TOWER OF HANOI PROBLEM

The Tower of Hanoi is a mathematical game or puzzle. It consists of three pegs and several ring disks of different sizes that can slide onto any peg. The puzzle starts with the disks in a neat stack on one peg in increasing order of size, with the smallest on the top, thus making a conical shape.

The objective of the puzzle is to move the entire stack of disks to another peg, obeying the following simple rules: (1) Only one disk can be moved at a time, (2) Each move consists of taking the top disk from one of the stacks and placing it on top of another stack, and (3) A disk cannot be placed on top of a disk of smaller size.

With three disks, the puzzle can be solved in seven moves. The minimal number of moves required to solve a Tower of Hanoi puzzle is $2n - 1$, where n is the number of disks.

In this study, a VELE of Tower of Hanoi was established. A virtual 3D Tower of Hanoi with three disks was placed on a virtual experiment table in a virtual classroom, as shown in Figure 4.

In this scenario, the goal is to solve the Hanoi Tower puzzle with 3 disks in seven moves. Repeat this process three times, so that the learner can understand the Tower of Hanoi problem by intuitive hands-on experience.

3) EMBODIED INTERACTION

Users could freely explore the digital scene and manipulate the objects (such as picking up the kettle in scene 1 and moving the disks in scene 2) using HTC vive handheld controllers. The controllers were represented in the virtual environment as a pair of virtual hands that can act in real-time according to the actual hand movements and operation. It made users feel that they were manipulating the virtual objects with their own hands, which contributed to a good embodied interaction experience (Figures 3 and 4).

(a) VR HMD (b) 3D projection (c) AR HMD

FIGURE 5. Virtual experiential learning with three different display technologies.

To integrate HTC controllers with the Microsoft HoloLens, we matched the coordinate system of HoloLens with the coordinate system of HTC vive positioner in physical space. To integrate HTC controllers with the 3D projection, we use the steam VR plugin to connect Unity to the HTC controllers and mount relevant scripts on the virtual hands in Unity, and then configure the input and output results to realize the control of virtual hand; Using 3D plugin to render parallax images of two virtual cameras (left and right eyes), and then seeing 3D effects with 3D glasses.

4) EXPERIENCE TECHNOLOGIES

The two scenes were presented using three display technologies: VR HMD of HTC vive (Figure 5a), 3D projection with active shutter 3D glasses (Figure 5b), and AR HMD HoloLens (Figure 5c).

The VR HMD provides a fully immersive VR experience with a first-person perspective as if the user is in a simulated classroom. The 3D projection and 3D glasses provide a partially immersive VR experience with a body-based interaction paradigm using head tracking with perspective correction. HoloLens provides an AR experience. In contrast to the virtual scene used in the other two modes, the virtual teaching aids in the AR mode were not placed on a virtual experimental desk, but a real desk instead.

D. PROCEDURE

First, the tasks in the two experiential learning scenes were explained to the participants. Because the participants had no VR experience before, they were instructed how to operate the two-handed game controllers and practiced to be familiar with the basic operation to avoid the extra influence of familiarity on the results. Therefore, before entering the test scenario, we instructed them to practice in a practice scenario. After the practice, they experienced the learning contents of the two virtual learning scenes with the three display technologies one by one following a certain order. The participants were asked to immediately complete a

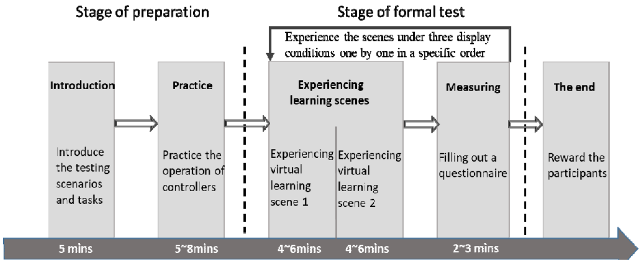


FIGURE 6. **The procedure of experiment.**

questionnaire after they experienced the learning scenes using one display technology. Then, the participants experienced the other two display technologies using similar procedures. Finally, the participants received a gift as reward which was worth 5 dollars. The procedures of the experiment and time to complete each step were shown in figure 6.

E. MEASURES

1) VISUAL COMFORT

A Visual Comfort Questionnaire (VCQ) was used to assess the participants' visual comfort when interacting in the VELE. The questionnaire was developed from Lambooij *et al.*'s questionnaire that evaluated the overall visual experience of 3D movies from four aspects: 3D experience, naturalness, viewing experience, and image quality [32], [33]. "Viewing experience" was further customized into "viewing experience in interaction" with three indicators: comfort in stability, fluency, and view point. Another aspect, "avoidance of discomfort," was added to the questionnaire. It included two indicators: avoidance of dizziness and avoidance of fatigue. Therefore, the developed questionnaire had 8 items. The items were assessed using a Likert scale with the adjectives [bad]–[poor]–[fair]–[good]–[excellent].

2) INTERACTION EXPERIENCE

According to Figure 1, interaction experience includes perceived usefulness (PU) and perceived ease of use (PEoU). They were measured based on the technology acceptance model. The measure items in this study were developed from Huang *et al.* [34]. These items were measured using a 7-point Likert-type scale from "1" (strongly disagree) to "7" (strongly agree).

3) LEARNING EXPERIENCE

Learning experience included five indicators: flow experience, intrinsic interest, concentration, behavior intention, and presence.

a: FLOW EXPERIENCE

Flow experience is a key component of user experience in VR activities. It represents a highly enjoyable mental state where the individual is fully immersed and engaged in the activity [35]. Flow experience is also measured with a Flow Short Scale. The scale has been proven to be a reliable measuring instrument [35], [36]. The items are assessed on a 7-point Likert scale from "1" (I don't agree) to "7" (I agree). Participants answered the scale immediately after they completed each experimental task.

TABLE 1. **Measures of learning experience.**

Indicators	Measures	Alpha
Flow experience	Flow Short Scale	0.909
Intrinsic interest	I enjoy learning in this environment Using this learning environment excites my curiosity Learning in this mode is intrinsically interesting ...	0.894
Behavior intention	I intend to recommend it to a friend. I'd be happy to experience this kind of learning again ...	0.779
Concentration	I'm totally involved in the virtual learning content All my attention is focused on the missions. ...	0.852
Presence	I forget about my immediate surroundings when I do the task I feel like I am inside the virtual world ...	0.870

b: OTHER USER EXPERIENCES

Based on previous studies in virtual learning [35], [37], learning experience in the experiment was measured with the following indicators: intrinsic interest, behavior intention, concentration, and presence (see Table 1). Our assessment was high correlated with the presence survey of Witmer and Singer [38]. These items were also measured using a seven-point Likert-type scale from "1" (strongly disagree) to "7" (strongly agree).

4) OUTCOME

Outcome included two indicators: satisfaction and performance.

Satisfaction was measured with two items that were developed from Huang *et al.* [34]. They were also measured on a 7-point Likert-type scale from "1" (strongly disagree) to "7" (strongly agree).

In this study, all the participants were familiar with the knowledge "calculation of cone volume", and "Tower of Hanoi problem. Therefore, the performance here didn't mean the acquisition of new knowledge which is meaningless for this study. The performance here means the success rate of

TABLE 2. **Descriptive statistics results of visual comfort for the different display technologies.**

Display conditions	3D experience *M(S.D)*	Naturalness *M(S.D)*	Image quality *M(S.D)*	Viewing experience in interaction *M(S.D)*	Avoidance of discomfort *M(S.D)*
VR HMD	4.42	4.28	4.31	13.58	8.92
	(0.95)	(0.93)	(.84)	(2.18)	(1.32)
3D Projection	3.88	3.88	4.08	10.38	8.15
	(0.95)	(0.88)	(.84)	(3.20)	(1.84)
AR HMD	3.73	3.64	3.77	9.77	7.65
	(1.04)	(0.99)	(.91)	(3.15)	(2.19)

participants successfully selecting and picking up the target virtual objects during the hands-on experiential learning. The rate was calculated with the number of successfully selecting and picking up the target virtual objects divided by the number of all attempts (i.e. the total times to pull the handle trigger). This indicator was chosen as a dependent variable because it could reflect the quality of users' judgment of visual distance and position in experiential learning, as well as the quality of positioning in hands-on operation.

V. RESULTS

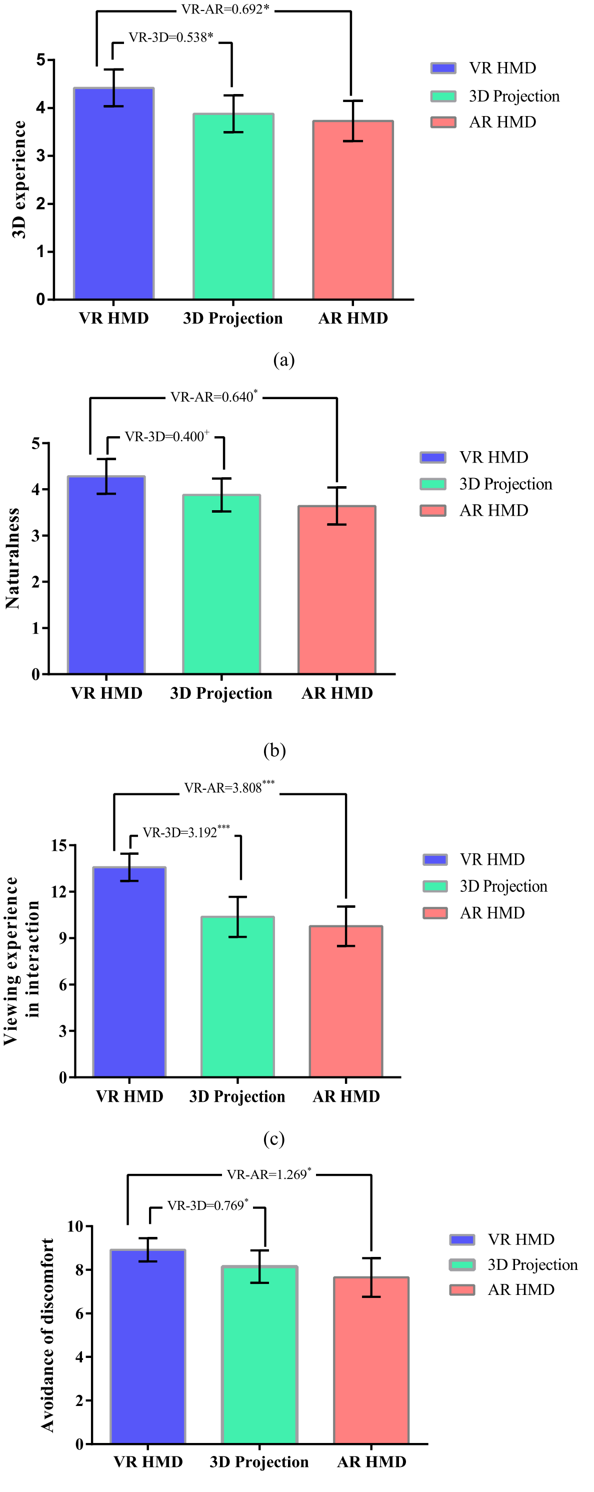
The purpose of this study was to test the role of 3D display, so the 3D display factor was the independent variable. Meanwhile, control modality was a control variable which remained the same in all the three conditions. Therefore, the effect revealed on those measures was due to the role of 3D display factor.

A. INFLUENCE OF DISPLAY TECHNOLOGIES ON VISUAL COMFORT

We first conducted a series of independent sample t-tests to investigate the gender differences, and found that there was no significant difference in indicators of visual comfort (ps > 0.05), indicating that gender didn't affect visual comfort.

To explore the effect of different display technologies on visual comfort, a series of repeated measurement ANOVAs were performed. The descriptive results are shown in Table 2.

Different display technologies had significant effects on visual comfort. Specifically, there were significant or marginally significant differences among the different 3D display technologies for 3D experience ($F = 3.404$, $p = 0.041$, $\eta_p^2 = 0.120$), naturalness ($F = 2.933$, $p = 0.063$, $\eta_p^2 = 0.109$), viewing experience in interaction ($F = 12.532$, $p < 0.001$, $\eta_p^2 = 0.334$), and avoidance of discomfort ($F = 3.638$, $p = 0.033$, $\eta_p^2 = 0.127$).



(a)

(b)

(c)

(d)

*p < 0.05, **p < 0.01, ***p < 0.001

FIGURE 7. **Results of difference tests on 3D experience (a), naturalness (b), viewing experience in interaction (c), and avoidance of discomfort (d) for the different display technologies. Error bars represent 95% confidence intervals.**

To further clarify the difference between different display technologies, a series of post hoc pairwise comparisons were performed with Least Significant Difference tests (LSD test), and the effect sizes of the LSD tests were showed in figure 7. Results revealed that the value of those dependent variables

TABLE 3. Descriptive statistics results of interaction experience for the different display technologies.

Display conditions	PU *M(S.D)*	PEoU *M(S.D)*
VR HMD	24.46(4.62)	25.50(3.30)
3D Projection	23.46(3.69)	24.35(2.99)
AR HMD	22.35(5.93)	22.38 (5.91)

TABLE 4. Descriptive statistics results of learning experience for the different display technologies.

Display conditions	Flow *M(S.D)*	Intrinsic interest *M(S.D)*	Behavior intention *M(S.D)*	Concentration *M(S.D)*	Presence *M(S.D)*
VR HMD	63.77	12.88	12.50	9.08	12.58
	(8.04)	(1.92)	(1.96)	(1.96)	(1.90)
3D Projection	56.12	11.23	10.69	9.19	10.42
	(11.68)	(2.97)	(2.91)	(1.67)	(3.32)
AR HMD	52.12	11.19	10.38	8.69	10.81
	(16.20)	(3.32)	(3.59)	(1.59)	(3.15)

for the VR HMD was significantly higher than that for the 3D projection and AR HMD [3D experience ($ps < 0.05$). The difference between VR projection and AR HMD on these indicators was not significant (Figure 7) between the 3D projection and AR HMD was significant ($t = 2.214$, $p < 0.05$), the value of viewing experience in interaction for 3D projection was significantly higher than that for AR HMD.

Although the effect of different display technologies on perceived image quality was not significant ($F = 2.204$, $p = 0.143$, $\eta_P^2 = 0.075$), the descriptive statistic results showed that the score for the VR HMD was higher than those for the 3D projection and AR HMD. All these results support H1.

B. INFLUENCE OF DISPLAY TECHNOLOGIES ON INTERACTION EXPERIENCE

To investigate the gender differences, another series of independent sample t-tests were conducted. There was no significant difference on indicators of interaction experience ($ps > 0.05$), indicating that gender didn't affect interaction experience.

To explore the influence of different display technologies on interaction experience, two additional repeated measurement ANOVAs were performed. The scores of PU and PEoU for different display technologies are shown in Table 3.

The influence of different 3D display technologies on PU was not significant ($F = 1.198$, $p = 0.31$, $\eta_P^2 = 0.046$). However, the influence on PEoU was significant ($F = 3.540$, $p = 0.036$, $\eta_P^2 = 0.124$), and the result of LSD test showed that the score for the VR HMD was significantly higher than that for the AR HMD (VR-AR $= 3.115$, $p = 0.034$). These results partly support H2.

C. INFLUENCE OF DISPLAY TECHNOLOGIES ON FLOW EXPERIENCE AND OTHER LEARNING EXPERIENCES

None of significant difference on flow or other experiences was found in the test of gender difference ($ps > 0.05$).

To explore the effect of different display technologies on learning experience, a series of repeated measurement ANOVAs were performed. The flow scores for different display technologies are shown in Table 4.

Results revealed that 3D display significantly affected flow experience in the VELE ($F = 6.206, p = 0.004, \eta_P^2 = 0.199$). The flow score for the VR HMD was significantly higher than those for the 3D projection and AR HMD (Figure 8a).

When looking at the results for other learning experiences, although display technology had no significant influence on concentration ($F = 0.585$, $p = 0.561$, $\eta_P^2 = 0.023$), it did significantly influence intrinsic interest ($F = 3.018$, $p = 0.058$, $\eta_P^2 = 0.108$), behavior intention ($F = 4.406$, $p = 0.017$, $\eta_P^2 = 0.150$), and presence ($F = 4.211$, $p = 0.020$, $\eta_P^2 = 0.144$). Then, a series of post hoc pairwise comparisons were performed with LSD tests, and the effect sizes of the LSD tests were showed in figure 8. Results revealed that the scores for the VR HMD were significantly higher than those for the 3D projection and AR HMD. The difference between the 3D projection and AR HMD in terms of these indicators was not significant (Figure 8b, d). These results support H3.

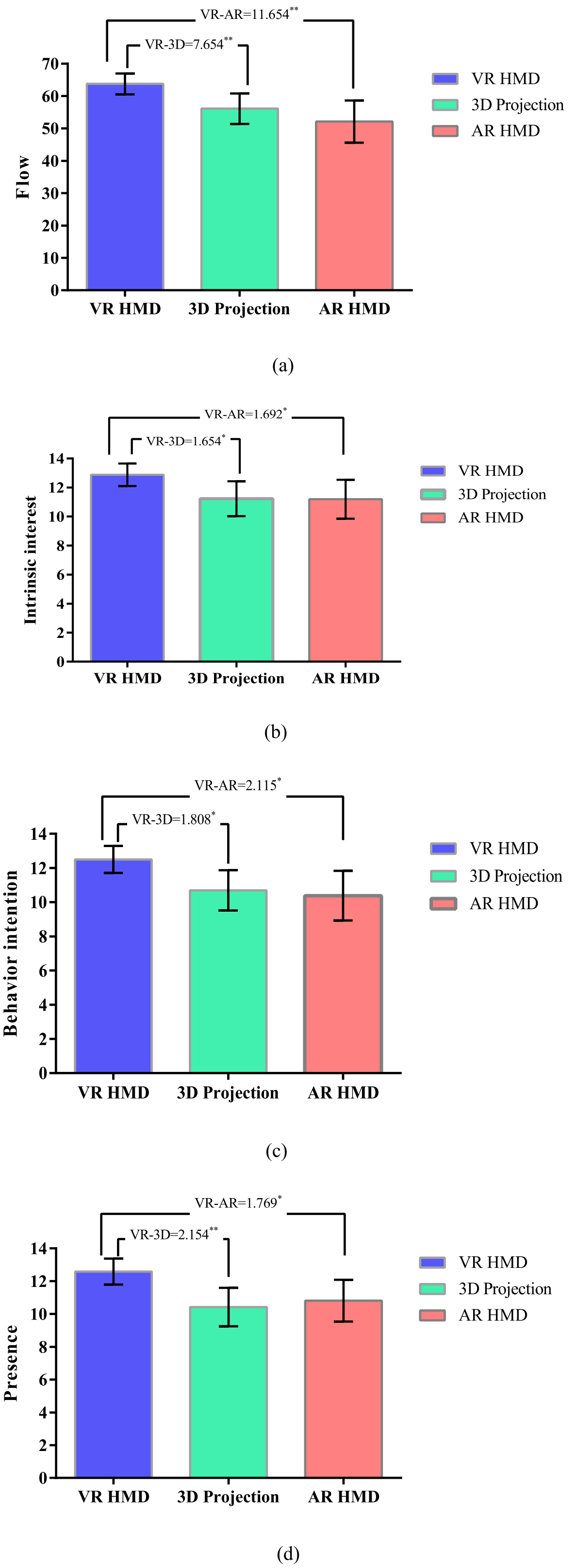
D. INFLUENCE OF DISPLAY TECHNOLOGIES ON OUTCOMES

Like the previous results, gender difference was not significant on outcomes ($ps > 0.05$). Moreover, Figures 9-10 show the values of learning outcomes under the all 6 possible combinations. From the results, it could be seen that there was no learning effect.

To explore the effect of different display technologies on outcomes in the VELE, two additional repeated measurement ANOVAs were performed. The influence of different display technologies on both satisfaction and accuracy of hands-on operation was very significant ($F = 5.140$, $p = 0.009$, $\eta_P^2 = 0.171$; $F = 17.793$, $p < 0.001$, $\eta_P^2 = 0.426$). Similar to the aforementioned results, the scores for the VR HMD were significantly higher than those for the 3D projection and AR HMD for both the indicators ($ps > 0.05$), which supports H4.

VI. DISCUSSION

The main purpose of this study is to identify the optimal 3D display technology (among three current mainstream types of 3D display technologies) for hands-on VELE, and understand the underlying mechanism. Specifically, three different display technologies, VR HMD, 3D projection, and AR HMD, were chosen and two learning scenes were designed to explore the research purpose. The empirical results of this study empirically supported the research hypotheses, which could help clarify the relationship between 3D display features and experiential learning.



*p < 0.05, **p < 0.01, ***p < 0.001

FIGURE 8. Results of difference test on flow experience (a), intrinsic interest (b), behavior intention (c), and presence (d) for the different display technologies. Error bars represent 95% confidence intervals.

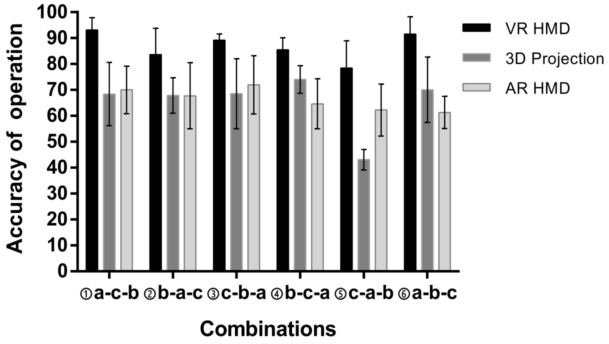


FIGURE 9. Results of difference test on flow experience (a).

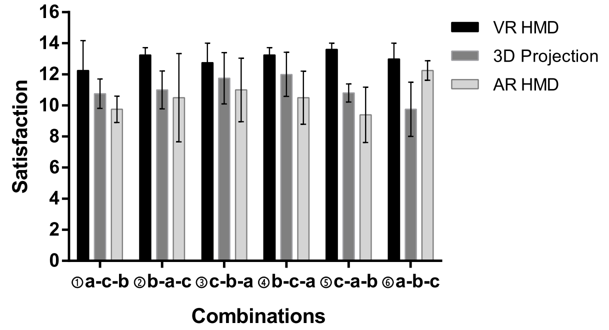


FIGURE 10. Results of difference test on flow experience (a).

A. EFFECTS OF 3D DISPLAY TECHNOLOGY ON VISUAL COMFORT

According to our theoretical framework, the direct consequence of 3D display technologies is on visual comfort. Indeed, results showed that different display technologies are indeed an important factor affecting the quality of visual comfort in a VELE, which supported H1. Visual comfort is partly determined by the display technology. For most of the indicators of visual comfort (3D experience, naturalness, viewing experience in interaction, and avoidance of discomfort), the values for the VR HMD were significantly better than those for the 3D projection and AR HMD. It can be concluded from these results that users achieve best 3D experience and naturalness in experiential learning under VR HMD condition. Moreover, when learning under VR HMD condition, they also achieve best viewing experience in performing hands-on tasks, and avoid discomfort to a greatest extent. This result is not difficult to understand because a VR HMD environment is fully immersive and provides a clear display of the simulated world while avoiding real-world interference. By contrast, the user's feeling of visual immersion is easily disturbed by the external environment in the 3D projection and AR HMD environments. Some supportive views can be found. Pelargos *et al.* [12] pointed out that the integration of these display technologies into hands-on experiential learning (e.g., clinical practice) is partly dependent on the vision and immersion [39]. Vision is vital to success. AR often has barriers in providing adequate vision. Conversely, VR systems would be most useful in providing an immersive experience and reaching a certain threshold of depth of field, depth of focus, field of view, and image resolution. It should be noted that there was no significant difference on perceived image quality among the three display conditions, indicating that the differences are not due to the factor of resolution or clarity of image. In addition to the controlled experiment presented in this paper, the VELE system was taken to a local primary school classroom where the pupils experienced it firsthand. Results from pupils' data also showed that they perceived higher resolution, brightness, and crispness of imagery with comfort of use while using the VR HMD.

The difference between VR projection and AR HMD for most of these indicators was not significant, but the difference in viewing experience in interaction between the 3D projection and AR HMD was significant. This meant that the difference was shown only when the participants performing the hands-on task. The reason may also be the limited vision: visual field of AR HMD is too small to support ideal hands-on interaction.

Another point should note was that the rating on avoidance of discomfort under VR HMD condition was the highest, which surprised us. According to the interview of previous studies [17], VR HMD is more likely to lead to visual discomfort such as fatigue and motion sickness. One possible reason is that the task time in the study scenario is relatively short and there is not much spatial movement, so disadvantages of VR HMD on this aspect are not shown. At least, it could be concluded from current results that VR HMD didn't bring much discomfort in short-term experiential learning. However, the visual discomfort in long-term experiential learning needs to be tested in future study.

B. EFFECTS ON INTERACTIVE EXPERIENCE AND LEARNING EXPERIENCE

According to our theoretical framework, when there are differences in visual comfort among different 3D display technologies, the interactive experiences (H2) and learning experiences (H3) among display technologies are also different, as supported by results.

When looking at the results on interactive experience, although the influence of different 3D display technologies on PU was not significant, the descriptive statistics score under VR HMD condition was still the highest (VR HMD >3D Projection>AR HMD, table 3). However, the influence on PEoU was significant: the PEoU score for the VR HMD was significantly higher than that for the AR HMD, and higher than 3D Projection in descriptive statistics score (see table 3). These results were consistent with the results on visual comfort and supported the theoretical framework: for the 3D display technologies with the highest visual comfort, users will achieve best interactive experience. Based on these results, it can be concluded that the difference of visual experience brought by the three technologies didn't affect PU of the system, but affect PEoU. In other words, the 3D display technology with best visual experience improved the participants' intuition of interaction and reduced the cognitive load.

When looking at the results on learning experiences, although display technologies had no significant influence on concentration, it did significantly influence flow experience, intrinsic interest, behavior intention, and presence. The scores for the VR HMD were significantly higher than those for the 3D projection and AR HMD. These results were also consistent with the results on visual comfort and supported the theoretical framework, especially result on the sense of presence would help to assess the role of display and control factors in discomfort and engagement. These results together show that: under the 3D display technologies with the highest visual comfort, users will achieve best learning experience.

This shows that the experiences for the VR HMD are significantly better than those for the 3D projection or AR HMD. It can be concluded that different display technologies lead to different levels of visual comfort, which can further affect the interactive and learning experiences. In addition, there may be other reasons, such as the quality of embodied interaction. After the experiment, a brief survey was conducted asking participants to name the display technology that brought them the best feeling of embodied interaction. A total of 88.5% participants thought the quality of embodied interaction was best in the VR HMD, followed by the AR HMD (7.7%) and 3D projection (3.8%). For the embodied interaction design in this study, a user probably perceives the virtual hands in the VR HMD as the most realistic. Therefore, they might feel more intuitive, just like performing the mission with their own hands. By contrast, the display quality in the AR HMD was less ideal, which lowered the interaction efficiency and experience. The 3D projection has a considerable disadvantage. The displacement between the user and the virtual object is far from natural in a 3D projection environment, so it is difficult for users to perceive the virtual hands as their own. In other words, the interaction process is not sufficiently intuitive.

C. EFFECTS ON LEARNING OUTCOME

According to our theoretical framework, the display technology that provides better visual comfort not only provides a better experience but also eventually provides a better outcome (H4), which was supported by the empirical results.

The effects of different display technologies on outcomes in the VELE were explored and results showed that the influence of different display technologies on both satisfaction and accuracy of hands-on operation was very significant. Similar to the aforementioned results, the scores for the VR HMD were significantly higher than those for the 3D projection and AR HMD for both the indicators ($ps > 0.05$), which supports H4. Based on these results, it could be concluded that the difference of visual experience brought by the three technologies could further lead to difference on behavior aspects, i.e. accuracy of hands-on interaction operation. Finally, all these differences contribute to the difference on satisfaction. However, it should be noted that the outcomes in this study focus on interaction efficiency and satisfaction in hands on task, not on knowledge learning. As explained earlier, the focus of this study is not to investigate knowledge acquisition, thus the knowledge in this VELE was not difficult. However, this is actually a very important part of the future will be devoted to the design and study of this issue.

D. DISCUSSION ON THE CONCEPTUAL FRAMEWORK

In current study, a conceptual framework was proposed to help explore the underlying mechanism of the effect of display features in hands-on virtual experiential learning. Actually, before they put forward their conceptual framework, the model for immersive VR-based learning developed by Salzman *et al.* [40] provided a starting point for this study's framework, and is supported by some technology-mediated learning models [41]–[44]. They emphasized the importance of scrutinizing how VR features work together with other factors (such as interaction and learning experiences) that influence the learning process. In our proposed model, the quality of visual comfort is added as a direct consequence of display features, and it plays a role as an anticipated factor that will further influence the interaction experience, learning experience, and even the outcome. All above results support the present study's conceptual framework along with that of Lee *et al.* [31]. This study not only supported these perspectives but also found that visual comfort is an important mediator for the influence of different display technologies on learning experience and outcomes during embodied interaction-based hands-on virtual experiential learning.

E. LIMITATIONS AND FUTURE DIRECTION

In summary, the VR HMD seems to outperform other display technologies on all measures in the tested hands-on VELE. However, the results have limitations. First, this study conducted relatively short/fast-paced experiments, and the learning content simulated in the VELE in this study is simple and the experience time is short. Whether the visual experience in the VR HMD mode will remain superior in complex missions and long-duration learning tasks cannot be concluded. Therefore, whether the study results still hold reliably in terms of more complex learning activities and long-term learning needs to be further studied. Secondly, this study focused on examining the effects of different display technologies on learning experience; however, the effect on learning performance remains unclear. These questions need to be investigated in future studies. Third, the sample sizes are small. We did not further expand the sample sizes because the analysis based on the existing sample size showed that the results had been significant and reliable. However, the small sample sizes may affect the reliability or stability of the outcomes, possibly limiting the generalizability of the results. Therefore, our findings need to be further tested with larger samples. Finally, a valuable research direction could be exploring what type of learning environment situations are each type of headset most suitable for, and what kinds of basic specification differences will account for different use experiences.

VII. CONCLUSION

Overall, this study empirically tested the optimal 3D display technology in hands-on VELEs. some conclusions can be concluded: (1) different display technologies significantly affected users' visual comfort, interaction experience, learning experience, and outcome in hands-on experiential learning. (2) VR HMD is the optimal 3D display technology in terms of hands-on virtual experiential learning: the VR HMD contributes to better visual comfort, interaction experience, learning experience, and outcome than 3D projection or AR HMD in the scenarios tested. (3) Our proposed conceptual framework can effectively explain how display features affecting experiential learning, and can be used as a reference framework for future research under this topic.

ACKNOWLEDGMENT

The authors would like to thank all reviewers for their valuable comments.

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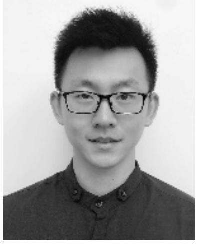

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