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Assess the Engagement with 3D Virtual Learning Tools during the COVID-19 Pandemic

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Abstract: The recent growth of learning technologies has catalyzed the surge in investments in e-learning systems across higher education to revolutionize pedagogical practices. Thus, the implementation of 3D virtual learning tools has become an indispensable, standard methodological tool in higher education. More recently, the enforcement of restrictions and emergency lockdowns to curb the spread of the COVID-19 pandemic compelled higher education institutions worldwide to cope with and meet the requirements of online education while preserving the quality of the learning experience at an equal pace. To develop a 3D physics laboratory, the appropriate equipment for physical experiments was first collected; then, the design software was applied to construct the 3D model. Software was then developed to edit the 3D experimental environment. Two practical tests were performed on the completed setup to verify the disadvantages and feasibility of the experiments. The present study develops and validates the incorporation of user satisfaction approaches to examine the quality of the most influential 3D learning tools during the coronavirus outbreak. The findings of this study confirm that 3D laboratories can positively influence learning attitudes when it comes to physics and improve learners' understanding of physics concepts; they also confirm that 3D laboratories are a suitable tool for teaching physics experiments. Finally, the difficulties and solutions encountered in the development of the 3D laboratory are outlined as a reference for subsequent studies.

Keywords: three-dimensional (3D); physics laboratory; learning theory; COVID-19

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1. Introduction

The last year has been a turning point, representing a critical paradigm shift in teaching and learning models. A rapid evolution has taken place in educational and clinical environments to flatten the curve of the spread of COVID-19, including the closure of schools and educational institutions, extensive implementation of social distancing, and home quarantine [1]. The COVID-19 pandemic has forced universities around the world to make use of a number of emerging online platform technologies and different teaching and learning tools, such as Zoom and Microsoft Teams. Universities have had to ask students and lecturers to use a range of different learning tools to ensure the educational process remains uninterrupted [2]. Therefore, educators have been forced to adopt 3D virtual learning tools in both instruction and assessment processes to enable students to continue with their education. Additionally, educational institutes have shut down worldwide due to the outbreak of COVID-19. This has led to several studies, such as that by Mahmood [3], which explored how different instructional strategies can help to implement online teaching in higher education.

The outbreak of the COVID-19 pandemic, with its associated lockdown and social distancing measures, has had a variety of consequences, such as the misuse of e-learning tools [4]. These impacts have had a devastating effect around the world not only in the field of public health, but also in the social–economic domains. In terms of the COVID-19 pandemic, Brooks et al. [5] reported that one significant adverse consequence was likely the misinformation and stigma around the fear of being infected. New learning systems and educational tools have the potential to create new opportunities for education [6,7]. However, there are also certain risks, arising mainly from the misuse of e-learning tools, which can lead to a decline in their adoption.

Teachers have increasingly highlighted the importance of the concept of student-centered learning in the design of teaching activities. Teachers must think of means to enhance students' learning interest in the classroom, provide appropriate teaching materials or tips, and arrange appropriate student activities. Student-centered learning emphasizes the priority of students' self-learning activities rather than teaching by the teachers [8,9].

An essential part of the learning experience of engineering students is practical laboratory demonstration, where virtual laboratories can supplement physical laboratories to reinforce crucial concepts from the courses [10]. Virtual laboratories in engineering education must be designed to enhance practical knowledge, as well as the ability to investigate and solve engineering problems and demonstrate how to report technical information with an appropriate level of independent thought and creativity [11]. Huang et al. [12] found that learner acceptance of such virtual learning environments is a critical issue when it comes to ensuring that they are used to the greatest effect. Syed et al. [13] suggested that the use of virtual learning technology in teaching can improve the undergraduate mechanical engineering curriculum by supplementing the traditional learning experience with outside-the-classroom materials.

Virtual learning environments (VLEs) are becoming more prominent in this new scenario [14]. VLEs can be defined as web-based platforms and can be used as more than a repository, e.g., a digital learning platform where subject-related resources, announcements, topic-related activities, assessments, student–student and/or student–teacher interactions within a subject, feedback, and grades can be hosted.

Huang and Lee [15] explored the learning usability factors of 3D modeling in a virtual environment. Their results may be of interest to 3D modeling software developers as a key reference in virtual reality (VR) learning interface design. Universities all over the world are considering the utilization of VLEs in engineering education to meet the demands of Industry 4.0 for future employment. The current state of knowledge as regards strengthening educational competencies has been systematically reviewed to identify the means to tackle the challenges of Industry 4.0 [16].

Accordingly, the research purposes of this study were (1) to develop a 3D laboratory using virtual reality (VR) technology and (2) to explore the operation interface, content of teaching material, and learning motivation of virtual learning experiments.

Based on the above research purposes, this study aimed to answer: (1) What is the relevant software and experimental environment required for 3D laboratories? (2) How do 3D laboratories influence students' learning attitudes?

2. Literature Review

While some claim that the unprecedented challenges encountered during the COVID-19 pandemic are what made the use of educational technology essential, this does not seem to be true, considering that even before COVID-19, the use of educational technology was necessary, and blended/hybrid learning approaches already existed. Additionally, there was research interest across all disciplines regarding examining the impacts of e-learning on education delivery [17]. Recent investigations have identified online education alternatives within a more inclusive instructional design. Nevertheless, rarely have there been impactful endeavors to investigate 3D learning tools used as a unified pedagogical framework.

2.1. Learning Theory

Based on the principle of enhancement, some pieces of computer software are designed to emphasize repeated practice, in order to help students memorize important information.

The working principle of software based on repeated practice is to increase the number of correct answers along with feedback.

Designers and developers of educational software have referred to the educational theory and taking into consideration of 3D environments to incorporate 3D environments into the software. Bakar and Zaman [18] described the design process for a virtual chemistry laboratory in a 3D setting. The modelling of the theoretical framework was divided into two parts: (1) analysis, design, development; (2) evaluation. Based on learning theories, such as constructivism–cognitivism–contextual, their study adopted learning-by-doing, contextual education, simulation, 3D animation and real time animation to create a 3D virtual environment based on reality.

Virtual learning environments combine classroom and distance lessons, and create new possibilities of interaction over the internet [19]. The virtual learning environment allows students to learn and experiment with electrical concepts in a user-friendly environment. In that study, the proposed prototype is a 3D replica of a real electrical system, so that the electrical components can be moved virtually to facilitate educational activities.

Musawi et al. [20] measured the effectiveness of the 3DL on students' acquisition of practical abilities and skills. They examined the effectiveness of the 3D lab in science education and scientific thinking acquisition, and found that students' attitudes are positive towards using the 3D lab in teaching. Improvements in logical and visual thinking were also observed.

In this study, a 3D laboratory was constructed to allow students to learn without the restriction of time and space, and understand the inherent scientific principles through operations of virtual experiments [21]. The construction of the 3D physics laboratory aimed to meet different learning stages of the users, streamline the hands-on operation in the learning environment, and make the learning process more effective. The construction concept was based on the educational theory of situated learning, while the virtual environment's design was based on the teaching activities. The behaviorist learning theory was integrated into design the 3D physics laboratory, in order to suit students' learning habits and associated benefits.

2.2. Situated Learning Theory

As indicated in the situated learning theory, knowledge and understanding is fundamental to a learning situation. Learning is situated and occurs by means of legitimate peripheral participation within the context of a community of practice. Based on the theory of situated learning, this study developed conceptual and technical approaches to build the 3D virtual laboratory.

The growing emphasis on learner-centered education focuses on intrinsically motivated learning via engaging problem-solving activities. HabiTable 3D learning environments, in which learners guide avatars through virtual worlds for role-based problem solving, hold great promise for situated learning [22].

Clarke and Dede [23] described how multi-user virtual environments can simulate immersive, collaborative learning environments intermediate in the complexity between recipe-like lab exercises and real-world inquiry situations. They presented a case study to illustrate how rich logfiles provide teachers with detailed data to understand learning processes, diagnose suboptimal patterns of student performance, and assess the knowledge and skills that the students have mastered.

The situated learning theory suggests that knowledge does not exist independently in the consciousness of any individual; rather, it is generated by the interaction between individuals and the real environment. Therefore, the best teaching approach is to place students in a real environment or simulate a real environment for students to ensure the best learning results. Situated teaching has been actively applied to different teaching fields, especially in the design of computer-aided learning and teaching software based on computer technology [24].

In this study, a 3D physics laboratory was developed to provide learning situations that conform to the situated teaching theory through the virtual environment.

2.3. 3D Virtual Environment

In engineering education, the visual component is one of the more relevant topics for students, and it is important to be able to interpret visual information correctly [25]. On the one hand, educators need to have an interactive system when teaching with 3D models. Hence, educators are searching for new methods adapted to the actual technology development, so as to enhance student learning and motivation [26,27] and researching their uses, benefits and potential problems [28]. A 3D virtual cranial model [29] was designed to improve surgeons skills and different cranial models can be recreated in a faster and cheaper way.

VR can be used to replace much or all of users' experiences in the physical world with synthesized 3D material such as graphics and sounds. VR-based technologies are expected to have a promising future as aids in the engineering education field, as they offer many advantages over traditional methods [30]. Fernandez et al. [31] proposed physical networking devices through virtualized devices; virtualization technologies may contribute to simplifying laboratory management tasks and allow the creation of affordable and more complex network scenarios. Ural [32] outlined a virtual bone testing laboratory that was developed and implemented in a biomechanics course as a part of the graduate mechanical engineering curriculum. It can induce the same feeling as in the real environment. Simply, VR simulates the world on the computer and enables people to enter the world through a special user interface to experience the real situation. VR is a simulation environment formed by integrating 3D graphics and sound effects, and other human interfaces, and then, generates and controls a virtual world in which people can feel as if they are in a real environment with the computer. Virtual technology can create an environment that interacts with users and simulates the real world. With the special computer peripheral devices, people can see, hear or even virtually contact the same objects or things as in the real world, and interact with objects in the virtual environment.

In this study, the characteristics, advantages, and disadvantages of 3D learning systems were analyzed for the construction of the virtual physics laboratory.

3. Methodology

3.1. Participants

The subjects of this study were freshmen of a university in central Taiwan who were enrolled in a general physics course. Two practical tests were performed over the period of three weeks. The first practical test was conducted on six freshman students. The second practical test was conducted on fifty freshman students.

3.2. Instruments

The questionnaire was based on a Likert 5-point scale, ranging from 5 (strongly agree) to 1 (strongly disagree).

3.3. Construction of the Virtual Laboratory with 3D Tools

The construction of the 3D physics laboratory requires VR software, but most of the traditional development tools require programming backgrounds and knowledge of programming codes. In recent years, several pieces of VR development software have been released, allowing users without any programming background to develop VR programs. Users can focus on content design without the hassle of learning programming.

In this study, Virtools [33] was used as a development tool to construct a 3D physics laboratory. Figure 1 shows the framework of Virtools. Its hallmark is the interactive behavior module, which is similar to stacking blocks. Drag and Drop allows users to add the built-in interactive behavior module to the appropriate objects or characters, and the processing order of the behavior module is determined in the form of a flowchart. Virtools is suitable for users with no programming backgrounds, and even beginners can use the software easily. Virtools has more than 500 available interactive modules, and the edited interactive module group can be combined into a new single interactive module to facilitate reuse or editing. Furthermore, designers with programming backgrounds can also use Script to write the program modules and control any object in the situation, which is quite flexible in terms of the design of the 3D environment.

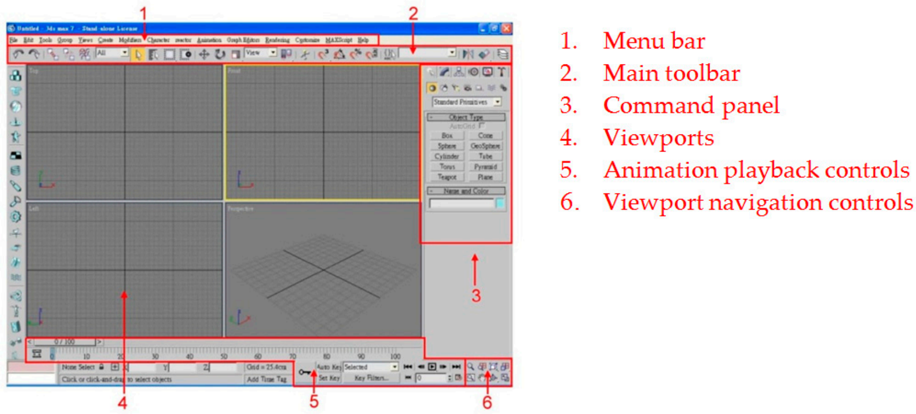

Figure 1. The framework of 3D virtual learning tools (Virtools).

In this study, Virtools was used to construct a 3D virtual environment, and its advantages include: (1) clear file resource management: in the operation interface, all the files of the objects are displayed in different parts according to the classification; (2) behavior module database: users can drag and drop more than 500 built-in behavior modules to the objects, and use the existing behavior modules and combine them into a new behavior that can be separately saved as a file for other users or on other projects; (3) debugging tools: the tools can be used at any time when the users are editing the behavior modules to check whether there are logical errors and correct them; (4) entities setup: each object has its own setup interface, which can be modified or set according to different parameters in different classes.

3.4. Assessment of the 3D Laboratory

Figure 2 shows the home menu of the 3D physics laboratory. Figure 3 shows the collision experiment. After the laboratory was constructed, practical tests and evaluations were conducted. The relevant test methods are described as follows:

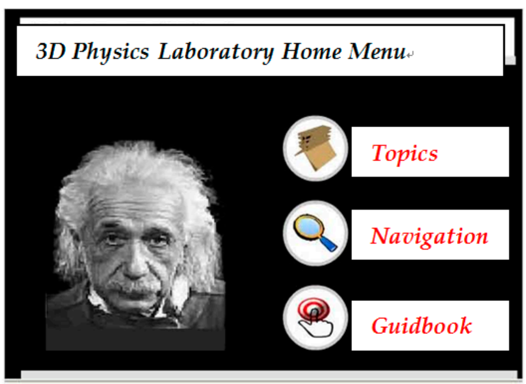

Figure 2. The home menu of 3D physics laboratory.

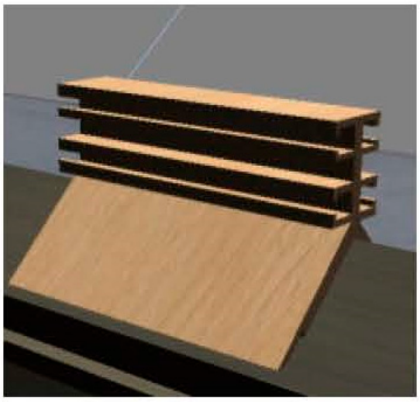

Figure 3. The collision experiment.

3.4.1. Practical Tests of the Users

The subjects of this study were freshmen who enrolled on a general physics course. Two practical tests were performed, described as follows:

(1) The first practical test: the subjects were six freshman students on a general physics course. Before operating the 3D physics experiments, the students had already performed a real collision experiment in their general physics course.
(2) The second practical test: the subjects were 50 freshman students on a general physics course. Before operating the 3D physics experiments, the students had never performed a real collision experiment.

3.4.2. Comparison of Virtual and Real Experiments

In this study, experiments were performed in the teaching unit of Collision in physics experiments. The data of virtual and real experiments were compared for the reference of system developers in virtual environment construction and data correction.

4. Results

4.1. First Practical Test and Analysis

The 3D physics laboratory operation questionnaire was revised by two university graduates and professors, and then filled in by six students in the first practical test. The feedback responses of the six students were recorded, and the questionnaire was revised to complete the expert content validity.

Before commencing the test, the course instructor explained the operation of the virtual experiments to the students and provided the operation manual of the 3D physics laboratory to the students. After the test operation and the collision test record table were completed, the students filled out the questionnaire to understand their opinions on the 3D physics laboratory. The results were analyzed in terms of the operation interface, the content of teaching materials, students' learning motivation, and their learning outcomes on physics concepts.

4.1.1. Operation Interface

In terms of standard deviation (SD) and mean (M) of the operation interface (M = 3.60), as shown in Table 1, most users thought that the 3D laboratory interface is user-friendly and easy to use. To improve user satisfaction, the researchers revised the 3D physics laboratory according to the suggestions by the users.

Table 1. Statistical results of operation interface.

Items	M	SD
1-1. I think this is a user-friendly simulation interface.	4.00	0.89
1-2. I think the 3D laboratory interface looks visually comfortable.	3.83	0.98
1-3. I do not need to be proficient in computer operation to easily operate the 3D laboratory.	3.83	0.75
1-4. I find that the execution of the 3D laboratory is smooth and there is no delay.	3.00	0.63
1-5. I think the operating interface of the 3D laboratory is suitable for students.	3.33	0.52
Average mean	3.60	

4.1.2. Content of Teaching Materials

In terms of the standard deviation (SD) and mean (M) of the content of teaching materials (M = 3.50), as shown in Table 2, most users thought that the description information on the 3D laboratory is sufficient and easy to understand, with appropriate content. The users could easily find the content they need to operate quickly.

Table 2. Statistical results of content of teaching materials.

Items	M	SD
2-1. I think the description information on the topic in the 3D laboratory is sufficient and easy to understand.	3.67	0.82
2-2. I use the 3D laboratory for a quick search on what I want to operate.	3.50	0.55
2-3. I think the 3D laboratory is similar to the real experimental setting.	3.00	0.89
2-4. I think the content on the topic in the 3D laboratory is appropriate.	3.83	0.41
Average mean	3.50	

4.1.3. Learning Motivation

In terms of the standard deviation (SD) and mean (M) of the learning motivation (M = 3.59), as shown in Table 3, most users thought that the 3D laboratory makes them more interested in the content of the class and the related physics knowledge.

Table 3. Statistical results of learning motivation.

Items	M	SD
3-1. I think the 3D laboratory has made the course more interesting, and inspired me to be more interested in the content of the class.	3.67	0.52
3-2. I think after learning through the 3D laboratory, I am more interested in the related knowledge.	3.50	0.55
Average mean	3.59	

4.1.4. Suggestions for the Openness of the 3D Laboratory in the First Practical Test Questionnaire

Operation Interface

(1) Considering the operation interface, students could better understand the origin of the data if the formulae of momentum and mechanical energy were attached.
(2) Considering the operation interface, it would be better if the color of the data presented could be more different from the background color.

Content of 3D Laboratory

(1) The operation could be more flexible and practical if the users could input some of the experimental data.
(2) The expansion of functions of the experimental equipment in the 3D physics laboratory could be of more value, and the 3D physics laboratory could operate the experimental parts that are more difficult to operate in reality.

Based on the above suggestions, the researchers revised the 3D physics laboratory, improved the presentation of the questionnaires and experimental records, and then carried out the second practical test.

4.2. Second Practical Test and Analysis

After the first practical test, the researchers revised the 3D physics laboratory based on the feedback and suggestions of the subjects, including the operation interface of the 3D physics laboratory, the content of the teaching materials, the experimental record table, and the laboratory operation questionnaire. After the revision, the second practical test of the 3D physics laboratory was conducted, and 50 users completed the test.

The students spent two hours operating the 3D physics laboratory and filling out the questionnaires. Before starting, the researcher explained the operation of the 3D physics laboratory to the students, and provided an operation manual to each student. After the operation, the students filled out the experimental record table and questionnaire. A total of 50 valid questionnaires were retrieved. The experimental record table, data calculation accuracy, and operation questionnaires were analyzed.

4.2.1. Completion Rate of Experimental Record Table

The completion rate of the experimental record table can provide insight into whether the data interface of the 3D physics laboratory is obvious, clear, and easy to understand. The completion rate of the experimental record table is discussed in the form of two aspects, as described below:

Completion Rate of Observation Data

Observation data refer to the proportion of the students who successfully observed the speed data before and after the collision displayed on the interface after they operated the 3D physics laboratory, conducted the collision experiment, and recorded the data on the record table, as shown in Table 4. Specifically, 88% of the students recorded the observation data successfully, suggesting that the users were able to display and record the desired observation data accurately and quickly after operating the 3D physics laboratory.

Table 4. Completion rate of observation data.

Completion Rate	**Number of People**
Students who did not complete	6
Students who completed	44

However, six students did not complete the data calculation, and the possible reasons are:

(1) The experiment record table contains too many blanks for students to fill in.
(2) The students took a long time to become familiar with the operating process, so that they had enough time to complete the record table.

Completion Rate of Calculation Data

Calculation data refer to the proportion of test students who could correctly calculate the observed data after the observation, as shown in Table 5. Thirty-three students did not complete (below 60%) the data calculation. The possible reasons may be:

(1) Too many decimal points: The speed data recorded by Virtools is up to four decimal points, causing difficulty in the calculation for students. To address this problem, the researcher reduced the number of decimal points to two for the speed data.
(2) Too many tables: There are too many tables to be calculated, and the calculation process is too complicated for the students. To address this problem, the researcher designed an Excel file to assist the calculation, and students only needed to enter the observed data to complete the calculations.

Table 5. Completion rate of calculation data.

Completion Rate	Number of People
Below 60%	33
60–80%	9
Above 80%	8

4.2.2. Data Calculation Accuracy

Calculation accuracy indicates whether the students calculated the observed data in the table correctly, as shown in Table 6. Specifically, 40 students reached a data accuracy of over 60%, indicating that most students had an understanding of collision after operating the 3D laboratory and could accurately calculate the data before and after the collision.

Table 6. Data calculation accuracy.

Accuracy	Number of People
Below 60%	10
60–80%	2
Above 80%	38

4.2.3. Analysis of Operation Questionnaire

The analysis results of the questionnaire are discussed in terms of the operating interface, the content of teaching materials, learning motivation, and the learning of physics concepts.

Operating interface: 18% of the users strongly agreed and 42% of the users agreed that the operating interface is user-friendly, suggesting that the operating interface of the 3D physics laboratory is appropriate.

Content of teaching materials: 17% of the users strongly agreed and 50% of the users agreed that the content of the teaching materials is useful, indicating that the content of the teaching materials in the 3D physics laboratory is appropriate.

Learning motivation: 19% of the users strongly agreed and 51% of the users agreed, indicating that the 3D physics laboratory has a positive influence on the learning motivation of the students.

4.3. Assessment of Physics Concepts Learning

Considering the learning of physics concepts, 15% of the users strongly agreed and 50% of the users agreed that the 3D physics laboratory has a positive influence on their learning of physics concepts.

4.4. Suggestions for the 3D Laboratory in the Second Practical Test Questionnaire

The students provided some suggestions on the questionnaire, including: (1) mark the next action on the screen; (2) enhance the authenticity of the setting; (3) increase the size of the font used.

4.5. Revision to the 3D Laboratory

According to the suggestions collected in the second practical test, the researcher revised the content of the 3D physics laboratory for improvement. Figure 4 shows the 3D laboratory. The improvements are explained as follows:

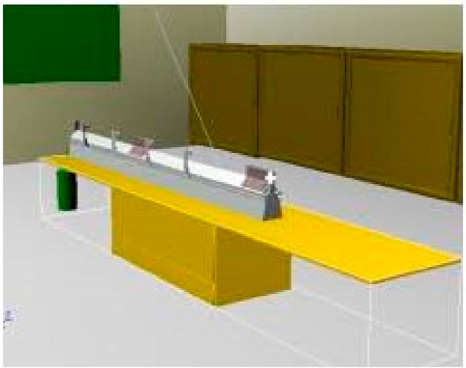

Figure 4. The 3D laboratory example.

(1) Mark the next action on the screen: Some students might ignore the instructions on the webpage, causing operating problems. Thus, in actual teaching practice, the instructor should strengthen the explanation of the operation so that users can fully understand the operation of the 3D laboratory.
(2) Improve the authenticity of the setting: Considering the operation smoothness and the network transmission convenience of the 3D physics laboratory, all the 3D objects are only presented by color, thus reducing the authenticity of the real 3D laboratory.
(3) Increase the size of the font: The size of the font was changed according to the users' suggestion.

5. Discussion

In this study, a 3D environment for teaching physics was developed. In order to assess the effectiveness of the 3D laboratory, two practical tests were conducted. The students suggested that the 3D physics laboratory positively influenced their learning attitude and their understanding of concepts of physics. They considered it to be a suitable auxiliary tool for physics experiments. In this study, Virtools software was used to construct a 3D virtual environment. However, one of its drawbacks is its steep learning curve, meaning that students need some time to understand the operation of Virtools. References in terms of books and online help are limited [33].

Han et al. [34] and Varela-Aldás et al. [35] developed VR-based learning systems for cognitive rehabilitation purposes. They implemented the spaced retrieval method for cognitive rehabilitation, but digitized the systems using immersive environments. The systems could be used to evaluate the patients' ability to retain information over time. Different universities started transforming their education-delivery methods to virtual learning. An affordance of 3D laboratories is that reality can be adapted. Students can conduct activities about unobservable phenomena with lengthy investigations [36]. Laboratory-based learning by using technology is an effective platform to supplement the theory. Students are able to conduct experiments in the virtual laboratories multiple times to review their work, test different conditions, and discuss the results [37]. Other research findings compared the effectiveness of different traditional teaching approaches with that of virtual learning, and found the learning outcomes to be close [10,38].

In this study, after practical operation, 60% of the users strongly agreed or agreed that the interface design of the 3D laboratory is user-friendly, while 67% of the users strongly agreed or agreed that the content of teaching materials is appropriate. In addition, 70% of the users strongly agreed or agreed that the 3D laboratory could arouse learning motivation, while 61% of the users strongly agreed or agreed that the 3D laboratory could improve their learning of physics concepts. The results indicate that the 3D laboratory could increase the users' learning motivation and improve the learning of physics concepts.

5.1. Operating Interface of the 3D Laboratory

The total mean of the first practical test (M = 3.60) shows that the users are satisfied with the interface design of the 3D laboratory. In the second practical test, 18% of the users strongly agreed and 42% of the users agreed that the operating interface is user-friendly. This suggests that the users are satisfied with the interface design of the revised 3D laboratory, and most users have a positive impression about the interface design of the 3D laboratory.

5.2. Content of the Teaching Materials of the 3D Laboratory

The total mean of the first practical test (M = 3.50) shows that the content of the teaching materials in the 3D laboratory is appropriate. In the second practical test, 17% of the users strongly agreed and 50% of the users agreed that the content of the teaching materials is appropriate. The findings suggest that after the revision of the 3D laboratory, the users thought that the content of the teaching materials is appropriate. The users have a positive attitude towards the content of the teaching materials in the 3D laboratory, and the arrangement and use of the content of the teaching materials in the 3D laboratory are appropriate.

5.3. Learning Motivation of the 3D Laboratory

The total mean of the first practical test (M = 3.59) shows that the 3D laboratory could arouse students' learning motivation. In the second practical test, 19% of the users strongly agreed and 51% of the users agreed that their learning motivation improved after using the 3D laboratory.

6. Conclusions

This study contributes to the existing literature regarding educational technologies and e-learning when it has been abruptly adopted as an alternative to face-to-face classes due to emergency situations, such as the COVID-19 pandemic.

This study constructed a 3D laboratory with Virtools, following the teaching activity theory. The repeated operation practice of the virtual laboratory could strengthen students' impressions, which aligns with behaviorist learning theory.

In this study, the characteristics of 3D virtual learning tools were used to develop the physics experiments and were applied in teaching. Positive outcomes were reached. The 3D laboratory provides students with a self-operating learning environment. With operating instructions and experimental records, the interaction of the users with the virtual teaching materials has been improved. The users can gain a stronger impression of the physics phenomena, indicating an obvious effect of memory preservation. In general, combining the operation and experimental equipment, the 3D laboratory allows users to experience self-learning, and obtain valuable learning experience through the simulation process. The main limitation of the study is that the assessment was only based on the students' perception of the effectiveness of the 3D laboratory. First, there were no data available to compare the students' performances with or without operating the 3D laboratory. Second, the sample size of the students who completed the surveys was relatively limited.

The 3D laboratory developed in this study has the advantages of enhancing learning interest, strengthening the learning of physics concepts, and overcoming time and space limitations. However, due to the lack of research time and funding, flaws still exist. Therefore, some suggestions are proposed as a reference for future research and development. First, the content of teaching materials could be expanded. Teaching materials for different subject units can be added to broaden the breadth of the teaching materials. Second, the 3D laboratory cannot be accessed from home. Thus, a web-based virtual laboratory that can be accessed from home can be developed for the students. Third, in future works, the acceptance and intention to use e-learning systems and assessments can be explored.

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