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# Design and Comparison of Immersive Interactive Learning and Instructional Techniques for 3D Virtual Laboratories

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# Design and Comparison of Immersive Interactive Learning and Instructional Techniques for 3D Virtual Laboratories

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**Abstract**

This work presents the design, development, and testing of 3D virtual laboratories for practice, specifically in undergraduate mechanical engineering laboratories. The 3D virtual laboratories, implemented under two virtual environments—3DTV and Computer Automated Virtual Environment (CAVE)—serve as pre-lab sessions performed before the actual physical laboratory experiment. The current study compares the influence of two instructional methods (conventional lecture-based and inquiry-based) under two virtual environments, and the results are compared with the pre-lab sessions using a traditional paper-based lab manual. Subsequently, the evaluation is done by conducting performance and quantitative assessments from students' pre- and post-laboratory performances. The research results demonstrate that students in the virtual modules (3DTV and CAVE) performed significantly better in the actual physical experiment than the students in the control group in terms of the overall experiment familiarity and procedure and the conceptual knowledge associated with the experiment.

**I Introduction**

Virtual reality (VR), as a learning environment, plays an important role in engineering education. Utilizing the VR-based learning environment as a supplement to engineering-based laboratories can be especially beneficial for students to prepare for the physical experiment and to grasp the experiment objectives and procedures. Such an environment may have positive impacts on students' learning outcomes. Students tend to pay attention in an immersive virtual environment due to an increased level of engagement, involvement, and sense of presence over a traditional paper-based lab manual setting. Therefore, this may lead to an enhanced learning experience, better memorization of the key objectives and concepts, and essentially improvements on the laboratory performance (Bailenson, Yee, Blascovich, Beall, Lundblad, & Jin, 2008). The goal is to present the physical laboratories in a VR-based practice module that would prepare students better than the current paper-based pre-lab manuals do. This would allow students to become better familiarized with laboratory experiments and be more prepared at the time of experiments, which could lead

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to less time needed to conduct the actual experiments and less wear and tear on the actual equipment. This paper presents the design and development of the 3D virtual laboratories and aims to investigate (i) whether utilizing VR learning environments such as 3DTV-based and CAVE-based engineering laboratories affect students' learning experience, and (ii) which specific VR learning environment is more effective and suitable as an optimal engineering educational tool for virtual laboratories.

## 2 Background

### 2.1 Virtual Reality (VR)

Virtual reality is an imitation of the real-world environment in a virtual space generated by computers that provides users with abilities to navigate through the virtual world and interact with virtual objects (Manetta & Blade, 1995). Modern VR technology convinces users with its visual effects, bringing them spectacular visual experiences through 3D stereoscopic displays. Other than the appealing visual effect, VR is capable of presenting information through a combination of different sensory information such as sound and touch, giving users the impression of being in the real world.

VR can be categorized into three major types based on levels of immersion: low-immersive, semi-immersive, and immersive (Ramaprabha & Sathik, 2012), depending on the user's awareness of the virtual environment. A low-immersive VR is the least immersive environment. An example is desktop VR systems, where the 3D virtual environment is displayed on a computer monitor. Users are able to interact with the virtual environment by using input devices such as a keyboard, a mouse, or a joystick. A semi-immersive VR usually contains a large screen for displaying the virtual environment. Some of the display screens can project stereoscopic vision, which allows the user to view the virtual scenes in 3D by wearing a pair of 3D glasses. Examples of semi-immersive VR include a 3D theater and a 3DTV. A full immersive VR is capable of seizing users' attention and making the physical surroundings hardly noticeable. Examples of a full immersive VR include a CAVE and a head-mounted display (HMD). A CAVE is typically a cube-shaped room with

projection screens on the front, left, and right walls. Computer-generated images or 3D scenes are projected on the walls. Users are able to interact with the virtual scene through various input devices such as a data glove or a gaming controller. An HMD is a helmet-shaped display device that can be worn on the head with data glasses in front of the eyes, providing full immersive experiences and isolating any visual contacts from the outside world.

### 2.2 Immersion

Immersion is a psychological state where one's awareness of the physical surroundings is isolated by the engrossing environment. The level of immersion in a VR system is measurable, and heavily dependent on the rendering software and types of sensory displays. The visual level of immersion measures the realism of the virtual environment (VE) system visual output to the real-world visual stimuli (Bowman & McMahan, 2007). Compared to other senses of immersion such as hearing, smell, and touch, the visual level contributes significantly to the overall level of immersion (Ramaprabha & Sathik, 2012). Field of view, display size and resolution, stereoscopy, realism of lighting, and frame rate are examples of key components in visual level (Bowman & McMahan, 2007). Other important factors that affect the overall level of immersion include the isolation of the participants in the virtual environment from the physical environment, participants' perception of feeling part of VE, interaction and control perception, and participants' perception of self-movement (Witmer & Singer, 1998). Since immersion is measurable, one system can have a higher level of immersion than another depending on the aforementioned factors (Bowman & McMahan, 2007). For instance, a desktop VR system with a 3DTV as the visual display has a higher level of immersion than a desktop VR system with an LCD computer monitor does due to the stereoscopic image displayed by the 3DTV, which increases the realism of the visual effects significantly. Although the 3DTV and the CAVE are equally capable of projecting stereoscopic images on the screen, the CAVE produces a higher level of immersion due to its larger field of view, which offers the partici-

pants a more vivid immersive experience by projecting the stereoscopic images on multiple walls.

Immersion deals with the amount of real-world awareness in a virtual environment. Less awareness of the actual physical surroundings leads to a higher degree of immersion in the virtual environment. According to Bowman and McMahan (2007), immersion can provide potential benefits in spatial understanding. These two researchers suggested that the human brain can reconstruct 3D scenes actively although “human vision only senses the 2D projection of the environment.” This leads to exploitation of the depth cue, which is the ability to perceive the world in three dimensions visually.

### **2.3 VR Applications in Engineering Education and Training**

With the recent maturation of VR technology, applications in VR have offered numerous innovative and effective methods for information communication and virtual training. Many researchers have shown the benefits of using VR as an effective learning and training tool for engineering and science students as well as working professionals. Unlike conventional learning methods such as reading textbooks or listening to the instructor, VR may lead to more interactions, engagements, and collaborations, motivating students to learn with more enthusiasm.

Bell and Fogler (1998) demonstrated the use of a 3D interactive VR based simulator Vicher I and Vicher II (Virtual Chemical Reactors module) in preparing chemical engineering students for understanding the topics of catalyst deactivation and non-isothermal effects, respectively, in chemical reaction engineering. Dede, Salzman, and Loftin (1996) discussed the development of the “ScienceSpace,” which is a collection of virtual worlds designed to aid students in learning more complex and abstract scientific concepts. Goldberg and McKhann (2000) conducted a study on the effectiveness of delivering the course material of an undergraduate introduction to a neuroscience course at Johns Hopkins University through a multimedia software application as the virtual learning interface. Seevinck, Scerbo, Belfore, Weireter, Crouch, Shen, et al. (2006) developed a simulation-

based virtual training system for surgical wound debridement. The goal of this system was to provide a virtual training platform for the health care providers to perform a surgical debridement procedure on an injured human leg with a force-feedback haptic device. Sampaio and Henriques (2007) used VR models on the visualization of construction activities in civil engineering education. Such virtual models can assist students by visually simulating the construction activities, thus helping students better understand the construction sequences and building structures. Wang, Cui, Yang, and Lian (2009) presented the use of a VR learning module to help undergraduate engineering students master abstract mathematical concepts. Shanku, Sharko, and Prifti (2011) introduced an interactive virtual lab module for the electrical power system engineering class as pre-lab exercises before performing the lab experiments. The authors observed that the virtual module provided students with hands-on experience and helped them understand fundamental power system concepts better. Peniche, Diaz, Trefftz, and Paramo (2011) developed an immersive virtual training system for mechanical assembly. Users were able to go through the training process by interacting with the virtual system using stereoscopic vision and optical tracking. The system proved to be as effective as the traditional training method. All of these systems showed that with the help of VR, students are able to gain hands-on experience and understand complex engineering concepts better.

### **2.4 Virtual Learning Environment**

Virtual learning environment (VLE) refers to a set of computer-based learning tools designed to specifically support and enhance teaching and learning experiences in educational settings (d’Entremont, 2004). The VLE provides learners with unique experiences in learning and absorbing information through multimedia tools, allowing them to interact with the virtual learning scenes by engaging multiple sensory channels including visual, audio, and touch. For instance, an HMD projects digital images on the data glasses attached to the device, bringing participants potentially spectacular visual experiences. Surrounding speakers help to project the sound

coming from the VLE, allowing participants to receive information via the aural senses. Input devices such as data gloves allow participants to interact with the virtual objects in the virtual environment.

VLE supports active learning by not only improving the depth of learning, but also enhancing the entire learning experience by triggering interactions between students and the virtual environment. Active learning is defined as an educational process where high levels of learning interactions and mental involvement are initiated by the learner. Major characteristics of active learning techniques include learners' engagement in activities such as reading, writing, and discussion; more development of learners' learning skills rather than plain information transmission; emphasis on exploration of attitudes and values; enhancement of students' learning motivation; ability to receive immediate feedback from the instructor; and involvement in higher-order thinking such as analysis and evaluation (Bonwell & Eison, 1991).

In classroom settings, these attributes can be gradually developed through the following activities: class discussions, collaborative learning groups, in-class interactive games, and short writing exercises. In general, students' engagement in the learning process can range from passive to moderately active to very active (Cuseo, n.d.). For example, passive learners are unlikely to pay attention and become involved in discussions whereas moderately active learners are more mentally engaged with the learning materials and focus only when the instructor addresses something important. The highly active learners not only listen to the instructor attentively, but also demonstrate a high level of involvement in class participations (e.g., peer discussion, asking questions, and collaborative in-class projects). In summary, learners are more likely to be actively involved in learning materials with writing, speaking, and use of information technology rather than just listening (e.g., web-based interactive material and virtual learning tools) (Cuseo, n.d.).

Compared to conventional classroom settings, the characteristics of active learning can also be achieved in virtual learning environment settings. Information can be presented dynamically with animation and sound, thus seizing learners' attention easily. In addition, stu-

dents are able to interact with given virtual agents such as listening to instructions, asking questions, and receiving immediate feedback. A collaborative virtual environment (CVE) is a computer-generated virtual space shared by multiple participants across the network (Benford, Greenhalgh, Rodden, & Pycock, 2001). The CVE offers participants a great opportunity to learn and work as a team. Through CVE, participants are able to interact and communicate with each other. This allows them not only to gain learning experiences, but also to practice social skills, a feature that is an integral part of learning within teams, such as in participating on team projects.

The VLE is developed based on the constructivism theory to teach active construction of the environment (Bricken, 1990). Constructivism is a learning theory developed for improving learning and instruction. Its primary objectives are to (i) trigger learning motivated by understanding the nature of learners and (ii) identify the role of the instructor as a facilitator rather than an information transmitter. Constructivism puts the learner in an active learning mode. The theory suggests that learners are essentially the active agent of knowledge construction, and their learning outcomes are directly related to their participation, engagement, and interaction during the learning process (d'Entremont, 2004). Thus, the learner actively participates in defining knowledge instead of passively receiving knowledge.

The VLE enables students to learn through interactions and collaboration with others. In other words, rather than learning through symbolic abstractions, the VLE serves as a knowledge facilitator and provides dynamic interactions between the learner and the learning task. Consequently, instead of learning through passively receiving the information, learners focus on construction of knowledge from "learn-by-experience."

## 2.5 Instructional Methods

Instructional methods are typically used to facilitate students' learning by selecting the techniques that most appropriately match the learning objectives and subject materials. Prior to selecting the appropriate method of instruction, instructors must fully understand the teaching materials and resources available to support

**Table 1.** *Instructional Methods (Reigeluth, 1999)*

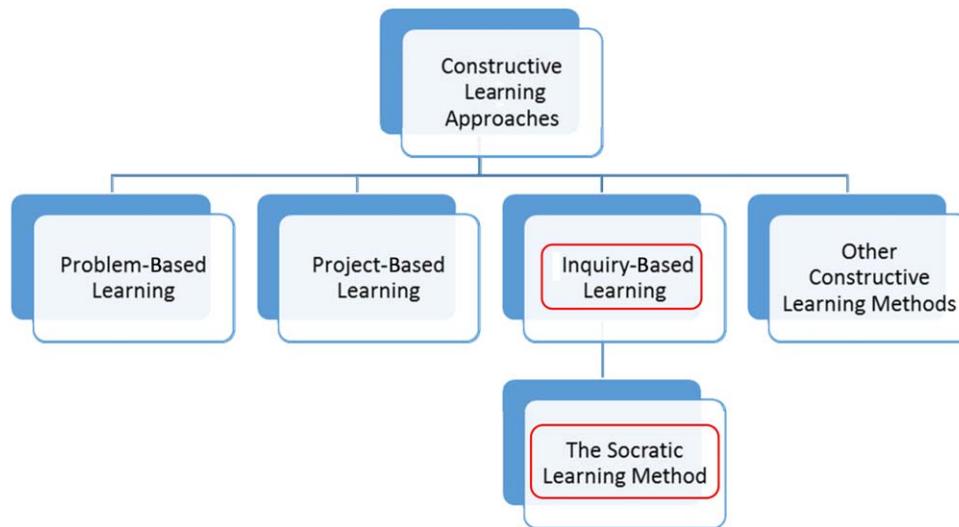
Method	Strength
Lecture/presentation	Efficient, standardized; Structured
Demonstration/modeling	Eases comprehension; Application
Tutorial	Customized; Learner responsible
Drill and practice	Automatized; Mastery
Independent/learning control	Flexible implementation
Discussion, seminar	Meaningful, realism, owned, customized to learner
Cooperative group learning	Ownership; Team-building
Games	
Simulations	
Discovery	High transfer
• Individual	High motivation
• Group	
Problem solving/lab	High level thinking in ill-structured problems

the subject matter. The following paragraphs present a few suitable instructional methods that are used in virtual laboratory settings such as the simulation instructional method, the inquiry-based method, and the Socratic method.

The simulation instructional method uses the VLE, offering interactive learning in a simulation-based environment. This method helps students explore and investigate learning objectives and concepts actively, and thus it is especially useful in engineering laboratory environments. Reigeluth (1999) summarized a table of instructional methods (shown in Table 1), suggesting that the simulation instructional method provides high transfer of knowledge from the virtual to real context and high motivation from the learner.

The inquiry-based method, by definition, is an instructional method “that combines the curiosity of students and the scientific method to enhance the development of critical thinking skills” (Warner & Myers, 2008). Inquiry-based teaching places the student in the role of the investigator. The National Academy of Science has suggested that when students engage in inquiry-based learning, they “(i) question, (ii) investigate, (iii) use evidence to describe, explain, and predict, (iv) connect evidence to knowledge, and (v) share findings” (Warner & Myers,

2008; National Science Education Standards, 1996). Similar to the inquiry-based instructional method, the Socratic method, named after the classical Greek philosopher Socrates, is an instructional method implemented by a series of questions and answers. Hyman (1970) suggests that implementing an instructional method in a constructivist approach may stimulate learners’ memory. When learning under the Socratic method, students go through a four-step approach: “(i) elicit relevant preconceptions, (ii) clarify preconceptions, (iii) test one’s own hypothesis and propositions, and (iv) decide whether to accept the hypotheses or propositions” (Lam, 2011). According to Lam’s research thesis, the inquiry-based method has no clear set of rules or guidelines of what kinds of questions can be asked in the process. By contrast, the Socratic method is more systematic in that it can lead to certain types of questions (Lam, 2011). Lam also suggests that the Socratic method belongs to a branch of the inquiry-based learning/instructional method (shown in Figure 1) since the Socratic method is one of the earliest learning/instructional methods through inquiry; whereas the inquiry-based learning/instructional method is categorized as one of the branches in the constructivist approach (Lam, 2011). Consequently, both learning/instructional methods fell



**Figure 1.** Learning/Instructional methods classification (Lam, 2011).

into the category of constructivism. Compared to the conventional instructional methods, where students learn by completing a series of tasks without much interaction with the teacher, the inquiry-based/Socratic method not only puts students in the learning process actively, but also helps clarify obscure concepts. More importantly, from Çelik's research, the Socratic method is believed to stimulate the learning memory from back-and-forth concentrated question-and-answer sessions (Çelik, 2007; Hyman, 1970). Thus, by implementing the inquiry-based/Socratic method in the virtual laboratory setting, it is possible to enhance students' memorization of the experimental procedure as well as the lab equipment components.

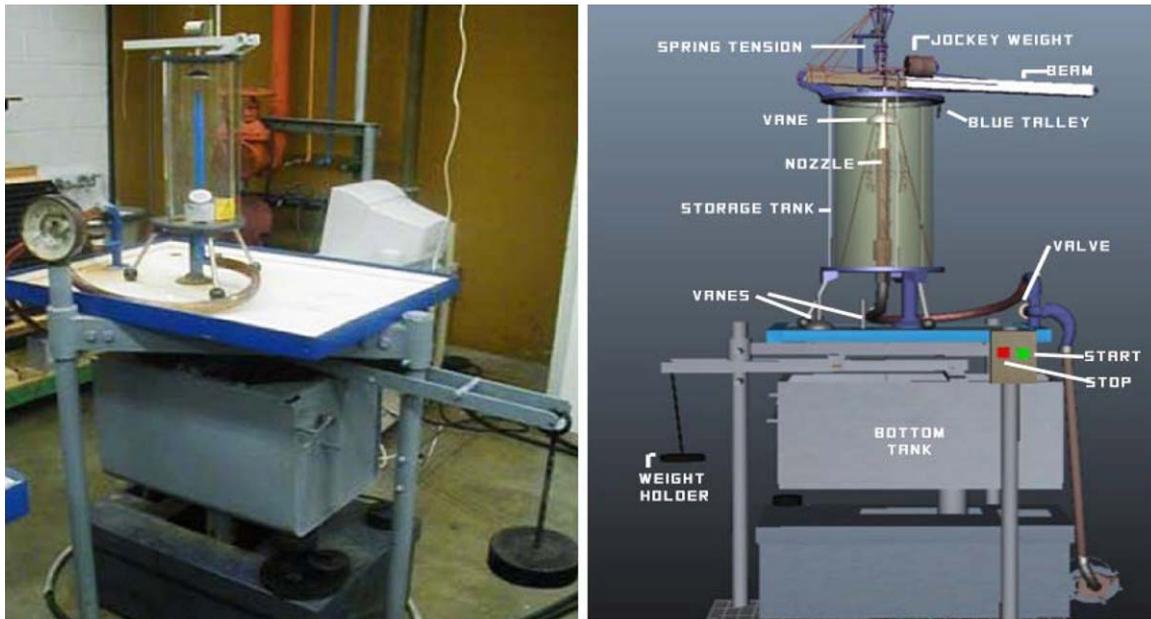
### 3 Virtual Lab Implementation

#### 3.1 Laboratory Experiment

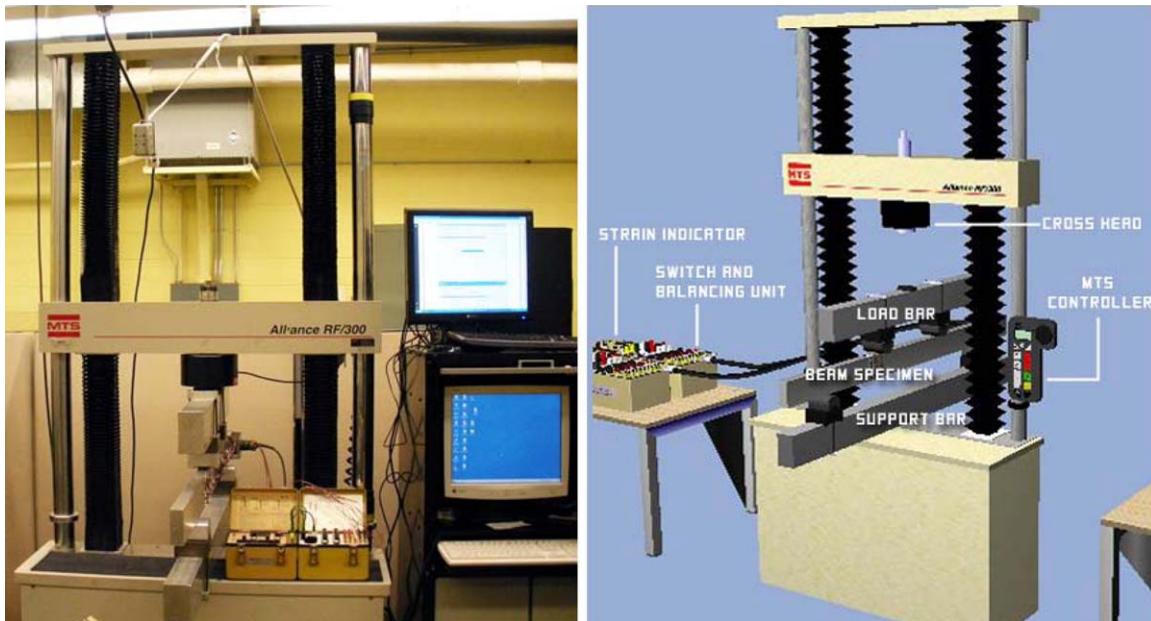
The Jet Force Experiment, from the junior level lab course ME 305 Thermal-fluids Laboratory at Old Dominion University, demonstrates the reactions of the jet impact force from a water jet hitting various shapes of target vanes. The relationship is described as the equation " $F = Cm^m$ ", where the letter  $F$  represents the impact force,  $m$  represents the mass flow rate, and  $C$  represents the type of vane. Initially, a type of vane, which

includes a flat shaped vane, a funnel-like shaped vane with a narrow mouth, and a funnel shaped vane with a relatively wider mouth (all vanes have narrow stems), is attached to a jockey sliding weight beam mounted on top of the cylindrical lid. Water is discharged through a nozzle inside the transparent cylindrical storage tank to form a jet, which has impacts on the vane. The flow rate of the water can be adjusted through a valve in low, medium, and high settings. As the flow rate changes, the force deflects the beam from the horizontal position. Thus, the jockey weight can be slid along the beam to bring it back to the horizontal position, which is indicated by a blue tally mark. As water continues to impact the vane, it falls to the bottom tank for recirculation. Mass flow rate then can be measured through a stopwatch by collecting a given amount of mass over time. The experiment can be repeated with other shapes of vanes for several mass flow rates.

The Beam Bending Experiment, as part of the lab experiments in a sophomore level laboratory course ME 225 Solid Mechanics Laboratory, studies the variation of the axial strain through various depths of an aluminum beam and compares the experimental strain values with the assumptions made in bending theory. In the physical set-up, a four-foot long beam specimen with cross section of  $4'' \times 1.5''$  is loaded in between a support beam



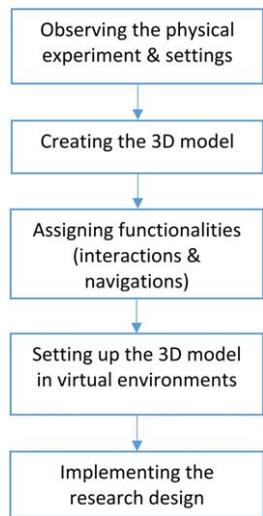
**Figure 2.** Comparison of the physical vs. virtual models of the Jet Force Experiment.



**Figure 3.** Comparison of the physical vs. virtual models of the Beam Bending Experiment.

and load beam. There are fourteen strain gages mounted on the surface of the beam specimen at various depths (side, top, and bottom). Students are asked to initialize and balance all fourteen gages through a strain indicator

and a switching and balancing unit. Next, 2000 lbs of weight is loaded on the beam, followed by a 4000-lb load. At each load, the strain values are recorded. Figures 2 and 3 illustrate the comparisons of the physical model



**Figure 4.** *The implementation process of a 3D interactive virtual lab.*

and the 3D model for both the Jet Force and Beam Bending Experiments. The video tutorials for both virtual experiments can be found through the website [www.mem.odu.edu/virtualreality](http://www.mem.odu.edu/virtualreality) (the most recent Adobe Flash Player must be installed to view the video tutorials).

### 3.2 Implementation Process

Building a 3D interactive virtual laboratory consists of five design steps including (i) observing the physical experiment settings and understanding the experiment procedure, (ii) building the 3D model of the physical laboratory setup via computer modeling software, (iii) making the 3D model interactive and navigable by adding animations and enabling input device controls, (iv) implementing the finished product on different virtual environments such as a desktop computer, a 3DTV, or the CAVE for higher levels of immersive experience, and lastly, (v) applying research design for statistical analysis. Figure 4 summarizes all the essential steps of the mapping process of a physical laboratory to a virtual laboratory in a flowchart.

### 3.3 3D Modeling and Texturing

It is important to first understand the lab procedure, be familiarized with the functionalities of each

equipment component, and obtain the dimensions of physical equipment before the modeling and texturing task takes place. Completion of the 3D model prototype typically requires two steps: modeling and texturing. 3D modeling refers to the process of constructing an object represented by a collection of points in three-dimensional space. With the help of 3D modeling software such as AutoCAD MAYA and Google SketchUp, any physical objects can be modeled through a mixture of modeling techniques including polygonal modeling and non-uniform rational B-spline (NURBS) modeling. Polygonal modeling is typically used to model 3D components with straight edges and surfaces, whereas NURBS modeling is appropriate for modeling objects with curvy shapes such as wires and cables. Texturing involves the process of texture mapping, which wraps 2D images around surfaces of 3D objects, enhancing the realism on 3D object texture. Overall, modeling provides the bone structure of a 3D object, and texturing gives the 3D object “skin.” The completed 3D model can be imported to gaming engines such as Unity 3D or Virtools for further animation and interaction developments.

### 3.4 Assigning Functionalities

The advantage of a 3D virtual lab over 2D is that the user has the ability to observe the experiment set-up from different viewing angles by rotating the viewing cameras. This offers participants additional interactions, navigations, and realistic experiences so they can examine the experiment procedure in close detail. Building such interactions and navigations for the 3D model requires programming various functionalities in Virtools. This includes two major parts: assigning behavior functions to 3D objects and selecting a proper input device for user interaction.

**3.4.1 Assigning Behavior Functions in Virtools.** Building Blocks (BBs), serving as behavior functions, are pre-written in a Virtools library that allows developers to assign any behaviors such as linear translation, rotation, and scaling to the 3D objects. Developers can drag and drop the BBs to the 3D objects to assign

the specific animation/behavior that they desire. In addition, creating multiple camera views allows the developer to observe the same 3D scenes from different perspectives and viewing angles. Functionalities in the physical experiment can be mapped to the 3D model by applying a mixture of different behavior functions. For instance, if the actual physical equipment has a button that turns on the LED display, the developer can implement that same functionality for the 3D model by assigning related behavioral functions to the 3D button accordingly so that it performs the identical task on the virtual model.

**3.4.2 Input Device Mapping.** The input device builds the interactions between the human and the computer. The typical Human Computer Interface (HCI) input devices are keyboards, mice, and joysticks. The Xbox controller is selected as the input device for the 3D virtual laboratory because of its software compatibility and low cost. Input device mapping is the process of assigning a particular task or command to a respective button or a gesture on a specific input device. Examples may include assigning a button on a joystick for “using/selecting” a particular virtual object or assigning the directional pad on a gamepad for navigation purposes. The mapping process is not only limited to buttons and keys mapping, but is also associated with motions and gestures mapping, depending on the properties of the input device. Examples of motion/gesture controllers include Wii Remotes and data gloves, which can map gestures to commands. Once the mapping process is completed, the input device can be used to interact with the virtual scene. Table 2 shows an example of the mapped buttons on the Xbox controller for the Jet Force and the Beam Bending Experiments.

### 3.5 Configuring the VR System

A VR system consists of software and hardware components. *Software components* may refer to engines or platforms that run the 3D virtual module, whereas *hardware components* refers to physical parts such as display monitors and input devices. The implementation of the VR system is a process of configuring the 3D virtual

**Table 2.** Mapped Buttons on the Xbox Controller for Both Virtual Experiments

Jet Force Experiment	
Button	Description
A (green button)	Select/use
Left thumbstick	Move cursor
Start	Complete view
Up	Jockey view
Right	Tank view
Left	Valve view
Down	Handle view
Beam Bending Experiment	
Button	Description
B (red button)	Increase value
X (blue button)	Decrease value
A (green button)	Select/use
Left thumbstick	Move cursor
Right thumbstick	Zoom in/out, move left/right
Left bumper	Previous camera view
Right bumper	Next camera view

module on a specific displaying device. The 3D virtual laboratory modules in this research study are implemented in two VR systems, namely the 3DTV VR system and the CAVE VR system.

**3.5.1 Setting up the 3DTV VR System.** The VR engine (in this case Virtools) carries the developed 3D virtual module and runs on a main computer, which acts like a command center for the entire 3DTV VR system. The 3DTV is connected to the HDMI port on the graphic card of the host computer with an HDMI cable, which is necessary for enabling the stereoscopic images on the 3DTV. Users are able to interact with the 3D virtual laboratory through an input device such as an Xbox controller connected to the USB port of the host computer. A pair of 3D glasses allows users to view stereoscopic images on the TV screen. The sound system, including a set of 2.1 stereo speakers, can be connected with the



**Figure 5.** *The 3DTV VR system.*

host computer to project surrounding sound. Figure 5 shows the 3DTV VR system hardware components.

The 3DTV VR system set-up process involves exporting the finished 3D virtual module in Virtools to a .vmo file, which can be run on most of the Internet browsers such as IE, FireFox, or Google Chrome. However, the 3DVIA player plug-in needs to be pre-installed. The .vmo file and related sound files are placed in the same file folder. Users can run the 3D virtual module by loading the .vmo file to a web browser. Lastly, the display option on the 3DTV should be set to 3D stereoscopic display.

**3.5.2 Setting up the CAVE VR System.** The projection screens in the CAVE consist of three projection walls with dimensions of 12"  $\times$  9.5" and four projectors projecting the front, left, and right walls as well as the floor. These projectors are connected to dual graphic card ports on a computer workstation. In addition, this workstation controls the audio system and runs the VR engine, which contains the VR library and the VR pack. Similar to the 3DTV VR system, a wireless Xbox controller is connected to the workstation for user interaction. Figure 6 shows the CAVE VR system hardware components.

### 3.6 Virtual Lab Interface

The interface of the virtual Jet Force and the Beam Bending Experiments are illustrated in Figures 7 and 8, respectively. The 2D cursor on the screen serves as a pointer. Users are able to move the 2D cursor anywhere within the display frame by using the left thumbstick of the Xbox controller. Once the 2D cursor intersects with a certain 3D virtual object, users can interact with the 3D object by pressing the select button (button "A" on the Xbox controller). More controller button mapping detail information for the two virtual labs can be found in Table 2.

## 4 Study I: Jet Force Experiment

### 4.1 Research Design

The Study 1 research design consists of quantitative and performance assessments based on students' performance in the Jet Force Experiment. The quantitative assessment contains the statistical analysis of students' performance on the post-quiz while the performance assessment uses subjective judgments on students' actual lab performance through direct observation and post-experiment survey questionnaires.



**Figure 6.** The CAVE VR system.



**Figure 7.** The Jet Force Experiment interface.

The MAE 305 Thermo-Fluids Lab had three sections (Monday morning, Wednesday afternoon, and Wednesday evening). Each section was divided into three small student groups, each with four or five students who

rotate through a number of other laboratory experiments throughout the semesters. The experiment was implemented in three different learning environments, as pre-lab sessions prior to the actual physical experiment:



**Figure 8.** *The Beam Bending Experiment interface.*

(1) the traditional paper-based lab manual session, (2) the VR session on the 3DTV, and (3) the VR session in the CAVE. Students from all learning settings are required to perform the actual experiment followed by a post-quiz a week after the pre-lab session.

**4.1.1 Quantitative Assessment.** Participants were given a 20-minute post-quiz right after the completion of the physical lab experiment. The post-quiz consisted of 13 multiple choice questions, which were based on the experiment procedure and fundamental theories. The post-quiz results were used to determine whether the virtual experiment modules contributed to the enhancement of the learning effectiveness by students.

**4.1.2 Performance Assessment.** Direct observation data were collected by the teaching assistants (TA) while students were performing the physical experiment. The direct observation was designed based on the overall familiarity with the experimental procedure as well as two main observatory components of (1) Balancing Jockey Weight over the Beam and (2) Mass Flow Rate Determination during the experiment, based on the Likert scale of 1 to 5 (1 = least familiar and 5 = very familiar). In Task Component 1, students were asked to balance the deflected beam due

to the impact of the water jet by sliding the weight to a proper position. In Task Component 2, which is also the last step of the experiment, students were asked to measure the mass flow rate with a stopwatch by collecting a given amount of mass over time. Other than observing the task components, both group kinetic data and time lapse measurement were collected. The kinetic data determines the levels of students' engagement. Alpha students appear to be more actively involved in given tasks while beta students stay on the passive side and have less involvement. Time lapse measurement was not to determine improved speed of completing the experiment, but to show performance advantage in time with one group over another (i.e., faster or not faster).

## 4.2 Participants

There was a total of 193 students who participated in the Jet Force Experiment throughout four school semesters (semesters A, B, C, and D). The Monday morning section (a total of 68 students, also known as the control group) practiced the pre-lab session using the traditional paper-based lab manual prior to the physical experiment. The Wednesday afternoon section (a total of 75 students, known as the 3DTV group) practiced the pre-lab session using the virtual modules on the

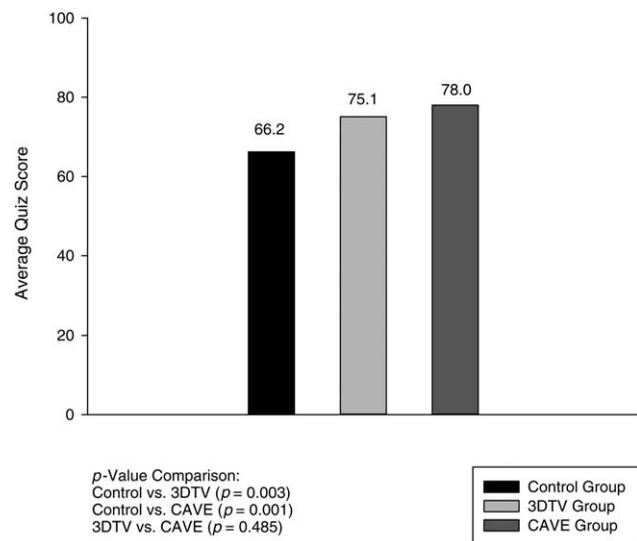
3DTV prior to the physical experiment. Lastly, the Wednesday evening section (a total of 50 students, known as the CAVE group) practiced the pre-lab session using the virtual experiment in the CAVE prior to the physical experiment. It is worth mentioning that that students were pre-screened as to the level of their computer/technology/gaming literacy, so that each group was balanced with a similar portion of students in terms of computer literacy level. The same pre-screen procedure was done in Study 2.

### 4.3 Procedure

Students who participated in the virtual modules (3DTV and CAVE) from one school semester were trained by the conventional instructional method. Students had approximately five minutes to review the virtual lab experiment tutorial guide that shows the step-by-step experiment procedure handed out by the TA at the beginning of session. Next, each student completed the virtual lab experiment in rotation under the guidance of the TA. The learning roles of students with the conventional instructional method were intended to be passive. Students from another school semester were trained by the inquiry-based instructional method, which involved not only the experiment guidance, but also a series of questions from the TA regarding the information that they read from the tutorial guide, such as general lab procedure and lab equipment component, before they started the virtual experiment. The tutorial guide provided to students was the same for both conventional and inquiry-based instructional methods. Both virtual module groups as well as the control group were asked to perform the experiment on the actual equipment a week after the pre-lab session, followed by a post-quiz.

## 4.4 Results

**4.4.1 Quantitative Assessment Result.** The quiz results from semesters A, B, C, and D were analyzed by a Mann-Whitney U test using the statistical analysis software SPSS to compare mean quiz score differences among all three learning settings. It was assumed that the dependent variable (quiz score) is not normally dis-

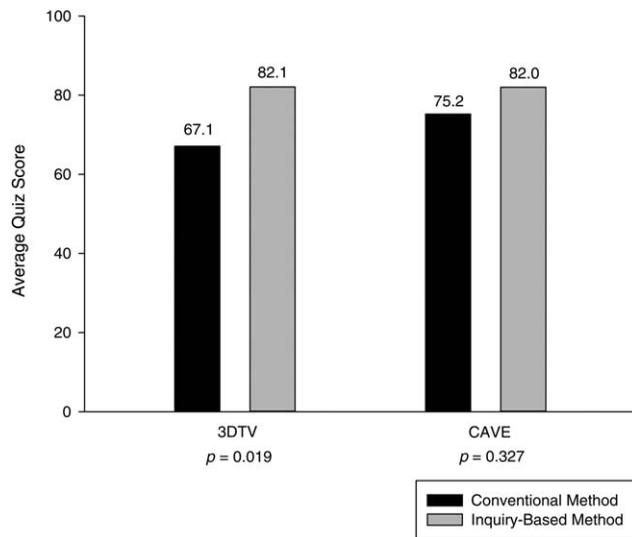


**Figure 9.** Mean quiz score comparisons among student groups.

tributed. To assess the learning setting differences, the level of significance was set at  $p < 0.05$ . Significant effects ( $p = 0.003$ ,  $p = 0.001$ ) were found between the control ( $n = 68$ ,  $M = 66.2$ ,  $SD = 19.9$ ) and the 3DTV groups ( $n = 75$ ,  $M = 75.1$ ,  $SD = 18.0$ ), as well as between the control and the CAVE groups ( $n = 50$ ,  $M = 78.0$ ,  $SD = 14.8$ ). There were no significant effects ( $p = 0.485$ ) found between the 3DTV and the CAVE groups. Results are illustrated in a chart in Figure 9.

To determine the more effective instructional method, another Mann-Whitney U test was done by categorizing students' quiz scores from semesters A and B only (instructional methods from semesters C and D were not used) in terms of the two instructional methods and comparing their mean score differences. Figure 10 illustrates the comparison results under the 3DTV and the CAVE setting. A significant effect ( $p = 0.019$ ) was found when comparing the procedure ( $n = 17$ ,  $M = 67.1$ ,  $SD = 19.0$ ) and inquiry-based methods ( $n = 19$ ,  $M = 82.1$ ,  $SD = 13.6$ ) in the 3DTV learning setting. However, no significant ( $p = 0.327$ ) difference was found by comparing the procedure ( $n = 21$ ,  $M = 75.2$ ,  $SD = 17.2$ ) and inquiry-based methods ( $n = 10$ ,  $M = 82.0$ ,  $SD = 9.2$ ) in the CAVE setting.

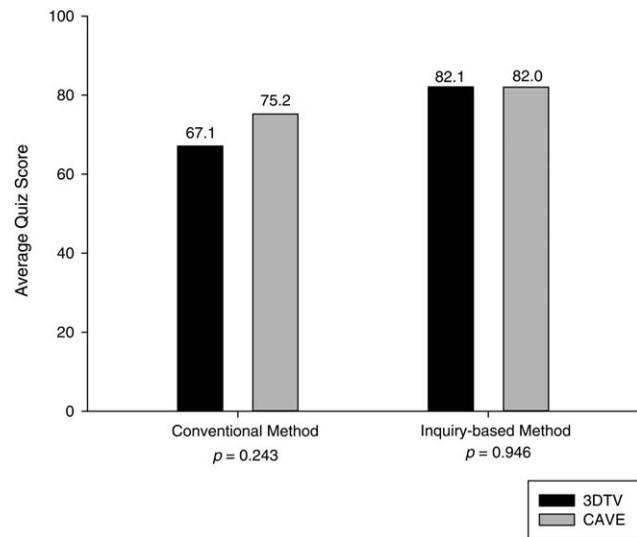
The sample statistical analysis was used to compare the same instructional method under different learning set-



**Figure 10.** Mean quiz score comparisons (conventional vs. inquiry-based method) in the 3DTV and the CAVE settings.

tings. It was observed that no significant effects were found when comparing the procedure-based method ( $p = 0.243$ ) and the inquiry-based method ( $p = 0.946$ ) between the 3DTV and the CAVE settings. Figure 11 describes the outcome.

**4.4.2 Performance Assessment Result.** Direct observation data were collected from only three semesters (A, B, and C). It was observed that the 3DTV (scale 3.79/4.13) and the CAVE groups (scale 3.23/3.43) have slightly higher Likert Scale scores in the two main observation factors than the scores of the control group (scale 1.79/2.46). In addition, students from the 3DTV group (13.60/19.13 s) spent the least average time completing the given tasks, achieving 29.42%/8.16% faster time than the control group (19.27/20.83 s) and 53.90%/33.81% than the CAVE group (29.50/28.90 s). This indicated that students from the 3DTV group appeared to be more familiarized with the laboratory materials and procedures than students in other groups. The group kinetics implied that there were more alpha and fewer beta students in both virtual module groups, while the control groups had fewer alpha and more beta students. It was also suggested that more engagement was involved in the virtual module groups. Nevertheless, although the Likert Scale values of the two virtual mod-



**Figure 11.** Average quiz score comparisons in terms of the same instructional methods under different settings.

ule groups were higher than the values of the control group, it was unexpected to see that the CAVE group performed the worst in terms of the time spent on the tasks. We believe this was caused by an outlier in the CAVE group, where one of the students had some difficulties in navigating in the virtual environment. From the general comments, a greater amount of interaction among the group members and higher levels of involvement appeared to occur more frequently in the 3DTV and CAVE groups compared to the control groups. Results are summarized in Table 3.

## 5 Study 2: Beam Bending Experiment

### 5.1 Research Design

The research method for the Beam Bending Experiment in the laboratory course MAE 225 Mechanics of Solids Lab was done in a similar fashion to the Jet Force Experiment. The laboratory class had one section in semesters A and B. Similar to the group division in the Thermo-Fluids lab, the section was divided into three small groups with five students in each group. The experiment was implemented in three different learning environments: (1) traditional paper-based lab manual prior to the physical experiment, (2) prior VR session on

**Table 3.** Direct Observation Data Table (Jet Force Experiment)

	Task	Control <i>n</i> * = 9	3DTV <i>n</i> = 9	CAVE <i>n</i> = 9
Average Likert Scale* (1–5)	(1) Balancing Jockey Weight over the Beam (2) Mass Flow Rate Determination	1.79 2.46	3.79 4.13	3.23 3.43
Average Time Elapsed (s)	(1) Balancing Jockey Weight over the Beam (2) Mass Flow Rate Determination	19.27 20.83	13.60 19.13	29.50 28.90

\**n* = total number of sections, Likert Scale (1 = Lowest, 5 = Highest)

the 3DTV plus posterior physical experiment, and (3) prior VR session in the CAVE plus posterior physical experiment.

**5.1.1 Quantitative Assessment.** Participants from three learning groups were given the pre- and post-quiz an hour before and after the actual physical experiment. Both pre- and post-quizzes consisted of the same free response questions with the maximum score of 16 points, which were mainly based on the experiment procedure, lab equipment components, and fundamental theory behind the Beam Bending Experiment. The pre- and post-quiz results were used to determine whether the virtual experiment modules have a positive impact on students' learning.

**5.1.2 Performance Assessment.** Direct observations were conducted on all three groups from each section while students were performing the physical experiment. Direct observation was designed based on the overall familiarity with the experiment procedure as well as two main observatory components of (1) Connecting Color-coded Wires and (2) Balancing/Calibrating Gages for the Experiment during the experiment, based on the Likert Scale of 1 to 5 (1 = least familiar and 5 = very familiar). In Task Component 1, students were asked to connect color-coded wires from 14 strain gage channels on the beam specimen to the switch and balancing unit. The wire from each strain gage channel has three color splits (red, white, and black). Students need to identify which wire color goes to which connector (P+, D, or S-) on the switch and balancing unit. The next task component asks students to balance each

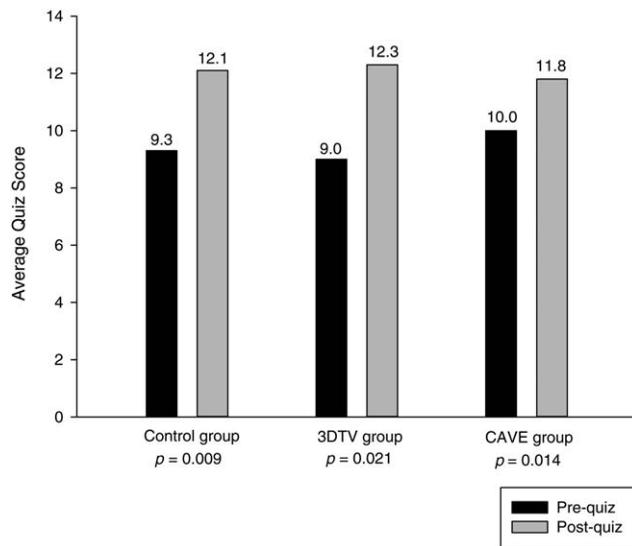
strain gage channel value to zero. Students need to go through each channel by rotating the channel knob, and then balancing each strain gage value to zero by rotating the balancing knob. On top of collecting the observation data, both group kinetic data and time lapse measurements were collected. Kinetic data determine the levels of students' engagement. Alpha students appear to be more actively involved in the given tasks while beta students stay on the passive side and have less involvement.

## 5.2 Participants

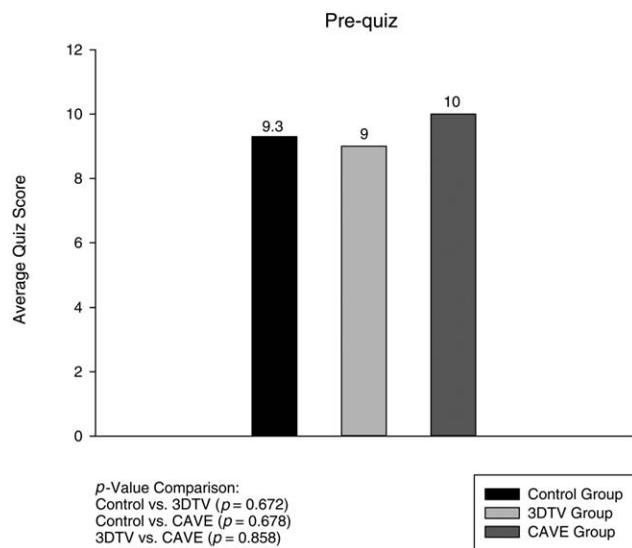
A total of 30 students participated in this experiment. Fifteen active students in each section were formed into three equal-sized groups for semesters A and B. The control group practiced the pre-lab session using the paper-based lab manual prior to the physical experiment. The 3DTV and CAVE groups practiced the pre-lab sessions using the virtual modules on the 3DTV and the CAVE, respectively, prior to the actual lab experiment.

## 5.3 Procedure

Students were asked to attend the pre-lab first. The control group studied the paper-based lab manual while the virtual module groups prepared the pre-lab from the virtual environments in a similar fashion as it was done in Study I. The only significant difference was the additional pre-quiz, which was used to measure the amount of students' pre-existing knowledge on the lab materials. All students were asked to take a pre-quiz and a post-quiz an hour before and after the actual lab experiment, respectively. The evaluation then was done a week after the actual lab experiment. Due to the relatively small

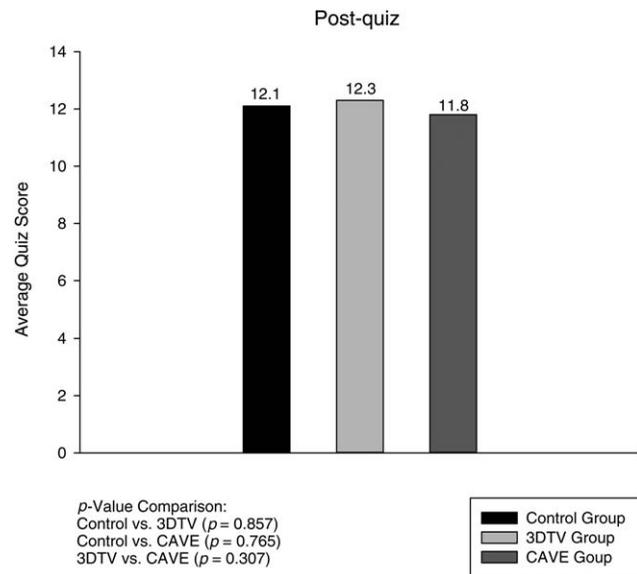


**Figure 12.** Test statistics and p-value comparison of average pre- and post-quiz scores ( $\alpha = 0.05$ ).



**Figure 13.** Test statistics and p-value comparison of mean pre-quiz scores ( $\alpha = 0.05$ ).

sample size, students from the 3DTV group were instructed only through the conventional instructional method, while students from the CAVE group were trained only through the inquiry-based instructional method. Comparing the conventional method in the 3DTV group with the inquiry-based method in the CAVE group would be incomparable to and inconsistent with what we did in Study 1. Thus, comparing the effec-



**Figure 14.** Test statistics and p-value comparison of mean post-quiz scores ( $\alpha = 0.05$ ).

tiveness of instructional methods will not be studied in this experiment.

## 5.4 Results

**5.4.1 Quantitative Assessment Result.** The results were analyzed by the Wilcoxon Signed-Rank test, which is equivalent to the dependent  $t$ -test, by using the statistical analysis software SPSS to compare mean differences between the pre- and post-quiz scores. It was assumed that (1) the dependent variable (quiz score) is not normally distributed, and (2) the independent variable consists of matched pairs (pre- and post-quiz from the same group). To assess whether there were significant improvement in the quiz scores, the level of significance was set at  $p < 0.05$ . Significant effects were found from all three learning settings (control group:  $p = 0.009$ , 3DTV group:  $p = 0.021$ , and CAVE group:  $p = 0.014$ ) when comparing the mean scores between the pre- and post-quiz. Results are illustrated in Figure 12.

Next, the average pre- and post-quiz scores were compared among three learning settings using the same statistical method. Figures 13 and 14 illustrate the comparisons results respectively. No significant effects were found in any cases.

**Table 4.** Direct Observation Data Table (Beam Bending Experiment)

	Task	Control <i>n</i> * = 2	3DTV <i>n</i> = 2	CAVE <i>n</i> = 2
Average Likert Scale* (1–5)	(1) Connecting Color-Coded Wires	3.5	3.5	4.5
	(2) Balancing Gages for the Experiment	3.5	3.5	4.5
Average Time Elapsed (s)	(1) Connecting Color-Coded Wires	41.5	28.7	26.1
	(2) Balancing Gages for the Experiment	21.5	28.6	20.7

\**n* = total number of sections, Likert Scale (1 =Lowest, 5 =Highest)

When comparing the mean pre-quiz scores among the three groups, the results showed no mean differences. On the other hand, when comparing the average post-quiz scores among the three groups, we expected a mean difference between the control group and the two virtual module groups. However, the results failed to meet our expectations. Because of the small sample size, more sample data may be needed in the future for further statistical analysis.

**5.4.2 Performance Assessment Result.** Results in Table 4 show that the control group and the 3DTV group appeared to perform relatively the same in terms of Likert Scale values. It was observed that the CAVE group (scale 4.5/4.5) outperformed the 3DTV group (scale 3.5/3.5) and the control group (scale 3.5/3.5) in terms of the Likert Scale. Additionally, in terms of the time elapse on the two tasks, students from the CAVE group (26.1/20.7 s) spent the least average time completing the given tasks, achieving 37.1%/3.7% faster time than the control group (41.5/21.5 s) and 9%/27.7% than the 3DTV group (28.7/28.6 s). The 3DTV group seemed to outperform the control group on Task 1 (30.8% faster), but failed to do so on Task 2 (24.6% slower). However, in terms of group kinetics and general involvement, groups with virtual modules seemed to outperform the control group. Consequently, more sample data will be needed to draw a solid conclusion.

## 6 Discussion

This study aimed to achieve (i) the development and implementation of the virtual laboratory modules

for the undergraduate mechanical engineering laboratories under two virtual environments, (ii) a comparison of the influence of virtual environments and instructional methods on students' learning, and (iii) the evaluation of the impact of performance and quantitative assessments from students' post-laboratory performance. From overall results, the study demonstrated satisfying achievements either fully or partially. The virtual lab modules were successfully developed and implemented in two virtual learning settings, namely the 3DTV and the CAVE, through computer-modeling software including MAYA, Google SketchUp, and Virtools. Students with virtual lab modules showed more interest and engagement in learning laboratory materials than students without the virtual modules, thereby producing more active learners. The inquiry-based instructional method helped students refresh their memories on general lab procedures, resulting in slightly better performance on the laboratory post-quiz. Both performance and quantitative assessments were conducted to evaluate the effectiveness of the virtual modules as pre-lab practice sessions.

In the Jet Impact Force experiment, students' mean quiz scores indicated that the CAVE group performed the best, followed by the 3DTV group and the control group, respectively. Overall, students with virtual modules (3DTV and CAVE) showed significant improvement over the control group. We also compared the mean quiz scores between the conventional and inquiry-based instructional methods under both virtual environments. Although it seemed clear that students with the inquiry-based instructional method scored slightly higher than students with the conventional lecture-based

instructional method, the analysis showed that only the 3DTV group had the statistically significant improvement. In addition, we compared the mean quiz scores between the same instructional methods but under different virtual environments. The results didn't appear to be statistically different. From these performance results, it seemed that virtual modules support students' knowledge construction from the experiment significantly. Additionally, the direct observation data demonstrated satisfying results in terms of the experiment procedure. Students from virtual module groups demonstrated better performance, as there were fewer mistakes made on the experiment, more collaboration and a higher level of involvement among group members, and shorter amount of time spent on the experiment in general. Most of the feedback from the survey showed favorable compliments from the students. Overall, many students considered the virtual module to be effective and useful for learning engineering lab materials, and these students encouraged more virtual modules to be developed for other engineering labs.

In the Beam Bending Experiment, we compared the mean pre- and post-quiz scores among the control, the 3DTV, and the CAVE groups. Significant improvements of the mean scores were found from those comparisons, which met our expectations of having better mean post-quiz scores over the pre-quiz scores. In addition, we first compared the mean pre-quiz scores among different groups, and the results showed no significant difference. Next, we observed the same outcome when comparing the mean post-quiz scores among the three groups. This result failed to meet our expectations since we assumed that students with the virtual modules would perform much better than the control group. Aside from the performance results, the direct observation data showed that the CAVE group performed well in terms of the experiment procedure, as they spent less time on the designated tasks and had higher Likert Scale values than the other two groups. The 3DTV group in general outperformed than the control group, but seemed to struggle with Task 2 in the experiment especially. Therefore, no solid conclusion was drawn due to the small sample size, although the groups with virtual modules seemed to demonstrate a positive trend.

## 7 Conclusion and Future Work

In summary, the implementation of the 3D virtual lab modules was successful. Through careful observation and research in this study, we have concluded that the virtual modules, as pre-lab practices, have definitely showed improvements in the actual laboratory performance in terms of the experimental procedure and effectiveness of learning the knowledge from the experiment. However, when factors such as cost, maintenance, and accessibility are taken into consideration, the 3DTV learning environment may provide the optimal solution in the long run. Additionally, many students found virtual modules to be more helpful in preparing them for the physical experiment and grasping the lab objectives and procedures. This finding would be the most important for enabling a distributed VR learning capability for virtual laboratories in distance learning. Students became more familiar with the experiment steps after going through the virtual module, indicating that training in the virtual environment is completely transferable. Though the 3D virtual module resembles the properties of the physical experiment well, it should not be a full replacement. Rather, the virtual learning environment should be applied with a physical learning environment to produce the best learning outcome. In our future studies, we plan to collect more data to obtain a larger sample size in the coming semesters to improve the statistical analysis.

The future work of this study includes extending the current research study, building a virtual laboratory framework, and implementing the virtual laboratory in a collaborative learning setting. We plan to break down the whole experiment into small task components so that each component can be individually analyzed and compared. This will allow us to examine the learning effectiveness of each task in detail. We are also interested in building a framework that focuses on the development of the general structure and mechanisms of a virtual laboratory. With this framework, users could apply it to any virtual laboratory settings not limited to these specific engineering laboratories. Finally, collaborative learning in virtual laboratories helps users work as a team to achieve the learning objectives in the same virtual work-

space. This allows users to share their ideas and learn from each other. Developing an interactive virtual laboratory capability for collaboratively performing physical experiments will also be a future endeavor.

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