Experiential Learning of Engineering Concepts in Immersive Virtual Learning Environments (VLEs)

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Abstract

Immersive virtual reality (VR) provides a platform to rethink and design new ways to teach engineering topics in virtual learning environments (VLEs). Students can interact with objects and perform experiments in VLEs that are not accessible in a traditional classroom setting. However, literature has conflicting studies on both the advantages and disadvantages of learning in immersive VR. In this study, we compared two groups: traditional lecture setting and traditional lecture setting with VLE addition after the lecture. Two VLE modules were developed for materials and mechanical engineering concepts on tensile testing, mechanical properties, and Poisson's ratio. In these VLEs, students performed tensile tests on real-size samples and explored material behavior with different properties using hand controllers. In-VLE questions on mechanical properties were asked after virtual tensile testing. Student learning was improved for only tensile testing concepts. Despite the significant hand-controlled interaction with the materials in the Poisson's ratio VLE, student learning was not improved with the addition of VLE after the traditional lecture. These results show that the VLEs need to be carefully designed following the main affordances of immersive VR and multimedia learning theories to enhance student learning.

Keywords—Immersive engineering education, virtual reality experiment, virtual laboratory, virtual reality, VR, embodied learning

I. Introduction

Virtual reality (VR) is defined as "a high-end user-computer interface that involves real-time simulation and interactions through multiple sensorial channels" [1]. Specifically, head-mounted displays (HMDs) stream a virtual 360° environment via screens in front of users' eyes and track the user motion, which creates a fully immersive virtual reality (IVR) environment (Fig. 1). Therefore, VR is a platform for students to experience Virtual Learning Environments (VLEs) that are designed by educators to teach specific topics. These VR modules have the potential to revolutionize engineering education by providing heretofore unexplored immersive learning environments. With the decreasing cost of HMD systems, educators have a great opportunity to offer one of the most exciting ways to interact with learners in a designed environment. However, literature has conflicting reports on both the benefits and disadvantages of learning in VR [2–9]. The use of VLEs was reported to increase students' learning, motivation, interest, and engagement [2–7]. Studies also reported ineffective learning in VLEs. For example, Parong and Mayer performed a media comparison study between VLE and PowerPoint slideshow [8]. The results showed that the VLE group had lower test scores compared to the slideshow group. Similar lower learning for VLE compared to computer simulations was reported by Makransky et al. [9]. In another study, the authors reported the effects of VLEs on student learning of botany concepts. They concluded that the higher presence in HMD did not improve learning compared to desktop display [10]. Note that the studies [4, 8–10] compared HMD media to computer screen simulations/presentations. Whereas [5, 6] compared HMDs to traditional lecture/laboratory settings, and [7] performed a comparison between traditional lecture and the same lecture followed by HMD activities.

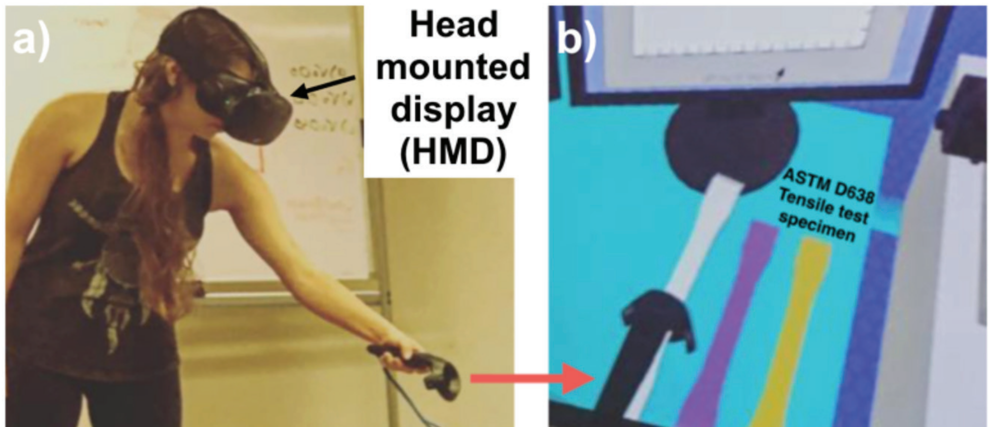

Fig. 1. a) Student with a head mounted display (HMD) and remote controller reaching to ASTM specimen, and b) student's view through the HMD.

II. Background

A. Learning in Immersive VR and multimedia learning

We ground the current study on theories of embodied cognition, multimedia learning, and cognitive load. Embodied cognition theories argue that learning and thinking are strongly connected to the sensorimotor system, bodily actions, and physical interaction with the environment. Accordingly, embodied learning activities, where students' physical interactions are in line with the concept to be learned, often enhanced learning and conceptual understanding. In this context, IVR provides a unique platform to design bodily activities and physical interactions that can enhance learning of a specific topic. As a result, the main affordances of learning in IVR have been reported as presence and embodiment with the related agency [11, 12].

Presence has been simply defined as sense/feeling of "being there" [12–14] or "particular form of psychological immersion, the feeling that you are at a location in the virtual world" [15]. The fully immersive nature of the HMDs creates a virtual world, where users can walk and explore the environment without seeing anything outside. HMD or other mixed reality headsets such as Apple Vision Pro tracks the user's movement and updates the scene seen. This creates a self-presence and physical presence that is different than the presence felt using low or medium immersion environments such as smartphones, 2D computer screens, or cave automatic virtual environment (CAVE) systems.

In addition to movement freedom in IVR, users can manipulate objects and perform tasks using hand controllers. This opens unlimited opportunities to design learning environments for many topics. Specifically for engineering concepts, immersive VLEs provide a platform to perform experiments, which can be expensive or impossible to perform with a large group of students. VLEs also offer the use of laboratory equipment that might be costly to operate or not available in many institutions. However, from an embodied learning perspective, the bodily activities need to be designed to support the targeted learning outcomes or understanding of the concepts [16–18]. The VLEs in this study did not include any bodily activities that directly align with learning outcomes. The bodily activities can range from moving the whole body, arms, and hands to fingers and eye movements. Addition of motoric modality to visual and auditory modalities is hypothesized to enhance learning as more neural pathways are activated [11]. In our VLEs, students manipulated objects using hand controllers and changed the stress acting on objects by raising or lowering their arms/hands. Therefore, students had control over the virtual environment. This "feeling of generating and controlling actions" is defined as agency [19].

From multimedia learning and cognitive load points of views, the following learning theories and principles were considered for the development of our VLEs:

1) Multimedia learning theories argue that any well-designed medium for learning is grounded in cognitive theory of multimedia learning [20] and cognitive load theory [21]. In essence, these theories argue that learners have limited amount of cognitive load processing. If a medium results in a high cognitive load that is not directly related to learning (i.e., extraneous processing), it may hinder learning. To minimize extraneous cognitive load in IVR, our VLEs were designed as simple and easy to navigate as possible. That is, we developed our VLEs to only include the equipment and materials essential for the concepts to be learned. This aligns with the coherence principle, which argues that individuals learn better when extraneous material is excluded rather than included [22–24]. Extraneous material or information increases the cognitive load and take attention away from the main content. For example, non-essential constantly moving animations were considered as extraneous material that could add to the learners' cognitive load [8]. Therefore, the VLEs excluded any other non-essential material and equipment, which might be present in real laboratories.

2) Segmentation principle argues that people learn better when learning materials are presented in learner-paced segments, which can be controlled by the learner, rather than a continuous unit without any learner control [25, 26]. Accordingly, we created VLEs that are learner-paced and leverage the interactive capabilities of IVR. Therefore, we comply with the segmentation principle.

3) Motivational theories argue that student motivation plays an important role in learning. Based on motivational theories, properly motivated students may increase their effort, use more cognitive energy, and stay focused during longer, continuous sessions [27, 28]. Compared to slideshows or reading materials, VR technology is more exciting for the students. Because of this excitement, it is likely that the students are more willing to use IVR longer as a part of their learning. Increased time and effort on learning can increase students' learning of concepts. Studies reported that IVR increases enjoyment and intrinsic motivation compared to less immersive medium of teaching [29–31]. Recently, Makransky and Petersen described a detailed theoretical framework on learning in IVR, which can assist in future VLE developments [12].

Overall, we developed VLEs including only essential materials/equipment for a user-paced exciting learning experience that requires bodily activities to perform tensile testing and observe the effects of Poisson's ratio.

B. Virtual learning environments (VLEs)

VLEs have been suggested and used since 1990s [32]. Early studies on VLEs realized the potential impact of VR on education. The literature includes claims about the use of IVR teaching and learning. For instance, Brelsford claimed that VR increases information transfer between the environment and student as VR makes educational task more intuitive [33]. VR was also suggested to "offer a superior learning experience through increased immersion, fidelity and learner participation" [34]. Whitelock et al. proposed that representational fidelity, immediacy of control, and presence were key characteristics of learning in a virtual environment [35]. In another study, Alhalabi investigated the impact of VLEs on "students' performance," students were given quizzes related to knowledge skills, cognitive skills, mathematic skills, and graphics/charts. For all these quizzes, HMD VR group achieved higher test scores compared to the "No-VR" group [3]. Here, the control group No-VR was described as "traditional education approach" without any details [3]. Note that HMD VR resulted in slightly better quiz scores compared to a corner CAVE system, which is less immersive than HMD [3]. VLEs were also used to teach queuing theory within manufacturing system design concepts, which was reported to increase students' understanding of conceptual contents and analytical skills, tested by six multiple-choice questions [7]. In this case, the same group of 36 students took a pre-test after a 15-minute lecture presentation on queuing theory and then, students performed tasks in HMD VR, followed by a post-test [7]. Questions in the pre- and post-test were reported to be similar; therefore, IVR module could have boosted the student scores by repeating the queuing concepts in IVR [7]. A similar increased knowledge retention and transfer was reported when a short 1.5-minute pre-training material is given before IVR lesson [30]. These studies show that pre-training of the concepts helps learning in IVR.

On the other hand, Makransky et al. reported a decrease in learning with VLE compared to non-immersive VR on a computer screen [9]. Mobile-phone-based HMDs were used in this study to deliver a commercial VLE on biology and biological lab techniques [9]. The low resolution of the mobile phone VLE could be a factor in lower learning through VLE. Moreover, the mobile-phone HMD limits the interaction of students with the environment, which can be seen as "medium-low embodied lesson" that lacks the kinesthetic advantage of HMDs with hand controllers [11]. In another study by Parong and Mayer, students were shrunk—viewpoint of the student is in the blood vessel—to learn about cells in a bloodstream using HMDs with a narrative [8]. The control group had the images from the VR simulation and narration as a text in a slideshow format. The conclusion was that the VR group learned less compared to the slideshow group from a computer screen while spending less time—12 minutes in VR and ~8 minutes for the slideshow. One of the reasons for this decreased learning was the increased cognitive load due to animations that also demanded attention during narration [8]. Furthermore, electroencephalogram (EEG) studies showed an overstimulation during VLE experience, which can hinder learning [8].

We believe VLEs are particularly strong alternatives or supplemental media for laboratory classes when they are designed according to the main IVR affordances and learning theories [11, 12, 30]. For instance, McCusker et al. investigated the viability of VLEs "as an alternative to the traditional hands-on lab experience" [5]. Students explored and manipulated virtual electronic equipment in the VLE. The virtual session was concluded when the students felt that they fully explored the VLE, lasting 15-30 minutes. The control group was traditional laboratory students who built basic circuits on the breadboard and tested the circuits using the electronic equipment in four 2-hour sessions. The VR group had significantly lower score compared to the traditional laboratory students for the equipment identification quiz (factual knowledge). However, both groups scored similarly for the equipment use quiz (procedural knowledge). Note that the VR group spent less than 30 minutes compared to traditional laboratory group who spent a total of 8 hours, which can explain the lower factual knowledge score for the VR group [5]. Similarly, IVR lesson was reported to be less effective compared to 2D slideshow lesson for factual knowledge acquisition [8]. IVR could be better positioned to enhance procedural knowledge, such as how to use an equipment or how to perform an experiment. This is because the virtual environment, hand controllers, and haptic devices allow repetition of the procedure and close examination of the steps involved in the procedure at a user pace [36]. As a result, IVR has been used for topics that are challenging, dangerous, or expensive to teach, such as fire safety, surgery, and flying airplanes [37–40].

The current literature does not provide a conclusion about the effectiveness of IVR on learning engineering concepts. In general, there is lack of theory-based development of VLEs, sample sizes are small for IVR tests, reports lack pre-/post-test examples, and quality of the IVR systems can range from mobile phones to higher-resolutions IVR headsets that can impact learner interaction [3, 5, 8, 9]. In this study, we explored the impact of VLE addition after a traditional lecture on learning, because VLE after traditional lecture was shown to enhance learning [7] and pre-training also enhanced knowledge retention after IVR [30].

III. Research Question

Inspired by the above-mentioned literature and learning theories, this paper investigates the following research question:

To what extent does using immersive VLEs as a learning/instructional medium after a traditional lecture help or hinder engineering student learning?

IV. Method

In this study, we developed new VLEs to teach mechanical and materials engineering concepts. These VLEs communicate two concepts: tensile testing and Poisson's ratio (Fig. 2 and 3). We created both VLEs using the Unity 3D development program, which is commonly used to develop 3D computer games. An HTC Vive VR headset equipment allowed students to use a remote controller and interact in the VLEs. In these VLEs, students performed tensile tests with an observation of stress-strain diagrams of different materials and changed the stress acting on materials to observe the effects of different Poisson's ratio. The tensile testing VLE also included questions that checked students' understanding of basic concepts related to mechanical properties. For example, after the virtual tensile tests, students were asked to indicate the location of tensile strength, yield strength, and fracture strength on the stress-strain diagram.

A. Participants & the Introduction to Materials Course

San Jose State University (SJSU) sophomore and junior level materials, mechanical, aerospace, chemical, and biomedical engineering students participated in this study. SJSU is at the heart of the Silicon Valley and attracts a diverse student population. Participating students were attending the "Introduction to Materials (MatE 25)" course. In this course, typically, 18% of students are female and 23% of students are Hispanic. The MatE 25 covers broad range of fundamental and applied materials engineering concepts. This study focused on the mechanical behavior of materials. The study was conducted across two consecutive semesters, taught by the same instructor. The class met two times a week for a class period of 1 hour 15 minutes. The data were collected during Spring 2018 (N = 14) and Fall 2018 (N= 12). Seven female students in Spring 2018 and one female student in Fall 2018 participated in the VLE experiment. Before the students enroll in MatE 25, they were expected to have mastered the basic force concepts from introduction to physics classes.

B. Data Collection Procedure

The MatE 25 course was taught traditionally using lectures, in-class problem solving, and assessment by midterm and final exams. For both semesters, we randomly selected 15 students using a random number generator and asked them to volunteer for the research study. No extra credit was offered, but the use of VR attracted most of the selected students to participate in the study. Fourteen and twelve students joined the VLE study in each semester—a total of 26 VLE students. Basic concepts of tensile testing, mechanical properties, and Poisson's ratio were taught in a single traditional lecture setting using slideshow by the same instructor. After the traditional lecture, volunteered students experienced the 20-30-minute VLE study. We designed conceptual questions to assess the learning gains after the addition of VLEs to traditional lecture compared to just traditional lecture group. These questions were embedded in the class quiz that was conducted in the following week after the VLE experiment. The same questions were asked in the final exam too. These questions were re-graded at a concept level for this study, which were not used for the students' letter grade calculation. Only eight VLE students in each semester took the in-class quiz. Therefore, we only report a total of 16 VLE student results who took the quiz and final. The traditional group includes 46 students (12 and 34 students in each semester). The results are combined for each semester because there is no statistically

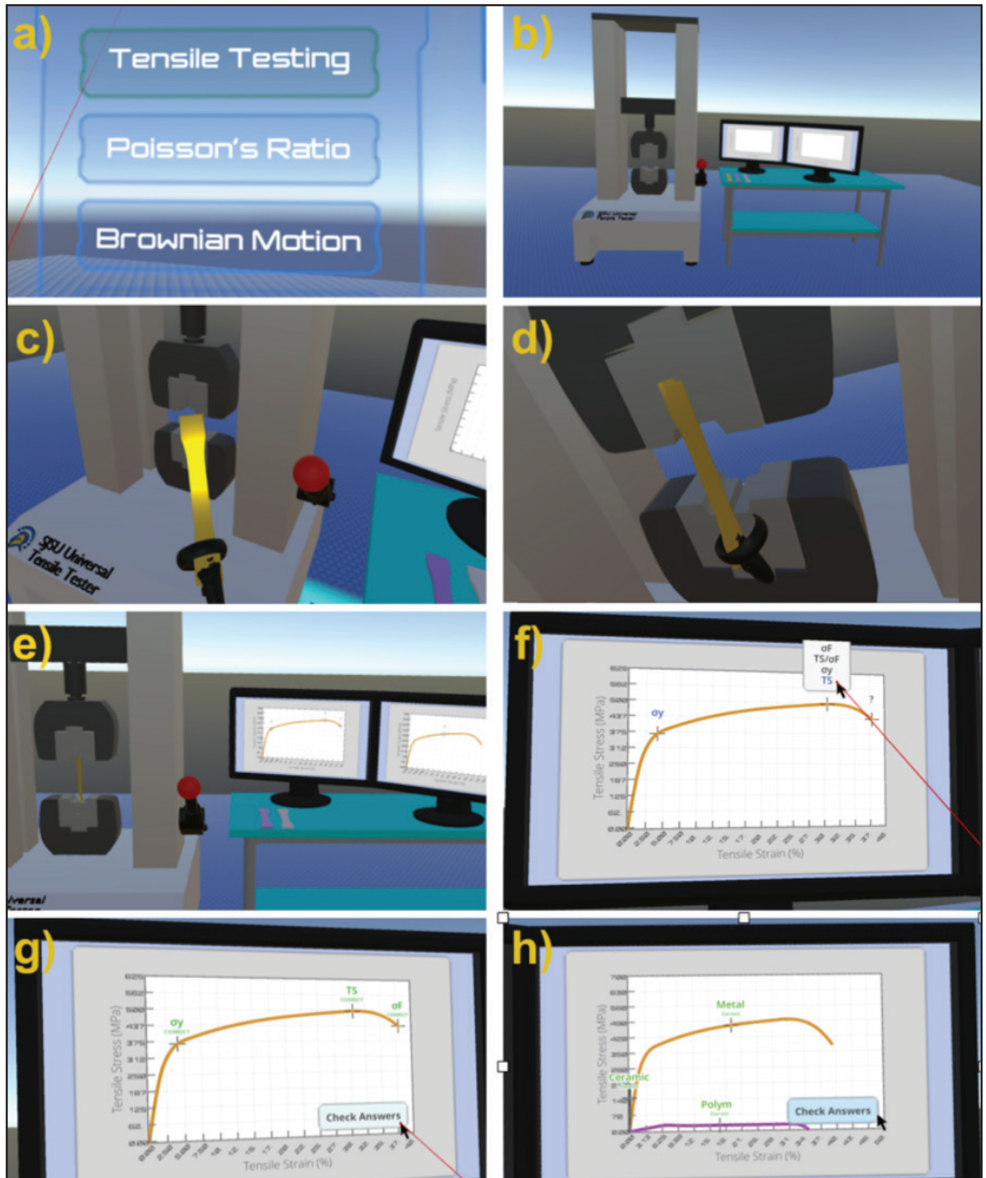

Fig. 2. a) Students select the VLEs from a virtual menu, b) SJSU universal tensile testing system and screens to show the stress-strain data, c) student holding an ASTM D638 Type I sample, d) student aligning the sample to be hold by the grips, e) stress-strain diagrams follow the tensile testing as the grips pull the sample, f) student being asked to identify the yield, tensile, and fracture strength, g) answers are checked by the student, and h) students check their answers on the prediction of the material types for three types of different mechanical behavior.

significant difference between the first midterms of all the groups before the VLE (midterm scores of 70±8 for traditional+VLE vs. 61±7 for traditional in the first semester and 73±4 for traditional+VLE vs. 67±3 traditional in the second semester (mean±standard error, out of 100 total score)). The grading was performed blindly by the same instructor.

C. VLE experiences for students

Students used an HTC Vive with hand controllers to perform tensile testing, which can be seen as an initial attempt to replicate real laboratory experience in IVR. Different VLEs can be selected in the beginning of sessions (Fig. 2a). Lecture instructor gave feedback on how to perform the tensile testing and indicated that students needed to answer the questions in the VLE.

The tensile testing VLE included: A) 3D model of a tensile testing machine with grips and a lever to start the testing (Fig. 2b). The specimen got elongated during the testing, but fracture was not included in this simulation. B) Three different real-size ASTM dogbone specimens were provided on a table next to the testing machine. These three samples represented metal, polymer, and ceramic materials. Students were able to hold the specimens and check their shapes closely (Fig. 2c). The simulation required students to attach the samples to the grips by getting samples in close proximity with the grips (Fig. 2d). Then, the samples automatically transferred to the grips. After the specimen is attached, students pulled a lever to start the testing. C) Two computer screens were also on the table (Fig. 2e): one showing the stress-strain diagram of the material being tested (Fig. 2f) and the other screen showing the stress-strain diagrams of the tested materials all in one graph (Fig. 2h). The stress-strain data were obtained from the real tests and digitized for the VLE. Experimental stress-strain curves representing metal, ceramic, and polymers were shown on the virtual testing computer. This allowed students to compare the mechanical behavior of the three common material types. D) After each test, the simulation asked students to identify the specific points on the stress-strain diagram shown in the computer screen (Fig. 2g). These points represented yield strength, tensile strength, and fracture strength. Students selected the representative properties until they find all the correct answers for all the properties. When selecting the correct answer on the stress-strain diagram, students needed to move their arms and hands, which, in turn, activated motor modality. After completing all three tensile tests, the other computer screen asked students to select the correct material type for the tested materials out of metal, polymer, and ceramic options (Fig. 2h).

Here, the use of Poisson's ratio example is to highlight the ability of VLEs for handling complex 3D shape changes that are hard to teach in a traditional classroom setting and could add to the learners' cognitive load. VLE for Poisson's ratio (ν) was created for three different materials shown as cubes and cylinders (Fig. 3a). These materials had ν=0, ν=0.2, and ν=0.45, representing cork, ceramics, and polymers, respectively. Students were able to interact with these shapes by applying either tensile or compressive stresses. The interaction was done by using the hand controllers on the knob along the stress control bar. This way, students raised or lowered their arms to increase or decrease the stress acting on cylindrical and cube samples. These stresses changed the diameter, increasing diameter under compression and decreasing diameter under tension for ν=0.2, and ν=0.45 (Fig. 3 c-b). The diameter does not change for ν=0 (Fig. 3 d-e). Students were asked to explore these three materials by applying uniaxial tensile or compressive stresses at their pace until they are done observing/interacting with the samples.

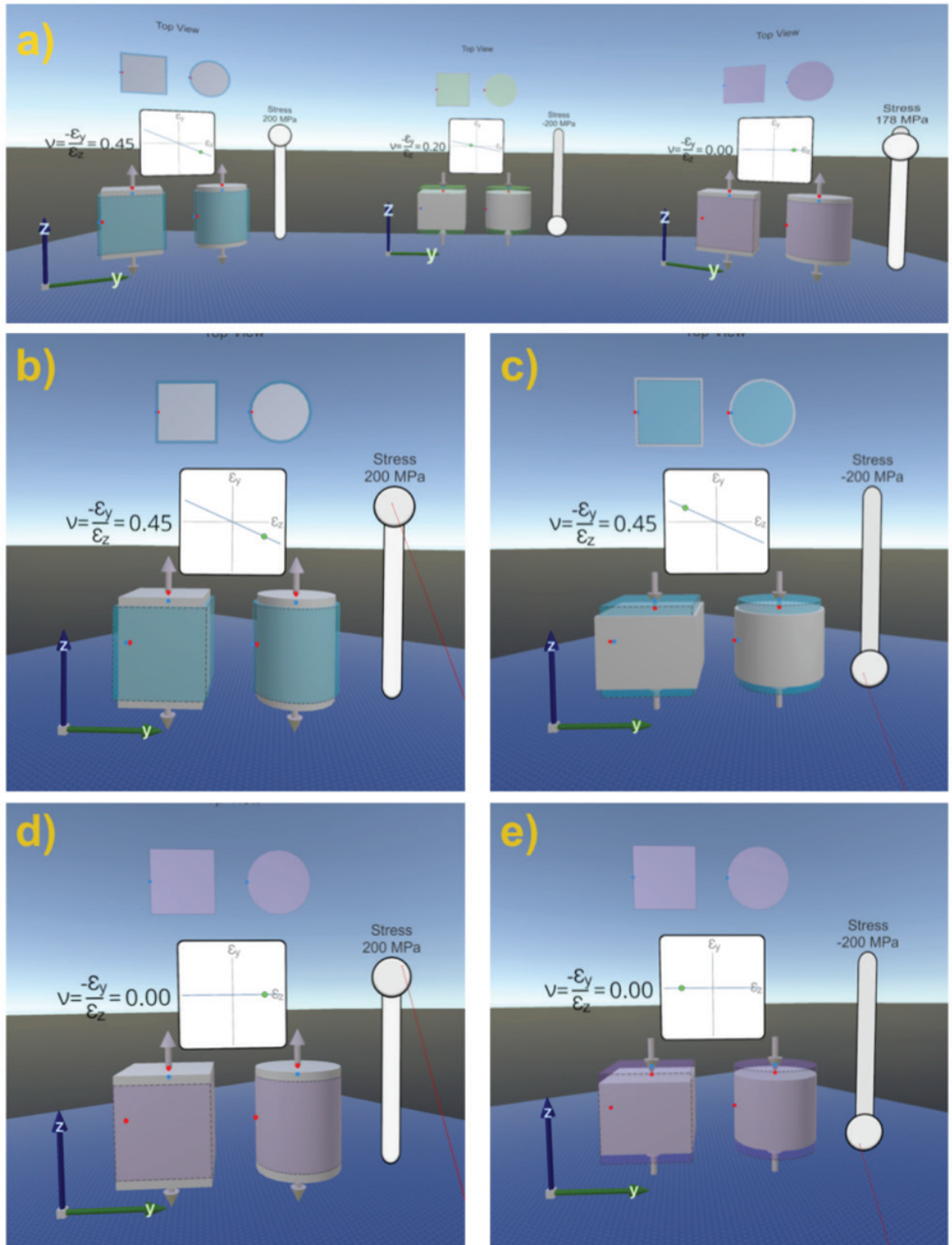

Fig. 3. a) Poisson's ratio (ν) VLE showing three different materials with ν=0.45, ν=0.2, and ν=0, b) tensile stress causing lateral contraction and c) compressive stress causing lateral expansion for ν=0.45; d) tensile stress and e) compressive stress not changing the lateral dimension for ν=0.

Grade	Explanation
0%	Fails to demonstrate an understanding of the concept
33%	Demonstrates a basic understanding of the concept
66%	Demonstrates a basic understanding of the concept and applies it to a simple situation
100%	Demonstrates a basic understanding of the concept and applies it to one simple and one advanced situation

Table1. Evaluation rubric used for the Questions 1 and 2.

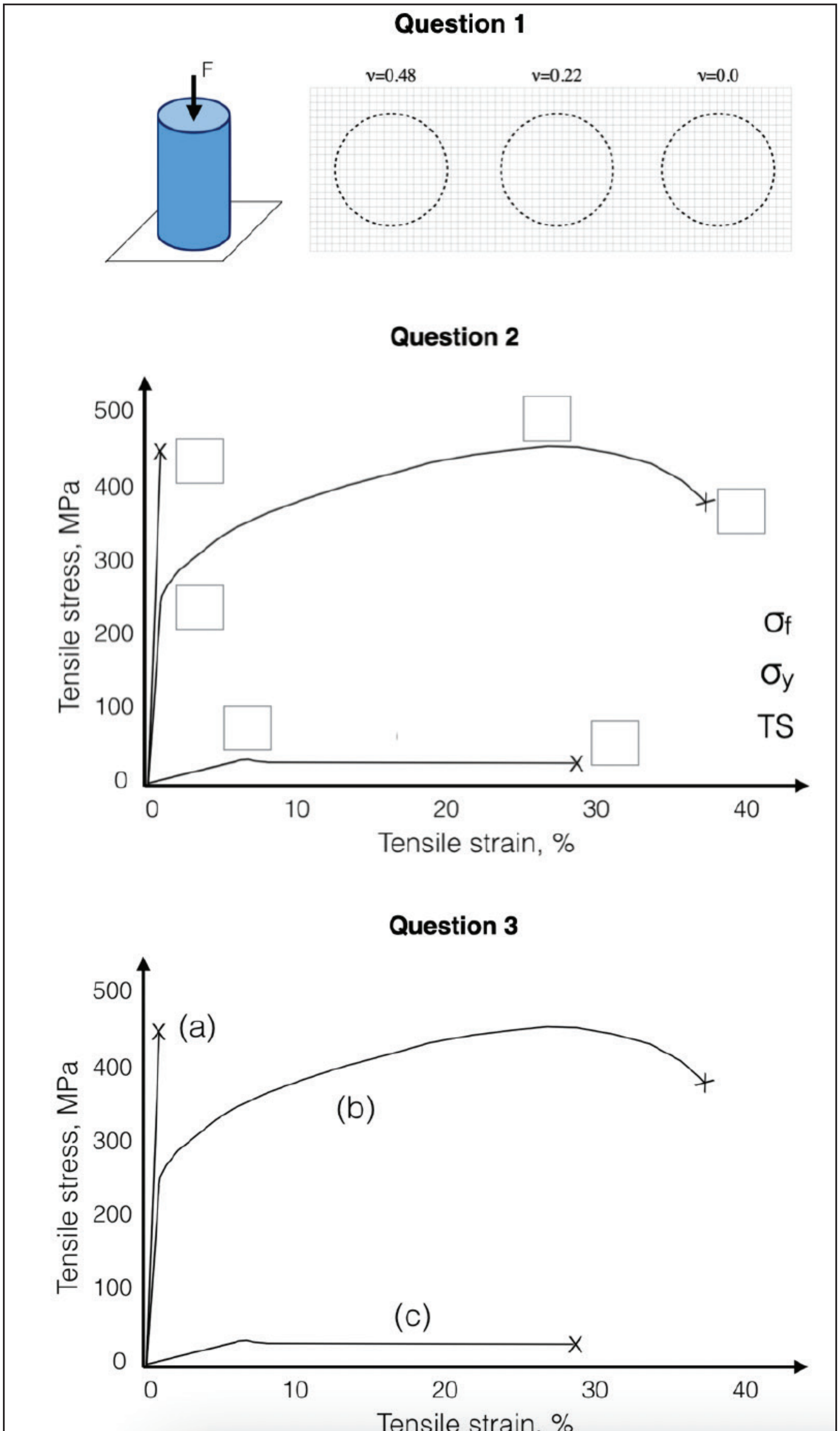

Fig. 4. Question 1 asked students to draw three circles representing the shape change in the bottom diameter of the cylinder under compression for different Poisson's ratios. Question 2 asked students to identify yield, tensile, and fracture strengths on the representative stress-strain curves for (a) ceramics, (b) metals, and (c) polymers. Question 3 asked students to identify the materials for the stress-strain curves of (a), (b), and (c).

D. Assessment of Learning with VLEs

The quiz and final questions directly tested the concepts that the students were expected to learn during VLE. An evaluation rubric was developed to grade these questions. Table 1 shows the rubric used for the evaluation of questions: 1 (on Poisson's ratio) and 2 (on stress-strain diagram) (Fig. 4). Question 3 only tested the student's understanding of three basic materials (type of material shown in Question 2 for (a) ceramics, (b) metals, and (c) polymers). Question 3 had a correct/incorrect format without the possibility of any partial credit. The same questions were repeated in the final exam as well.

V. Results

The results show that the addition of immersive VLEs after a traditional classroom lecture enhanced student learning for tensile testing, but not for Poisson's ratio. The average percentage scores of students in both groups are shown in Fig 5. It was observed that students in both groups scored similarly in question 1 on Poisson's ratio in the follow-up quiz and final exam. For the other two questions on tensile testing and mechanical properties, traditional+VLE group outperformed the traditional lecture group in both the follow-up quiz and the final exam. It was also observed that both groups performed better on all three questions in their final exam compared to the follow-up quiz. This was an expected result as the students were expected to gain more knowledge about the concepts as they applied them on the subsequent concepts in the course. In addition, the questions were the same for both the quiz and final.

To analyze the results statistically, an Analysis of Co-variance (ANCOVA) was conducted on the data for each question. The experimental group (traditional or traditional+VLE) was considered as the independent variable and the scores on each question were considered as outcomes. The score of each student in the midterm exam conducted before the intervention was considered as the covariate in the analysis. The midterm exam signifies the pre-knowledge that each participant possesses as they enter their intervention. For all three questions, the data were normally distributed, satisfying the first crucial condition for performing ANCOVA. The questions 1 and 2, the data satisfied the homogeneity of variance condition as well. For question 3, the homogeneity condition was violated, but ANCOVA was robust to this violation as the data were normally distributed. The results from the ANCOVA are shown in Table II. The analysis shows that for questions 3 (in both the quiz and the final exam), the VLE intervention shows significant improvement in participants' scores compared to the traditional instruction group, when treating their midterm score as covariate. For question 2, the impact of VLE was statistically significant only for the final. For question 1, no effect was significant for both the quiz and final. The scores for the midterm, quiz, and final are

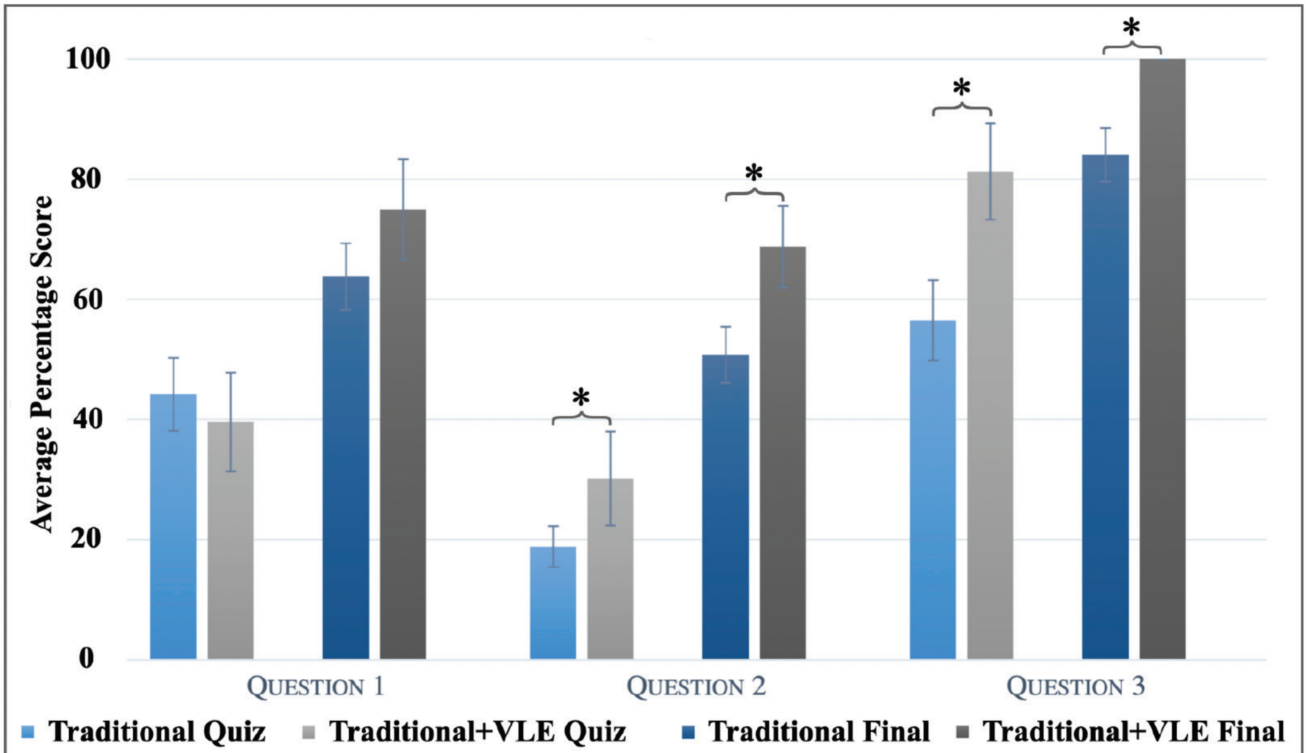

Fig. 5. Pair-wise comparison between the two experimental groups on the understanding of the concepts in the mechanism design module. * Represents statistically significant comparisons. All the error bars shown represent (±) 1 standard error (S.E.).

	Question 1		Question 2		Question 3	
	F	p-value	F	p-value	F	p-value
VLE effect on quiz scores	0.27	0.61	2.76	0.10	4.59	0.04*
VLE effect on final scores	1.80	0.18	4.34	0.04*	4.54	0.04*

* Statistically significant comparisons at $\alpha = 0.05$

Table 2. Results of ANCOVA

Group	N	Midterm	Quiz Q1	Quiz Q2	Quiz Q3	Final Q1	Final Q2	Final Q3
Traditional+VLE	16	71.5±4.3	3.9±0.8	4.1±1.0	2.5±0.2	6.9±0.7	8.5±0.8	3.0±0.0
Traditional	46	65.4±2.8	4.0±0.5	2.3±0.4	1.7±0.5	5.7±0.5	6.1±0.6	2.5±0.1

Table 3. Midterm, quiz, and final question scores for traditional and traditional+VLE groups. N is the sample size. Quiz and Final Q1, Q2, and Q3 are the same questions with maximum scores of 9, 12, and 3, respectively. Midterm is out of 100 total points. Mean scores are reported with ± standard error.

given in Table III. Although we did not use a pre-test to directly measure the students' understanding of the concepts, the midterm scores are within one standard error, indicating similar student performance before the VLE experience.For the question 1, VLE students had the opportunity to explore the behavior of three materials with different Poisson's ratios. The Poisson's ratio was included in the VLE as an example of tough/hard to teach 3D concept because manipulation of 3D objects in a traditional classroom setting is challenging and not possible to be performed individually by the students. The discussion on 3D shape changes in materials under stress is expected to have high cognitive load on students when taught traditionally using slides or whiteboard. This high cognitive load could be reduced in VR as the students can directly observe the shape changes. Despite the direct interaction with three different materials (i.e., agency through the control of stress on the materials), the quiz scores were statistically the same within one standard error for the traditional and traditional+VLE groups. Note that we did not design any gestures to align with the learning objectives for any of the VLEs. Moreover, students were not asked to answer any questions in the Poisson's ration VLE. As a result, observation of shape changes even with agency was not effective in enhancing conceptual understanding of Poisson's ratio.

On the other hand, the experimental condition (traditional or traditional+VLE) was found to have a statistically significant effect on the percentage scores for questions 2 and 3 (scores differed more than one standard error). From an embodiment point of view, Johnson-Glenberg et al. indicated "learners who are engaged in higher levels of embodiment will learn content faster and in a deeper manner because activating sensorimotor codes strengthens memory traces" [14]. For Questions 2 and 3, students were directly asked to take a tensile test specimen, put it on the grips of virtual tester, and perform a tensile test. The resulting stress-strain diagram was shown on one of the virtual screens. After the test, students were asked to identify mechanical properties on the stress-strain diagram and check the answers automatically. Students had to find all the correct answers before switching to another material. Three tests for metal, ceramic, and polymer samples were repeated. After the three tests, students had to correctly identify the types of materials for a given stress-strain diagram on a second screen in VLE. During this tensile testing VLE, sensorimotor activities of students were higher as they had to move around and use their arms/hands to answer questions on the virtual screen, which could have enhanced learning of tensile testing and mechanical property concepts [14]. In addition, the in-VLE questions can be seen as an opportunity for reflection that can also help with learning [11]. Therefore, the increased quiz/final scores for Questions 2 and 3 are due to multiple factors, which made the addition of VLE to traditional teaching effective in learning.

VI. Conclusions

Two modules of immersive VLE experiences were developed to teach concepts on Poisson's ratio and tensile testing related mechanical properties. These VLEs were introduced to students after a traditional lecture on mechanical behavior. The results show that the addition of VLEs after traditional lecture increased students' knowledge on mechanical properties. VLE addition increased question 2 scores 4.1±1.0 vs. 2.3±0.4 for the quiz and 8.5±0.8 vs. 6.1±0.6 for the final (out of 12 points, Table III). However, no difference was observed in student learning for the Poisson's ratio concept. VLE addition did not affect question 1 scores 3.9±0.8 vs. 4.0±0.5 for the quiz and 6.9±0.7 vs. 5.7±0.5 for the final (out of 9 points, Table III). During the tensile testing VLE, students performed tests on real-size samples using their hand controllers and interacted with the equipment similar to a real laboratory experience. After tensile testing in VLE, questions related to mechanical properties and material types were introduced. Students had to move around and use their arms/hands to perform the tasks and answer questions. These types of sensorimotor activities add to the visual and auditory modalities in VLE, which, in turn, could enhance learning due to increased active neural pathways [11]. The questions asked in the VLE also provide an opportunity for reflection and repetition of the concepts while arm/hand movements used to answer the questions. Students received correctness feedback when answering the questions as right or wrong and they had to answer all the questions correctly to finish the tensile testing VLE.

Whereas the Poisson's ratio module did not have any in-VLE questions. The Poisson's ratio module included hand-controlled interaction opportunities for students by letting students control an applied stress on materials with different Poisson's ratio. Students had to raise or lower their arms to change the applied stress on cylindrical or cube samples and observe the 3D shape changes under tension or compression. Despite the significant sensorimotor activities in the Poisson's ratio VLE, the student learning was not improved compared to the traditional lecture setting. The movements were not congruent to the Poisson's ratio concept, which can limit learning in IVR [11].

The design of the immersive VLEs needs to be based on the main affordances of IVR–presence and embodiment with agency–followed by multimedia learning theories [11, 12]. Literature shows that the use of pre-training (in the form of brief lecture or descriptive images showing key concepts that will be shown in IVR) improves the learning outcomes [7, 30]. In the current study, although we introduced VLEs after a traditional lecture, only one VLE on tensile testing mechanical properties enhanced student learning, in which students had to answer questions on mechanical properties and material types until they provide correct answers. The future VLE developments, therefore, should include gestures/body movements that are congruent to the concepts to be learned [14] and in-VLE questions that are potentially supportive for learning.

We did not collect data on the previous VR use of the students, but many of them reported that this study was their first time experiencing IVR. It should be noted that the negative impact of high levels of arousal in complex tasks can have a negative effect on student learning in the first session of using a VLE. Therefore, future VLE studies could include initial IVR sessions, during which the initial excitement may decrease and bring the arousal to an optimal level for learning new concepts. At the same time, the arousal level is not expected to drop as much as other academic tasks such as reading, which students may find boring. Another study showed high levels of motivation and engagement in three sessions of learning in IVR about the solar system [41].

Future studies should include a direct pre-test and involve larger number of students, which were the limitations of the current study. It is also important to create assessments for procedural knowledge acquisition as a potential advantage of VLEs compared to traditional lectures. The best practices to integrate IVR approaches into engineering curriculum remain largely unknown, but immersive VLEs offer unique ways to teach engineering courses. Students can perform all the engineering laboratory classes in IVR with the added benefit of visualizations that are not accessible in the physical laboratories. For example, students can observe internal structure changes during mechanical testing or manufacturing, current flow in complex circuits, heat generation as thermal maps, architecture of chips, and manufacturing of chips. Through IVR education, students can observe, tinker, play, try, fail, and learn material synthesis, manufacturing, processing, characterization, testing, mechanics, and other experiments in less-available synchrotron or electron microscopy facilities. Overall, we believe VLEs will impact engineering education with an expanding repository of VLEs that has heretofore unseen potential to enhance learning.

Software

GitHub page for the IVR modules can be found at: https://github.com/Apelsin/Engineering-VR-Lab-SJSU

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