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Introduction of a Virtual Reality Laboratory in a Tissue Engineering Course

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Introduction of Virtual Reality Laboratories in a Tissue Engineering Course

Introduction

The biomedical engineering (BME) industry is a highly practical field that involves specialized expertise in biomaterials, cell manufacturing, biomechanics, and other areas. Therefore, undergraduate BME students need intensive practical training on biomedical tools and equipment to adequately prepare them for industrial careers. It is expected that upon graduation, most students would seek opportunities in industry [1]. Laboratories offer the required real-world experience that is reported to significantly impact students' learning experience when integrated into the engineering curriculum [2].

However, the use of physical laboratories comes with high monetary implications for institutions in terms of equipment acquisition, equipment maintenance, and staffing requirements, especially in a rapidly evolving field like BME. Despite these challenges, there remains an increasing industrial demand for graduates with hands-on experience with the latest technologies for biomedical industrial and research applications [1]. Virtual Reality (VR) technology facilitates a potential alternative for providing similar practical learning experiences as obtained in physical laboratories, without the above-associated challenges [3]. This paper explores the integration of VR laboratories into the BME undergraduate curriculum for a Tissue Engineering course as a cost-effective and flexible means to expose students to a practical learning environment in preparation for future industry careers.

Studies within BME research have explored the use of virtual laboratories for a variety of courses, including biomolecular engineering [4], biomedical instrumentation [5], and tissue engineering [6]. We postulate that VR laboratories can be harnessed further in the field of biomedical engineering, with an emphasis on cell manufacturing education. Stakeholders have identified the shortage of a skilled cell manufacturing workforce as a major barrier to accelerating promising cell therapies into products. Current cell manufacturing lab curriculum often requires significant capital investment for the latest equipment and costly consumables; however, VR laboratories can be used to solve the challenges faced by institutions in acquiring well-equipped hands-on laboratories and to meet with industry demands. To effectively harness VR laboratories for BME education, a clear understanding of learners' perceptions of VR laboratories when integrated into classroom instruction is important.

This study investigates learners' perceptions of the usability, utility value, tool efficacy, and satisfaction level of a VR laboratory integrated into an undergraduate Tissue Engineering course at a public research university in the Southeastern United States. Assessment of these variables will inform the effective implementation of VR laboratories into BME curriculum. This study is part of a larger research agenda to leverage these VR laboratories for cell manufacturing education for workforce development. To achieve our objectives, we ask the following research questions:

(1) How did learners' perceptions of the VR lab module differ across student groups?

(2) To what extent did the perceived usability, tool efficacy, and utility of the VR lab module predict users' perceived satisfaction with the learning experience?

(3) How effective was the VR lab module in teaching the key concepts represented by the module?

Literature Review

Laboratories: Laboratories are foundational to engineering education as they serve to introduce students to existing practices in the field to prepare them for future careers. Thus, since the inception of engineering as a field, physical laboratories have been extensively used as learning environments in undergraduate and graduate programs to prepare students for engineering professional practice [1, 8]. There are three types of engineering laboratories: physical, VR, and remote laboratories. Physical laboratories are physically existing structures containing equipment and tools that learners can be trained to use in a specific location [10]. VR laboratories are a low-cost alternative for laboratory instruction with no physical or time restrictions [11], offering an interactive simulation to effectively represent theoretical concepts. Remote laboratories are laboratories that offer the flexibility of time and location for experimentation with physical equipment while allowing for real-time data analysis and interaction over the internet [12].

Virtual Reality Laboratories: VR laboratories, if accessible, help overcome scheduling flexibility and the constraint of physically locating experimentation, which is the case for physical labs. VR labs use immersive technology to simulate hands-on laboratory experiences, as users can manipulate virtual equipment in a virtual world [13]. VR laboratories' inexpensiveness and immersive degree of realism have fostered their use in educational classrooms [14] as an efficient form of training to improve engineering technical skills. They have been used in chemistry [15], bioscience [16], biochemical engineering [17], and biomedical engineering [1] to offer practical training to students at varied educational levels. In a study conducted by Dyrberg et al., it was proposed that VR laboratories can be used for preparatory activities before exposing learners to physical laboratory equipment [18]. The authors reported that the use of VR as a preparatory lab increased learners' confidence, motivation, and performance in real lab scenarios.

Although the initial setup cost for VR laboratories can be high, their continued usage is relatively inexpensive in comparison to maintaining physical laboratories. As such, undergraduate BME programs can provide the practical experience that students need at minimal cost by leveraging VR laboratories. In simple terms, VR laboratories enable higher education institutions to fulfill learning objectives with a low-cost budget without compromising the standard. Reported studies [17, 19, 20] explore this feature and report similar observations – the use of VR laboratories in science education reduces the financial burden for institutions and improves understanding of abstract concepts.

Study Motivation

The field of BME is constantly evolving and requires significant capital investment for purchasing and maintaining equipment to support the laboratory curriculum [1]. Cell manufacturing education is an aspect of the BME field embodied by a demand for a skilled and multidisciplinary workforce. Consequently, there is an urgent need to adequately prepare students to acquire the training and technical skills they will need to work in the cell manufacturing industry. Higher education institutions can leverage VR laboratories to offer authentic and cost-effective learning experiences to BME students without compromising the quality of training. As revealed in studies by Reeves et al., and Campbell et al., [21, 22] using VR laboratories for undergraduate engineering education produces learning outcomes similar to hands-on laboratories.

A study by Trumbower and Enderle [1] explored the use of virtual instruments for training BME students on bioinstrumentation, biomechanics, data analysis, and other key technical skills needed to build expertise for their industrial careers. The objective of their study aligns with our research goal to explore the use of VR laboratories as a cost-effective and viable alternative for training biomedical engineers in cell manufacturing education. Based on the review of the literature, we see increasing use of VR laboratories in varied ways across different engineering fields, however, we observed a limited number of studies in the BME field specifically focused on their effective design and implementation for cell manufacturing education. As there was no physical cell culture laboratory component associated with our BME program or accessible for instruction at the time of this work at our institution, we aimed to incorporate a VR lab into a Tissue Engineering course to provide learners with a more comprehensive experience. This study was informed by prior studies based on literature review that reported on the viability of VR laboratories to foster similar outcomes as physical laboratories.

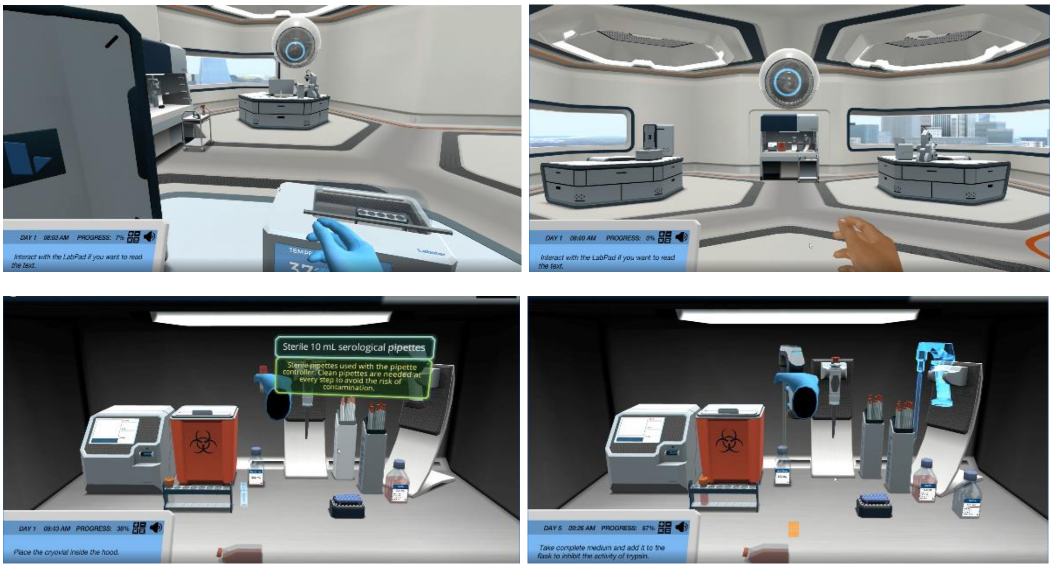
To guide future and effective implementation of VR labs, this study explored learners' perceptions of the Cell Culture Basics VR lab in terms of its usability, utility value, tool efficacy, and satisfaction levels. The authors of [17, 18, 23] show these variables to be important constructs for the integration of VR laboratories into classroom instruction. Furthermore, as recipients/end users of VR laboratories, learners offer invaluable insights on the effective implementation of VR laboratories into classroom instruction. We envision that this study will inform how we proceed with deploying and supporting future cell manufacturing education with VR laboratories. Findings from this study will also inform instructors and instructional designers about the significance of the examined variables on the effective integration of VR laboratories into cell manufacturing education in the development of skilled biomedical engineers.

Study Context: Tissue Engineering Course: The Tissue Engineering course is offered as an elective in the Biological/Biochemical Engineering degree program. The Tissue Engineering course aims to provide a fundamental understanding of the areas of science and engineering involved in the design and development of replacements for tissues and organs in the body. The course is offered as a split-level, undergraduate/graduate-level course, but is primarily taken by undergraduate students in the third or fourth year of their degree program to explore different areas of the biomedical engineering field. The course not only introduces them to a specific field, but also allows them to apply concepts of general sciences (i.e., biology, chemistry) and engineering they have learned throughout their degree program.

The concepts of biology, medicine, and materials science are applied in tissue engineering, where the overarching goal is to develop artificial tissues and organs that can be used to improve medical conditions faced by humans. These tissues can be used as replacements for damaged or diseased body parts *in vivo* or as model systems for studying medical conditions *in vitro*. The first step in being able to develop or design artificial tissues and organs is to understand the principles behind tissue engineering strategies that specifically focus on cell biology and materials science. This is one of the objectives addressed in the Tissue

Engineering course and supported by the Cell Culture Basics VR Laboratory. The VR lab particularly focused on simple, yet important laboratory techniques needed to culture cells, as is common practice used by researchers in the field. Another objective of the course is to ensure students understand the development of tissue-engineered constructs. The administered VR Laboratory provides insight into showing how the concepts are applied and the real-life applications of the experiments or procedures that are being conducted.

Selected VR Laboratory used in this Study: This study administered a commercially available desktop VR laboratory module from Labster, the Cell Culture Basics Laboratory, designed to allow participants to learn, observe, and apply their knowledge in a cell culture lab. The purpose of this laboratory was to help participants understand specific aspects of cell culture including the passaging and freezing of cells. Good laboratory practices are applied, including an aseptic technique, and participants can use a biosafety cabinet and practice the necessary precautions needed for cell culturing. An experiment in the VR laboratory lets participants thaw, plate, passage, and cryopreserve (freeze) mammalian cells *in vitro*. Participants were given information regarding cell viability and morphology in the form of lessons during the virtual experiment to support their understanding of cell culture. Participants encounter equipment such as an automated cell counter, incubators, microscope, and biosafety cabinet, which mirror what would be found in a physical laboratory. As the students complete the task, they are given the percentage of completion on the iPad in the left corner. Throughout the module, students were given directions on what to do along with the safety precautions that they would need to follow if the task was done in a physical laboratory.



Interact with the LabPad if you want to read the text.

Interact with the LabPad if you want to read the text.

Sterile pipettes used with the pipette controller. Clean pipettes are needed at every step to avoid the risk of contamination.

Place the cryovial inside the hood.

Take complete medium and add it to the flask to inhibit the activity of trypsin.

Figure 1. Cell Culture Basics Labster module.

Study Timing: This study took place during the Fall 2022 semester. Each student had free access to the VR laboratories using their institutional login credentials. The VR lab was incorporated into the Tissue Engineering course curriculum along with a pre-module lecture and a post-module activity sheet to provide background information and analyze the student's understanding of the concepts from the lab module, respectively. Before administering the VR laboratories, students received lectures on concepts and research scenarios related to the lab module. There were three main lectures provided to the students prior to administering the VR lab. The first lecture briefed the students about tissue engineering as a field of BME and its importance in the research field. The second lecture focused on the process of developing artificially engineered tissues, which introduced students to the need for cells and cell culture in the field. The third lecture primarily focused on the cells used in tissue engineering, in addition to the need of cells for cell culture. The lecture also went over how cell culture can be used for various analyses such as measuring cell viability, assessing morphology, determining effectiveness of treatments, etc. Likewise, the impact of these various aspects of cell culture on research was heavily stressed. At the end of the third lecture, students were instructed to work through the Cell Culture Basics Labster module. The VR lab specifically focused on cell passaging and freezing protocols as it served to simulate the basic protocols of cell culture. Afterwards, there was a post-module activity in which students were given a worksheet related to cell counting/seeding, which is directly related to one of the procedures in the Cell Culture Basics lab module, alongside a survey that assessed their perceptions of the usability, utility value, tool efficacy, and satisfaction level of the VR lab. More specifically, the post-lab module had a series of questions about cell passaging and seeding cells into flasks, well plates, or Petri dishes as if they were preparing the cell culture for experimentation. It helped students understand the necessary calculations for an experiment which was like the tasks they were given in the VR lab module.

Methods

Study Participants: Participants in this study were students in the College of Engineering of a public research university in the southeastern U.S. enrolled in a Tissue Engineering course. The course was offered as an elective for undergraduates and had pre-requisite courses on introduction to biochemistry, general biology, chemistry, and physics. Graduate students were also offered the course. The data used in this study consists of the responses of 28 students, who consented to be included in the research. A formal IRB protocol was submitted for the study and approved by the IRB unit (ID PROJECT00006672) of the institute, and student consent was obtained for their participation in the study

Participants included 28 students (15 females and 13 males), the majority of which were in their 4th year (71%) of undergraduate study in biological engineering (50%), biochemical engineering (39%), and other (11%) majors. Participants' prior experience with virtual reality technology ranged from average (14%) to little (54%) to none (32%).

Measurements

This study administered a 33-item instrument (with four sub-scales), adapted from [24] – perceived usefulness scale, [25] – System Usability Scale (SUS), [26] – satisfaction survey, and [27-29] – Perceived effectiveness scale, to assess the research variables on a quantitative scale. To gather qualitative data, we included a series of open-ended questions in the administered survey. Items were assessed on a 5-point Likert-type scale ranging from 1 to 5 – with 1 being "strongly disagree" and 5 being "strongly agree". The survey was administered online on the Google form platform.

Usability: The sub-scale uses the System Usability Scale (SUS) [25] and is intended to assess learners' perceptions of the extent to which the VR laboratories were easy to use with little or no technical difficulty. It measures VR technology in terms of complexity, consistency, and functionality.

Utility Value: The sub-scale uses the perceived usefulness survey adopted from [24] and measures learners' perception of the perceived future benefits of the VR laboratories for their overall learning. It evaluates the extent to which learners consider VR laboratories to be useful in progressing their learning in Cell Manufacturing beyond the Tissue Engineering course.

Tool Efficacy: The sub-scale uses the perceived effectiveness survey adopted from [27-29]. It assesses the level to which learners perceive the VR laboratories to foster effective learning outcomes.

Satisfaction: The sub-scale uses the satisfaction survey adopted from [26]. Learners' perception of their sense of contentedness with VR laboratories was assessed using this survey in terms of their learning experience and the learning environment.

Results

Prior to conducting specific statistical analysis to address the research questions, a preliminary analysis was conducted on the reliability of the sub-scales and to examine correlations among the variables, in order to determine whether the data satisfied assumptions necessary for conducting linear regression. Pearson correlation analysis revealed that the variables had moderate to strong correlations. Cronbach's coefficient of internal reliability of items on the sub-scales ranged between .75 and .92. Visual inspection of scatter plots revealed a linear relationship between each of the independent numerical variables and the outcome variable, and statistical assumptions for conducting multiple linear regression were met. The descriptive statistics, correlations, and reliability coefficients of the subscales are displayed in Table 1 below.

Table 1. Descriptive Statistics and Correlations among Variables

	Variables	1	2	3	4
1	Usability	1			
2	Utility Value	.596**	1		
3	Tool Efficacy	.543**	.733**	1	
4	Satisfaction	.576**	.787**	.719**	1
	M	3.86	3.72	3.78	3.81
	SD	0.42	0.82	0.59	0.67
	Skewness	-.22	-.97	-1.52	-1.19
	Kurtosis	.78	1.20	3.41	1.61
	Cronbach's α	.76	.89	.87	.91

** Correlation is significant at the 0.01 level (2-tailed)

Research Question 1: How did learners' perceptions of the VR lab module differ across student groups?

Students were categorized into groups based on demographic data of gender and level of experience (categorization based on responses to the open-ended question – "Describe your prior experience with virtual reality technology"- average, little, and no experience). An independent sample t-test to determine whether there were differences in participants' perceptions of the VR lab across gender was conducted. A one-way ANOVA test was further carried out, as our data met the assumptions upon which the test is based (comparison of two independent groups on a scale variable, normal distribution, and roughly equal variances of scale variable) to measure differences across participants' prior level of experience with VR. As represented in Table 2 we observed no differences in learners' perceptions of the VR lab based on gender. Similarly, we observed no differences in most of the learners' perceptions of the VR labs based on their prior level of experience with VR. We, however, observed a difference in learners' perception of the usability of the VR lab. This is represented in Table 3.

Table 2. Comparison of Learners' Perceptions by Gender

	Male		Female			
	Mean	*SD*	*Mean*	*SD*	*F*	*Sig*
Usability	3.91	0.35	3.88	0.41	0.05	0.81
Utility Value	3.85	0.92	3.62	0.73	0.03	0.47
Tool Efficacy	3.91	0.68	3.66	0.51	0.20	0.28
Satisfaction	3.95	0.68	3.69	0.65	0.39	0.33

Table 3. Comparison of Learners' Perceptions by Prior Level of Experience with VR

	Average		Lil		None			
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*F*	*Sig*
Usability	3.55	0.38	3.86	0.31	4.11	0.38	3.95	0.03
Utility Value	3.75	0.50	3.48	0.95	4.11	0.55	1.75	0.19
Tool Efficacy	3.72	0.41	3.63	0.69	4.05	0.41	1.46	0.25
Satisfaction	3.60	0.80	3.79	0.82	3.94	0.21	0.37	0.69

Research Question 2: To what extent did the perceptions of usability, tool efficacy, and utility of the VR lab module predict users' perceived satisfaction with the learning experience?

A forward model selection regression analysis method was conducted to examine the contributions of the predictors. Predictor variables were perceptions of utility value, usability, and tool efficacy. Perceived satisfaction was the outcome variable in the model. A model based on utility value as a predictor of satisfaction was significant, ($F(1, 26) = 42.41$, $p = .000$, $R^2 = .62$, *Adj.* $R^2 = .61$), indicating that participants' perception of the utility value of the

VR labs accounted for 61% of the variance in participants responses to the satisfaction sub-scale. The model excluded perceptions of usability and tool efficacy as they were not a statistically significant predictor of the variance in participants' responses on the satisfaction sub-scale. Results are reported in Table 4.

Table 4. Forward Selection Model for Satisfaction

Variables	B	SE of B	Β	T	VIF	F	R^2	Adj. R^2
Step 1								
Utility Value	.64	.1	.79	6.51	1			
						42.41	.62	.61

Research Question 3: How effective was the VR lab module in teaching the key concepts represented by the module?

Open-ended responses of participants' perceptions about their experience with the Cell Culture Basics VR lab were also obtained for inductive analysis. The lab was administered in addition to lectures on theoretical concepts in the Tissue Engineering course. Hence, this study explores how learners perceived the VR lab to have effectively taught the concepts it was designed for. The responses were analyzed to identify the major themes concerning our research question. The theme, 'concept representation' was generated from our data alongside 'overall perceptions' and 'feelings' which although do not closely align with our research question had a high frequency of occurrence among participants. These themes alongside specific examples from learners' responses are presented below.

Concept Representation: This theme discusses how learners perceived the VR labs to have displayed learning concepts they were designed for. Some of the participants commented that the VR labs displayed the intended learning concepts in a way that made them mentally relatable. Their perception of the VR for the lab reflected perceptions about the utility value and tool efficacy of the VR labs. More than half of the participants thought the VR labs gave a good visual representation of abstract concepts introduced during classroom lectures. For example, a student commented as follows:

> *"This was important in showing what a real cell culture would look like ………. better than having read a textbook."*

This thought was also re-affirmed by another student:

> *"The virtual laboratory experience allowed me to see how lab processes are conducted and showed me what the data obtained meant."*

Although re-occurring responses agreed that the VR lab gave a sense of realism and visualization, one of the learners perceived the VR lab to have skipped on vital concepts in cell culturing, thus, perceiving the VR lab to have fallen short of its role in simulating a real laboratory experience.

> *“Not skimping out on processes such as centrifugation would make this exercise even more valuable.”*

Learning: We discuss this theme as learners’ perceptions of their individual learning experiences. About 60% of the respondents perceived the VR lab to have had a positive effect on their learning process especially because it afforded them a low-risk and self-paced learning situation. This, however, does not refer to the actual learning impact but rather a perception as recorded by students.

> *“This virtual lab was useful in my learning because I could go at my own pace and was not rushed at all.”*
>
> *“It allows us to learn lab safety and lab techniques without the added risks in cost/harm/time.”*

Overall perceptions: Learners generally expressed emotions about the VR lab both concerning the lab structure and their perceptions of the satisfaction and usability of the VR lab environment. Overall, there was a general feeling of contentment amongst the students. About 90% of responses highlighting their experienced pleasure with the VR lab were observed.

> *“I really liked this lab experiment. I thought the lab assistant was really clear…….”*

Commenting specifically on the lab structure, one student mentioned:

> *“I liked that they have clear descriptions and labels for all the equipment.”*

Participants also expressed some dissatisfaction with technical issues they experienced while using the VR lab. For example, some complained that the VR lab crashed, had audio lag, and buffered to list a few,

> *“The simulation had crashed midway through the experiment which caused a lot of personal dissatisfaction with the experience…”*
>
> *“Sometimes it was weird with the audio. I had some issues getting started because of that.....”*
>
> *“The system buffered a lot and had to be restarted multiple times.”*

The VR lab used in our study was designed and supported by Labster. As such, complaints about technical issues with the labs provide an opportunity for addressing users’ concerns to reduce the frustrations students might encounter in future usage of the VR lab.

Discussion

In this study, we investigated students’ perceptions of the usability, utility value, tool efficacy, and satisfaction levels of a VR lab on Cell Culture Basics. There were no statistically significant differences in how the students of different genders perceived the VR lab environment. Hence, participants had similar perceptions of usability, utility value, tool efficacy, and satisfaction irrespective of their gender. This observation is similar to those made by [16] who observed non-significance in gender difference in how students perceived a virtual lab called “Second Life” that participants in their study had experienced.

In the same vein, participants expressed similar views about their experience learning in the VR lab environment irrespective of their prior knowledge or exposure to VR environments. The observed differences in perceptions of usability for the laboratory is reasonable since most of the learners had little to no prior experience with VR environments and so had some difficulty navigating the system. Although there was a lab manual, most students did not use it, they rather started the VR lab and navigated their way through as evidenced by their qualitative responses.

The current study showed that perceptions about the utility value of the VR lab predicted students’ satisfaction with the VR lab as a learning environment. This infers when learners perceive a VR laboratory to be useful in facilitating their learning (immediate and future), they tend to feel satisfied with their experience in the VR lab. This is consistent with prior studies that found that the perceived usefulness of instruction and learning tools predicts learners’ satisfaction with course content and learning technology [30, 31] and increases the likelihood of reusing the system. Although a previous study [32] reported that perceived ease of use of a system predicted satisfaction, usability did not predict satisfaction in the current study. Perhaps the usability used in this study was not sensitive enough to capture this relationship.

Learners’ perceptions about the usability, utility value, tool efficacy, and satisfaction levels of the VR lab used in this study were mostly positive. They found the realism and visualization of abstract concepts afforded by the VR laboratory to help clarify the central concept of the lab instruction. Students also perceived the self-paced learning affordance of the VR lab to be helpful. These observations are especially valuable to the viability of VR labs, especially when educators consider them as cost-efficient complements in supporting traditional laboratory instruction and experience.

VR labs also provide safe learning environments where the financial and psychological costs of breaking expensive equipment or sustaining personal injuries are minimized. Although respondents appreciated the VR lab platform, some opined that the Cell Culture Basics lab skimmed over laboratory practices vital for tissue engineering like centrifugation. As the VR lab was an off-the-shelf commercially available lab, it did not incorporate curricular details that instructors would have considered essential to the learning experience.

The role of the administered VR laboratory in providing basic knowledge and training while removing the pressure of spoiling expensive equipment or harming oneself was also reported among learners displaying an appreciation of a fundamental VR laboratory before advanced hands-on experience. However, responses perceiving the cell culturing lab to have skimmed over laboratory practices vital for tissue engineering like centrifugation were also observed. This reiterates observations from [32], that VR labs might fail to satisfy the learning experience when they are designed without input from educators.

Conclusion

This study investigated learners' perception of satisfaction, effective concept representation, utility value, and usability of a VR lab. No differences were observed across gender and levels of prior VR experience. While the VR lab used in this study was not initially designed for the specific course, the results provide insights into factors that play a role in the effective implementation of VR labs. Based on our observations conducting this assessment and evaluative study of the VR Lab used in this study, we recommend that VR labs should be easy to use with their utility value highlighted by instructors to facilitate a satisfying experience. Furthermore, our study provides evidence of a need for learners to gain exposure to VR laboratory environments beyond a single session to help establish a level of familiarity with similar environments.

Future Work

In continuation of our study, we will further explore the perceived usability, utility value, tool efficacy, and satisfaction levels of VR labs for cell manufacturing education, measure differences across labs and student groups, as well as report on findings from individual sub-scales. Our exploration is to further understand how to effectively leverage VR laboratories for cell manufacturing education in light of limited resources and increased workforce demands. An in-depth analysis of learners' feedback as to suggestions for improvement of the VR labs would also be carried out and used to guide the instructional design of the VR labs for the future administration of VR labs for BME education. We intend to implement these suggestions in future classroom instruction, further evaluate students' perceptions as well as learning, and propose a robust guide for instructors in facilitating the effective implementation of VR labs. We will also conduct replication studies on other BME labs and a larger sample size.

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