Proceedings of the ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference
IDETC 2018
August 26-29, 2018, Quebec City, Canada

DETC2018-86036

EVALUATING THE EFFECTIVENESS OF VIRTUAL REALITY AS AN INTERACTIVE EDUCATIONAL RESOURCE FOR ADDITIVE MANUFACTURING

John K. Ostrander
Engineering Design
The Pennsylvania State University
University Park, PA, 16802
Email: joo5126@psu.edu

Dr. Conrad S. Tucker
Engineering Design, Industrial and Manufacturing Engineering
The Pennsylvania State University
University Park, PA, 16802
Email: ctucker4@psu.edu

Dr. Timothy W. Simpson
Mechanical Engineering, Industrial Engineering
The Pennsylvania State University
University Park, PA, 16802
Email: tws8@engr.psu.edu

Dr. Nicholas A. Meisel
Engineering Design
The Pennsylvania State University
University Park, PA, 16802
Email: nam20@psu.edu

ABSTRACT
Demand for a highly skilled workforce in the field of additive manufacturing (AM) is growing but is underserved due to limited academic course offerings and high barriers for incorporating industrial AM systems into education. Virtual reality (VR) is proposed as a medium to help teach introductory concepts of AM to a broader audience in an interactive, scalable manner. Before implementing VR as a standard tool to teach the concepts of AM, we must evaluate the effectiveness of this medium for the subject. Our research aims to answer the question: can VR be used to teach introductory concepts of additive manufacturing in a way that is as effective as teaching the same concepts in a physical setting? The research looks at the learning differences between two groups: (1) students exposed to an interactive AM lesson in a traditional physical setting and (2) students exposed to the same lesson within a virtual environment. The study assesses participants' AM knowledge through pre-/post-AM lesson evaluation. AM conceptual knowledge gained and changes in self-efficacy are evaluated to make an argument for the effectiveness of VR as an AM learning tool.

1 INTRODUCTION
Additive manufacturing (AM, or 3D printing) is a rapidly growing industry and is expected to reach a worldwide revenue of over $21 billion by the year 2020 [1]. For this reason, AM is becoming an important means of manufacturing [2,3], and as the industry grows, demand for a skilled AM workforce grows with it. However, this demand is not currently being met due to the limited quantity of academic courses and in-depth programs available [4]. This failure to meet AM demand may also be attributed to the high cost of advanced AM systems (particularly with metal AM), which limits the ability to include them in many educational programs [5]. To keep pace with the rapid growth of AM technology and its prevalence, universities around the world are beginning to develop courses centered on AM [6].

While many courses offer useful information paired with hands-on training [7], they fail to scale to a wider audience and appropriately teach advanced AM technologies due to the hands-on nature of their curriculum and locational constraints. Online classrooms have the ability to reach a much broader audience, though at the moment are taught mainly using passive methods [8]. Massive Open Online Courses (MOOCs) are a great example of the growing popularity of accessible online education; however, the majority of content is taught using a traditional lecture style format [9]. Thanks to the low cost of desktop extrusion machines [10], many who are interested in learning more about AM may purchase their own machine and learn from free online videos and courses. However, the barrier to teach *metal* AM online is exceptionally higher given the cost and infrastructure needed for such systems, as well as the expertise needed to run them [5].

One technology that has the ability to reduce the educational barriers and enable scaling is Virtual reality (VR). For the virtual reality hardware used in this study, VR may be defined as: a synthetically generated three-dimensional environment presented to the user though a head mounted display complete

 Copyright © 2018 by ASME

with controls allowing for environment manipulation [11]. Immersive VR allows users to not only observe a surrounding artificial environment but also give them the ability to interact with said environment. The new abilities that VR brings have recently encouraged researchers to investigate how to incorporate interactive VR learning into their curriculum [12]. We are motivated by the idea that VR may act as a readily accessible tool to teach the concepts of AM, as it will allow interactive and scalable access to more advanced AM technologies without the equipment, infrastructure, and training barriers typically associated with industrial AM systems.

2 BACKGROUND AND MOTIVATION

The following research was conducted with two bodies of literature as the focal point of our motivation. Additive manufacturing in education and Virtual Reality in education were explored to gain further insight into the potential synergies between an integrated approach for education.

2.1 Additive Manufacturing in Education

In addition to meeting industry demand, AM has proven to be an important topic to teach in the classroom given its positive educational impact. AM gives young designers the ability to quickly detect and verify design errors [13], encourage collaboration in group projects [14], and encourage peer-to-peer learning changing the teacher's role to facilitator [15].

Schools around the world are starting to see the benefits of AM in education and are developing programs to teach this emerging technology. As an example, the Michigan Tech Open Sustainability laboratory (MOST) developed an open source online tutorial complete with written instructions, still images, and animated GIF images to allow students to learn 3D printer assembly and use [16]. Similarly, MIT has proposed a framework for teaching the fundamentals of AM involving interaction with desktop AM machines to learn the advantages and limitations of the process. The course reviews the major AM processes, industry application, machine controls and design rules and limitations for each AM technique. [7] The Pennsylvania State University has recently launched a graduate program in AM and Design. The prescribed courses explore the scientific backgrounds of AM, the processes involved, design for AM, materials for AM, and a hands-on laboratory experience [17]. There are other AM courses offered by UT Austin, Georgia Tech, NC State, and other universities that cover similar subjects within AM, including process overviews, applications, design, software, and hardware [4]. However, the hands-on laboratory experience included in these courses is not always possible; lab equipment, class size, and available assistants all serve as limitations to expanding the reach of AM in education. There is also no formalized agreement on which AM concepts students should know. While there is a commonly used AM textbook [18], it does not necessarily cover every AM topic in depth.

With the growth of the maker movement, the democratization of desktop material extrusion systems has made the technology increasingly accessible [10]. These machines are relatively inexpensive and are more commonly being used in the classroom allowing for more hands-on laboratory experience. Competitively larger, more expensive AM systems such as sheet lamination, vat photo polymerization, binder jetting, material jetting, powder bed fusion, and directed energy deposition [19] are often too expensive to be used at home [20] where the majority of AM is still being learned informally [19] and are likely too expensive to be commonly used in a classroom setting. Metal AM in particular is very expensive and requires extensive training before use [5].

Given the hands-on nature of many AM courses, translation to online offerings is difficult. In order to address this, the academic community needs an educational technology capable of expanding interactive AM learning to more expensive and industrial-grade AM processes. VR allows for immersion, hands-on interaction, and may be used to display computer-designed facsimiles of more advanced AM systems.

2.2 Virtual Reality in Education

Research has shown that the passive lecture style format commonly used in classrooms is incapable of active student involvement. When students participate in Computer Assisted Instruction or CAI, commonly seen in distance learning, they benefit from an interactive environment rather than a passive one due to real-time student practice and facilitator feedback. In an interactive environment, students have the ability to more easily control the pace of the lesson and explore applications for themselves [21]. One such technology that allows for enhanced student interaction in an online setting is VR.

VR has the potential to overcome many limitations and introduce many benefits in the field of education. Interactivity, realism, cooperation, and immersion with the added excitement of new technology can inspire students to be more engaged with what they are learning. As an example, the ability to immerse students within virtual games and simulations has been effectively used to stimulate interest in high school level courses related to math, science, and humanities [22]. VR has also been demonstrated as an effective tool in higher education. It was found that students in an immersive VR environment could assemble a product faster than students who were interacting with a non-immersive VR system. This suggests that students learning in an immersive VR environment have better performance outcomes; one of the key advantages attributing to this better performance is the ability of immersive VR to continually adjust to the perspective of the user [23]. In addition to artificial simulations and educational games, VR paired with other technologies may immerse an online student in a local classroom. With the help of RGB-D sensors, depth and color data can be captured as a point cloud in real time and display that data in a VR environment [24]. This new technology has the potential to change the dynamics of the online classroom, transforming the standard lecture video into a fully immersive live classroom experience via 3D scanning. Due to its demonstrated ability to improve learning in an engaging way, this emerging technology may serve as a successful platform for large scale interactive AM education. The following research was conducted to investigate VR as a potential resource in AM education.

Copyright © 2018 by ASME

2.3 Research Objectives

The primary research objectives in this work are to quantify the benefits of teaching AM in the classroom and explore VR as a possible alternative to traditional hands-on AM education by enabling interactive learning in an artificial environment. A controlled study was used to determine if VR is effective in teaching general design and manufacturing concepts related to AM. The following research questions were addressed:

RQ1: Will the chosen educational intervention with desktop additive manufacturing show an increase in AM learning regardless of group?

RQ2: Is there a significant learning difference between the VR and physical (i.e., non-VR) groups for any of the AM learning objectives?

RQ3: If there exist any learning differences between the VR and physical groups, what are the underlying reasons for these disparities?

These questions are further addressed in Sections 5.1 and 6. We hypothesize that there will be little learning difference between the VR group and the physical group (resulting in a high p-value in comparing the two groups). This would allow us to argue that AM learning in a virtual environment may be as beneficial as learning in a physical environment. To properly evaluate changes in AM learning, introductory AM learning objectives were chosen as a means of categorizing participant understanding. The objectives covered in this study and used to evaluate AM learning are as follows:

- *Build Time:* The student can identify how part volume and build orientation impact the time required to print a part.
- *Layer-by-layer deposition:* The student can understand how layers make up a part, what causes this, and what this affects.
- *Material use:* The student can identify how much material is used based on part volume and supports generated.
- *Support generation:* The student can identify a range of overhanging angles where supports are typically generated and understand that supports require extra material affecting build time, material use and other parameters.
- *Build orientation:* The student has the ability to orient a part to reduce build time and supports required.
- *Cartesian coordinates:* The student can understand the movement of various machine components in relation to a coordinate system with X, Y, Z, axes.
- *Extruder components and functions:* The student can understand the functions of various extruder components: axis travel, filament heating, gripping, and extrusion.
- *Hot end components and functions:* The student can understand the functions of various hot end components: filament heating, cooling, and extrusion.

The AM learning objectives covered in this initial study are non-exhaustive, but they were chosen as common elements of introductory AM knowledge [18]. In quantifying any learning gains, VR may be proposed as a method to teach more advanced AM systems to a larger cohort of students.

3. Metrics

To evaluate participant understanding of the AM concepts discussed previously, metrics were assigned to measure: (1) AM self-efficacy and (2) AM conceptual understanding based on student responses to pre- and post-tests. The learning differences between physical and virtual AM environments were measured with the use of these metrics.

AM Self Efficacy

The AM self-efficacy metric was split into two categories: (1) self-efficacy as it relates to comfort with the *functions* of AM, and (2) self-efficacy as it relates to comfort with *design* for AM. For comfort with the functions of AM, participants were asked to rate their understanding of the concepts listed in Table 1. Participants rated their understanding of the concepts using the descriptors outlined in Table 2.

Table 1 Functions of Additive Manufacturing Self-Efficacy

1	Layer by Layer Deposition	The physical process of material extrusion where filament is deposited layer by layer to form a physical object
2	Extruder and Hot End Components/Functions	The interaction of printer components required to build an object
3	Cartesian Coordinates	The range of movement of the extruder in relation to the Cartesian axes (X,Y,Z)
4	Cartesian Coordinates	The range of movement of the build plate in relation to the Cartesian axes (X,Y,Z)
5	Support Generation	Depositing sacrificial material to support a 3D printed object

Table 2 Scale for AM Functions Self-Efficacy, Ability to Understand and Explain the Listed Functions of AM

Level 1	Level 2	Level 3	Level 4	Level 5
No under-standing of this topic	Limited under-standing (cannot explain it)	Moderate under-standing (can explain some aspects)	Strong under-standing (can explain most aspects)	Full under-standing (can explain all aspects)

The AM function concepts were grouped by how they relate to the AM learning objectives outlined previously. Concept 1 relates to Layer by Layer Deposition. Concept 2 relates to Extruder and Hot End Components/Functions. Concepts 3 and 4 relate most closely to Cartesian Coordinates, and Concept 5 relates to Support Generation. The participants were asked to rate their understanding using the 5-point scale shown in Table 2.

The scale in Table 2 allowed us to determine each participant's ability to both understand *and* explain the listed functions of AM before and after the AM lesson. This method was inspired by Bloom's Taxonomy as it relates to cognitive thinking. Specifically, Table 2 relates most closely to evaluation of knowledge and comprehension [25]. The results of the self-efficacy survey were not the main focus of this study; they were only assessed if inconsistencies were found within our conceptual learning data-set. If any conceptual results deviated from expectations, self-efficacy results were explored to offer an explanation as to why conceptual results did not turn out as expected, this practice is further demonstrated in section 5.2.

Copyright © 2018 by ASME

For self-efficacy as it relates to comfort with design for additive manufacturing (DfAM), participants similarly rated their familiarity with and comfort in applying the following concepts in their design process, shown in Table 3.

Table 3 DfAM Self-Efficacy

6	Geometric Complexity	Designing parts with complex shapes and geometries
7	Support Generation	Using support structures for overhanging sections of a part
8	Surface Roughness	Accommodating desired surface roughness in a part
9	Orientation	Orienting a part on the print bed to efficiently build it

Table 4 Scale for DfAM Self-Efficacy

Level 1	Level 2	Level 3	Level 4	Level 5
Never heard about it	Have heard about it but not comfortable explaining it	Could explain it but not comfortable applying it	Could apply it but not comfortable regularly integrating it with my design	Could regularly integrate with my design

The DfAM concepts were also grouped by how they relate to the AM learning objectives mentioned previously. The participants were asked to rate their comfort with these concepts on the 5-point scale (see Table 4).

The scale in Table 4 allowed each participant to evaluate their familiarity with each DfAM concept, their comfort explaining it, as well as their comfort using the concept in design. Again, this method was inspired by Bloom's Taxonomy, and most closely relates to evaluation of knowledge, comprehension and application [25]. Each response suggests a higher level of understanding with respect to DfAM: higher knowledge of the topic leads to higher comprehension, higher comprehension leads to higher comfort in application. All AM self-efficacy questions and demographic questions as they were presented to the participants can be seen in the Penn State Made by Design Lab site: http://sites.psu.edu/madebydesign/design-cognition/

AM Conceptual Understanding

Conceptual understanding of AM was measured using a series of questions, each designed to evaluate the participant's knowledge of one of the eight (8) AM learning objectives: Build Time, Layer by Layer Deposition, Material Use, Support Structure Generation, Orientation, Cartesian Coordinates, Extruder Components, or Hot End Components.

Each question was given a maximum point value of 1. If the participant answered the question completely wrong, then they would receive the minimum score of 0 for that particular question. However, some questions had more than one correct answer, and in this case, students could receive partial credit for selecting a few but not all of the correct answers. For example, if a question had 4 correct answers and the participant selected 3 correct answers and 1 incorrect answer, then the participant would receive a total score of 0.5 for that question:

(3 correct – 1 incorrect)/4 total correct = 0.5

Figure 1 shows examples of two questions (Questions 2.1 & 2.2) that have more than one correct answer. Question 2.1 has five correct answers and has a total of ten possible answer choices. Question 2.2 has four correct answers and a total of six answer choices. Full credit for each question can only be given if the participant selects all of the correct answers and none of the incorrect answers. It is also important to note that every question gives the participant the option to circle 'I don't know' as an answer. Circling this results in an automatic zero score for that question. The 'I don't know' answer was included to discourage random guessing on the pre-/post-test, which would negatively impact the results of experimentation.

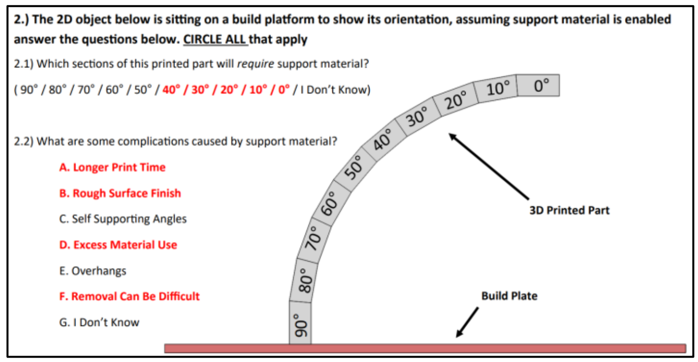

Figure 1 Questions With More Than One Correct Answer (Correct Answers Highlighted in Red)

Participant scores were averaged according to topic to yield a total score for each AM topic for each participant. In other words, for each participant, a final overall score for Build Time, Layer by Layer Deposition, Material Use, Support Generation, Orientation, Cartesian Coordinates, Extruder Components/ Functions and Hot End Components/Functions was calculated. A total of 24 questions were asked covering these objectives. All conceptual test questions and answers can be seen in the Penn State Made by Design Lab site: http://sites.psu.edu/madebydesign/design-cognition/. Table 5 illustrates the conceptual question number and its relation to the AM learning objectives evaluated.

It is important to note that the Orientation topic has overlapping questions with Build Time, Layer by Layer Deposition, Material Use, and Support Generation. While Orientation is an important topic in AM, it is difficult to be evaluated independently of other considerations. This is because as the orientation of an object is changed on a build platform, a taller or shorter print is often created, different supports are often needed, and the amount of material used may change, causing the build time to change with it.

Table 5 AM Learning Objectives and Related Conceptual Questions

AM Topic	Conceptual Questions Covered
Build Time	1.4, 3.1, 3.2
Layer by Layer Deposition	1.3, 3.5, 3.6
Material Use	1.1, 1.5, 3.7
Support Generation	1.2, 2.1, 2.2, 3.3, 3.4
Orientation	3.1, 3.2, 3.3, 3.4, 3.5, 3.6, 3.7
Cartesian Coordinates	4.1, 4.2, 4.3
Extruder Components/Functions	5.1, 5.2, 5.3, 5.4
Hot End Components/Functions	6.1, 6.2, 6.3

Copyright © 2018 by ASME

4 EXPERIMENT: AM LEARNING DIFFERENCES BETWEEN VR AND REAL WORLD SETTINGS

With the established self-efficacy metrics and conceptual understanding questions, the following experiment was designed to investigate the differences in AM learning when exposed to an interactive VR learning tool when compared to hands-on learning in a physical setting. Students participated in a lesson designed to teach introductory AM concepts in either a physical (REAL) or virtual (VR) environment. Their understanding of AM was evaluated using the previously discussed pre-lesson and post-lesson test covering AM self-efficacy and AM concepts.

4.1 Participants

Participants were recruited from an undergraduate first-year engineering design course at a large, northeastern public university. The course uses active, project-based learning to teach the engineering design processes and methods commonly used in team design projects. A total of 44 students (36 male, 8 female) participated in the study with ages ranging from 17 to 19 including one 26-year-old. Of the 44 students involved, their intended fields of study were: Aerospace Engineering (4), Biomedical Engineering (4), Chemical Engineering (5), Civil Engineering (5), Computer Engineering (1), Computer Science (1), Electrical Engineering (2), Engineering Science (2), Engineering Undecided (1), Industrial Engineering (3), Mechanical Engineering (15), and Nuclear Engineering (1). The majority of students either had some informal knowledge about 3D printing (20) or had previously received some formal 3D printing training (21). The majority of participants had no experience in VR (31) or some informal training (13), such as playing VR video games.

4.2 Procedure

After consenting to participate in the study, participants were randomly assigned to one of two AM educational environments: (1) the traditional physical setting (referred to as the REAL group) or (2) the functional computer-designed facsimile (referred to as the VR group). All were asked to report to an assigned testing room at the start of the experiment. Before starting, an overview of the experiment was provided to each participant and participants were asked to complete a pre-test consisting of 1) a demographic survey, 2) a self-efficacy survey, and 3) a conceptual exam. In completing the pre-test, participants were given unique identification codes to maintain anonymity.

Upon completing the pre-test and receiving an identification code, participants were instructed to go to a neighboring room, the lesson room, where they would engage in an interactive AM lesson (VR or REAL) with only a facilitator present. The audio for the lessons was previously recorded to ensure consistency in content delivery. The facilitator was present to explain to the participants that they must 'listen carefully, for the facilitator may not repeat any information or give any verbal/non-verbal clues while the lesson is in session for the sake of consistency.' The facilitator was also present to help participants acquaint themselves with the controls for the VR lesson, as well as the software and hardware controls for the REAL lesson.

Following completion of the lesson, participants were asked to take the post-test. The post-test was identical to the pre-test, except that the demographic survey was removed. The post-test was used to assess changes in self-efficacy and changes in content knowledge through questions on AM concepts.

4.3 Lesson Content and Approach

During the experiment, participants were instructed to touch and interact with a Lulzbot Taz 6 desktop extrusion machine paired with slicing software in either the physical (REAL) or virtual reality (VR) environment. In the REAL environment, participants interacted with slicing software, Ultimaker Cura, using a mouse. They controlled the 3D printer using the controller box integrated in the machine [26]. In VR, participants used an HTC Vive headset and controllers to interact with the 3D printer and slicing software. Interactions within the lesson included moving the printer axes, picking up printer components and printed objects, and moving the scroll bar to reveal layers of the printed part. The Taz 6 was reconstructed in a virtual environment using open source part files provided courtesy of Aleph Objects, Inc. [27]. A comparison of the Cartesian axes and the hardware components in both environments can be seen in Figures 2 and 3 respectively. A comparison of the slicing software in both environments can be seen in Figure 4.

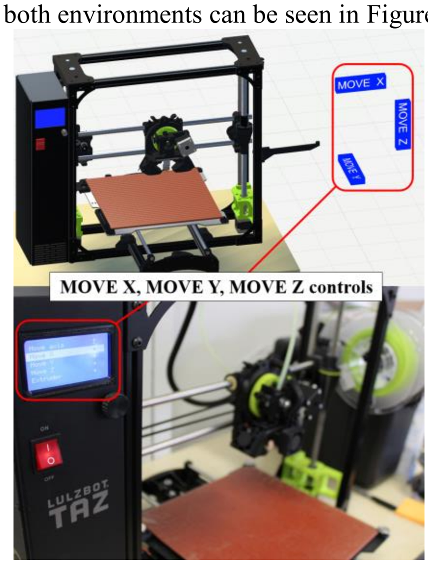

Figure 2 Cartesian Coordinates VR and REAL Similarities

Figure 3 Printer Components VR and REAL Similarities

Copyright © 2018 by ASME

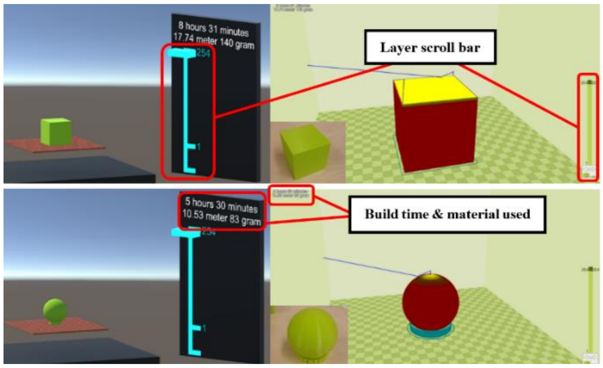

Figure 4 Slicing Software VR and REAL Similarities

Steps were taken to ensure there were no significant functional or interaction differences between the learning environments. Identical voice recordings gave participants step-by-step instructions for with the interactive lesson. The first half of the lesson was dedicated to teaching aspects of the 3D printer's hardware. Instructions were given to move the printer's axes by selecting control options labeled 'Move X', 'Move Y', or 'Move Z' (see Figure 2). Participants were also instructed to interact with a disassembled extruder, picking up various components to examine them more closely (see Figure 3).

The second half of the lesson was dedicated to teaching aspects of the slicing software. Instructions were given to load models into the software (Cube, Sphere, Hulk, Rocktopus). Both the REAL and VR environments displayed the number of layers in the printed part, the build time, the length of filament consumed, and how much material was used (see Figure 4). Participants were given the ability to view what the printed object would look like at different layers in the printing process; this was done to teach the concept of layer by layer deposition. Students were also able to pick up each printed object allowing them to obtain a better view of the support structures generated. An outline of the lesson plan, which includes both hardware and software-based elements, is illustrated in Tables 6 and 7.

Table 6 Hardware Functions and Learning Objectives Covered for Both VR and REAL Groups

HARDWARE	Lesson 1: Cartesian Coordinates	Lesson 2: Labeling Extruder	Lesson 3: Labeling Hot End
Cartesian Coordinates	X		
Extruder Components/ Functions		X	
Hot End Components/ Functions			X

Table 7 Software Part Designs and Learning Objectives Covered for Both VR and REAL Groups

SOFTWARE	Lesson 4: Cube	Lesson 5: Sphere	Lesson 6: Hulk	Lesson 7: Rocktopus
Build Time	X	X	X	X
Layer by Layer Deposition	X	X	X	X
Material Use	X	X	X	X
Support Generation		X	X	X
Orientation				X

Participants were exposed to a total of 7 consecutive lessons on AM learning objectives over the course of 15 minutes. Both VR and REAL groups were exposed to the same interactions, geometries, and AM concepts. The printed geometries that participants were exposed to can be seen in Figure 5. The following subsections offer more detail into each of the lesson elements.

Lesson 1: Cartesian Coordinates

Lesson 1 was used to teach the different directions the 3D printer moves and the components associated with those movements. Participants were instructed to interact with a Lulzbot Taz 6 desktop material extrusion system. They were first asked to move the X axis; the REAL group interacted with the control box knob, which they could turn left or right, while the VR group interacted with a bar that they could grab and drag left to right. As participants controlled the X axis of the printer, it was explained to them that the X-axis controls the horizontal movement of the extruder. Participants were then instructed to move the Y-axis as it was explained that the Y-axis controls the build plate forwards and backwards. Finally, participants were told to control the Z-axis, and it was explained to them that the Z-axis controls the vertical direction of the extruder.

Lesson 2: Extruder Components

Lesson 2 labeled different components of the extruder and explained the functions of each component in the material extrusion process. Participants were instructed to pick up various components of a disassembled extruder, labeled "motor," "extruder body," "axis mount," and "hot end." It was explained to them that the motor is used to control the feed rate of the filament through the hot end. It was then explained that the extruder body is used to hold the filament in place with a latch, but also move the filament through the hot end with the help of the feeding gear. Finally, the axis mount was explained to be the component used to help move the extruder along the x-axis.

Lesson 3: Hot End Components

Lesson 3 was similar to Lesson 2; different components of the hot end were labeled and each component function in the extrusion process was explained. After learning about the extruder components, participants were instructed to pick up the Hot End, to examine it more closely. It was explained that the Hot End consists of a brass nozzle to deposit filament, a heater cartridge to heat the filament, and a heat sink to disperse heat to prevent premature melting of the filament.

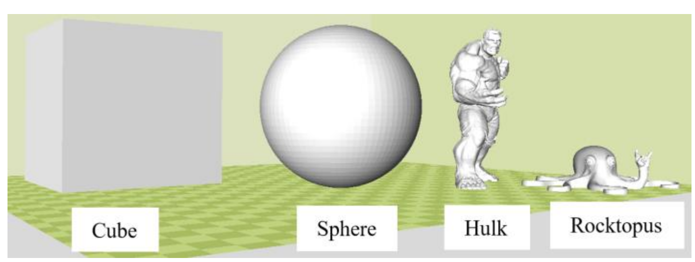

Figure 5 Printed Objects in AM lesson

Copyright © 2018 by ASME

Lesson 4: Cube

Lesson 4 was used to introduce how build time is related to material use and layer count. Participants were asked to load a 3D model of a cube into the slicing software. In the REAL scenario, this was done by dragging an STL file from their desktop to the software. In the VR scenario, this was done by picking up an object that resembles the STL file and placing it into a virtual "bin" taking them into a scene with the slicing software loaded. In both scenarios, participants were told to drag the scroll bar in front of them to the top layer of the print. Participants were then instructed to pick up the cube model to examine it more closely as the amount of material used and time it took to build was explained to them.

Lesson 5: Sphere

Lesson 5 was used to explain how certain overhangs require sacrificial support material, how support generation can affect material use, and how height of the design can affect layer count. Similar to Lesson 4, participants were instructed to load the 3D model of the sphere into their respective slicing software. In addition to observing how long the object took to print and how much material it used, participants were also instructed to take note of the support structures generated underneath the sphere. It was explained that support structures prevent a print from failing if an overhang is too steep, it was also explained that some overhangs may be self-supporting up to a certain point.

Lesson 6: Hulk

Lesson 6 was used to teach participants about self-supporting angles and how build time is unaffected by complex shapes. A 3D model of the Hulk (see Figure 5) was used to teach similar lessons as the sphere but served as a more complex example. In this lesson, participants learned that overhangs between 0 and 45 degrees will likely require supports, while overhangs between 45 and 90 degrees may be considered self-supporting and will not require supports. The Hulk was also used to show the advantage of geometric complexity that AM presents. It was explained that even though the Hulk model was more complicated than the Sphere model, it took less time to print because it used less material.

Lesson 7: Rocktopus

Lesson 7 was used to teach how orientation of a part may affect its build time, layer count, material use and support generation. The Rocktopus model was used to give an overview of Lessons 4 through 6, but also demonstrated the effects that orientation can have on these lessons. The Rocktopus model (shown in Figure 5) was oriented at 0 degrees (flush with the build plate), 30 degrees, 60 degrees and 90 degrees. Each orientation demonstrated different areas for support generation, different build times, different layer counts, and different amounts of material used

5 DATA ANALYSIS

Of the 44 participants involved in the study, 22 were randomly assigned to the VR group, and 22 were randomly assigned to the REAL group. To examine the learning differences between the two learning environments (VR and REAL) for each of the eight AM concepts, a two-way mixed ANOVA (ANalysis of VAriance) was conducted. The dependent variable was AM concept knowledge; pre-test and post-test scores acted as within-subjects factors. The independent variables were the two learning environments VR and REAL. The two-way mixed ANOVA was also run to identify any significant interactions between the two learning environments and the pre and post-test scores. Table 8 lists the 16 sets of data that were produced as a result of the experimentation.

Table 8 All Data Sets

Data Set	Pre-Test	Post-Test
1,2	Build Time	Build Time
3,4	Layer by Layer Deposition	Layer by Layer Deposition
5,6	Material Use	Material Use
7,8	Support Generation	Support Generation
9,10	Orientation	Orientation
11,12	Cartesian Coordinates	Cartesian Coordinates
13,14	Extruder Components	Extruder Components
15,16	Hot End Components	Hot End Components

After performing the two-way mixed ANOVA, steps were taken to ensure assumptions for the model were met [28]. Homogeneity of variances was met, as assessed by Levene's test ($p>0.05$) with the exception of the Hot End Components pre-test data set ($p=0.009$). Homogeneity of covariances were assessed by Box's test of equality of covariate matrices ($p=0.018$). The data also passed Mauchly's test of sphericity, In calculating the studentized residuals, a single outlier was found (SRES = -4.49) in the Orientation post-test data set. However, this outlier was found to not substantially affect the results; this was determined by running the two-way mixed ANOVA with and without the outlier. The assumption of normality was violated; however, the data could not be transformed as it contains opposite skews. Despite failing to meet this assumption, we chose to carry on as the two-way mixed ANOVA is considered to be robust against deviations from normality [28].

5.1 Results

After evaluating assumptions for two-way mixed ANOVA, the overall change in content knowledge was first assessed, discounting differences between AM topic groups. This was done to verify the effectiveness of the educational intervention as a whole. Results are shown in Table 9 and Figure 6.

Copyright © 2018 by ASME

Table 9 Testing the Main Effect of Time on Overall Scores

Independent Variable	Significance
VR: pre-test and post-test AM concept scores	p<0.001
REAL: pre-test and post-test AM concept scores	p<0.001

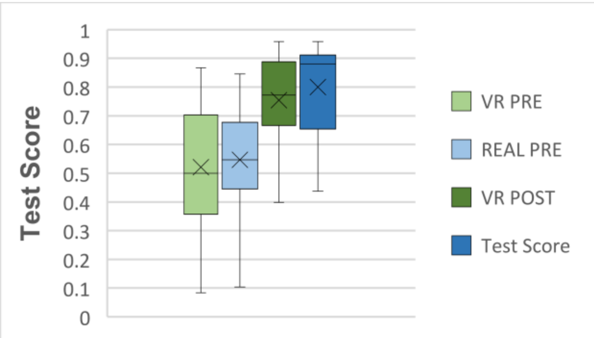

Figure 6 Overall Test Scores for VR and REAL Pre and Post Tests

Table 9 shows that over all of the AM learning objectives (split between VR and REAL), there was a significant change in AM content knowledge acquired by participants. This suggests that the AM lesson had an impact on participants' understanding of AM concepts. Figure 6 shows that the change in AM understanding was positive for both the VR and REAL groups. Finally, Table 10 shows the results for a t-test between the VR and REAL groups for cumulative pre-test scores, which yields no significant difference in AM knowledge between the two groups before engaging in the lesson. This confirms that there was no difference in starting AM knowledge between the two groups, preventing any unintended bias.

Table 10 T-Test Between VR and REAL Overall Pre-Test Scores

Independent Variable	Significance
VR and REAL pre-test	p=0.847

After quantifying learning difference regardless of group, within-subject contrasts were checked for each dependent variable group to ensure that there was a significant change in learning for each AM topic. This analysis provides an in-depth investigation of the validity of the lesson plan. Table 11 shows a significant change in content knowledge for each AM topic, when ignoring differences between the VR and REAL groups. This suggests a significant increase in learning occurred in the majority of AM content areas after participant exposure to the AM lesson, as desired. However the Support Generation topic did not see a significant difference in pre- to post-test concept scores. A possible explanation could be high pre-test scores in this area; students did well on the pre-test Support Generation questions with an average score of 64.5%, resulting in little room for improvement. This limited area for improvement could lead to insignificant learning differences for that topic.

After determining that the lesson and educational intervention produced statistically significant differences in pre- to post-test AM concept knowledge (shown in Table 11), two-way interactions were evaluated based on whether the participant was assigned to the VR or the REAL group; this allows for identification of significant differences in learning due to the specific educational environment. Interactions between the VR and REAL groups on pre- to post-test learning for each AM topic are listed in Table 12.

Table 11 Within Group Contrasts

Time (pre to post)	Measure	Significance
	Build Time	p<0.001
	Layer by Layer Deposition	p<0.001
	Material Use	p<0.001
	Support Generation	**p=0.111**
	Orientation	p=0.032
	Cartesian Coordinates	p<0.001
	Extruder Components/Functions	p<0.001
	Hot End Components/Functions	p<0.001

Table 12 Two Way Interaction Effects Group*Time

Time (pre to post) * Group (VR to REAL)	Measure	Significance
	Build Time	p=0.100
	Layer by Layer Deposition	p=0.673
	Material Use	p=0.271
	Support Generation	p=0.697
	Orientation	p=0.448
	Cartesian Coordinates	p=0.322
	Extruder Components/Functions	**p=0.042**
	Hot End Components/Functions	p=0.054

For the AM learning objectives of Build Time, Layer by Layer Deposition, Material Use, Support Generation, Orientation, Cartesian Coordinates, and Hot End Components/Functions, there is no significant interaction between the educational intervention format and pre- vs. post-test content scores. This suggests that the pre- to post-test learning differences for these particular objectives are relatively similar between the VR and REAL groups. The AM topic Extruder Components/Functions however does show a significant interaction effect (p=0.042) suggesting a difference in pre- to post-test learning between the VR and REAL groups.

5.2 Exploration of Inconsistencies

When exploring the results, we discovered themes that were inconsistent with our expectations involving overall AM learning as well as potentially significant VR and REAL interactions. In Table 11, it is shown that the AM topic Support Generation does not demonstrate a significant change in AM content knowledge. As discussed earlier, this may be attributed to high initial pre-test scores. To further explore this hypothesis, the mean pre-test score for Support Generation was compared to the pre-test means of the other AM learning objectives. A one sample t-test was conducted against a hypothesized pre-test topic mean of 0.54. The hypothesized pre-test mean was determined by calculating the average of the pre-test means of all the learning objectives that exhibited significant pre to post differences. The t-test yielded a p-value of 0.011, indicating a significant difference between the Support Generation pre-test mean and the hypothesized pre-test mean. This suggests that the average pre-test score for Support Generation was higher when compared to other AM topic pre-test scores. This explains the insignificant difference in Support Generation knowledge

Copyright © 2018 by ASME

gained. Since the pre-test scores are already high, it is difficult for participants to score significantly higher in the post-test.

When considering why participants scored higher on the Support Generation section on the pre-test, we hypothesized that students may have had previous experience relating to Support Generation resulting in higher self-efficacy compared to other AM learning objectives. This information can be gathered by looking at participants' self-efficacy ratings in the pre-test responses (see Figure 7). A non-parametric Wilcoxon signed-rank test [29] was performed to compare the Support Generation pre-test self-efficacy distribution to a hypothesized median based on self-efficacy scores of the other AM learning objectives. A hypothesized self-efficacy median of 2 was chosen based on self-efficacy scores of the other AM learning objectives. This test yielded ($p<0.001$) for the self-efficacy question: "Depositing sacrificial material to support a 3D printed object" and a p-value ($p<0.001$) for the self-efficacy question: "Using support structures for overhanging sections of a part". The Wilcoxon Signed Rank test shows a significant difference for both Support Generation self-efficacy questions with the observed median being higher than the hypothesized median. This shows that participants were in fact more comfortable with Support Generation as an AM topic in taking the pre-test. This could be because support generation has the most exposure of any of the AM learning objectives covered. Any student that has had some exposure to AM has likely come across the common consideration of support generation; support material is commonly discussed in frequently asked questions [30,31], and will typically be seen in exploratory prints.

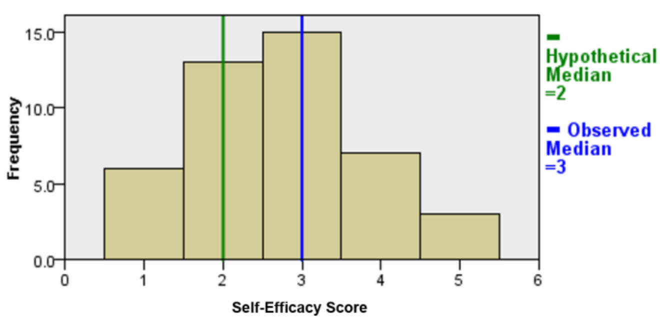

Figure 7 Wilcoxon Signed Rank Test for the Self-Efficacy Question: Depositing Sacrificial Material to Support a 3D Printed Object

An inconsistency was also found in the two-way interaction effects between groups (VR and REAL) and time (pre- and post-test). In Table 12, there is a significant interaction between the VR and REAL groups on pre to post learning for the AM topic Extruder Components and Functions. This suggests that one group learned more about this AM topic than the other. One potential explanation for this learning difference is that it is caused by different comfort levels between groups before the lesson. A Kruskal-Wallis H test [32] showed no significant difference between the two groups on the pre-test self-efficacy questions related to Extruder Components and Functions. For the self-efficacy question: *The interaction of printer components required to build an object,* a p-value of 0.198 was found. For the self-efficacy question: *The range of movement of the extruder in relation to the Cartesian axes (X, Y, Z),* a p-value of 0.261 was found. These results suggest that all participants had the same level of comfort in this topic before starting the lesson.

A Kruskal-Wallis test was run on the post-test self-efficacy questions as well to determine if either group felt more confident in the Extruder Components/Functions content questions after their lesson. For the self-efficacy question: *The interaction of printer components required to build an object,* a p-value of 0.046 was found. For the self-efficacy question: *The range of movement of the extruder in relation to the Cartesian axes (X, Y, Z),* a p-value of 0.238 was found. In the post-test, the group exposed to the lesson in VR felt they had a higher comfort with this AM topic. This is in alignment with the VR group's higher conceptual post-test score for Extruder Components/Functions shown in Figure 8.

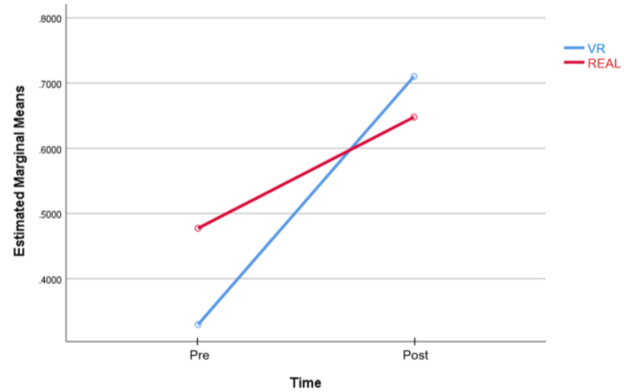

Figure 8: Significant Pre to Post-Test Conceptual Learning Differences Between VR and REAL Groups for Extruder Components/Functions

The interaction effects shown in Figure 8 suggest that the VR environment taught the AM topic of Extruder Components/Functions more effectively than the REAL environment. We hypothesize that this difference is due to the design of the conceptual understanding test. Questions on the conceptual understanding test relating to Extruder Components and Functions and Hot End Components and Functions included images of a disassembled extruder and hot end that were taken from the computer-designed facsimile that the VR group used. Participants in the VR group may have been more familiar with the images on the conceptual test (shown at the bottom picture of Figure 3) even though these images were of CAD models identical to components that the REAL group had available to them. The lighting and background used in the content questions would be familiar to the VR group, but not the REAL group.

6 DISCUSSION

The purpose of this study was to assess whether an interactive VR-AM lesson is as effective as an interactive AM lesson in a physical setting. If shown to be effective, VR may later be applied to more advanced AM concepts and technologies. Key findings and their relevance to AM in education are discussed within this section.

Copyright © 2018 by ASME

RQ1: The educational intervention yielded a positive overall change in AM learning regardless of group.

For the eight AM learning objectives that were covered in this study, there are no current, widely accepted standards for how they should be taught or evaluated. The lesson plan and examinations were created after consulting with AM faculty and AM experts, reviewing the general concepts taught in AM textbooks, and reviewing concepts taught in several AM courses. While the study does not cover all aspects of AM knowledge, after prior consultation we feel that the administered AM lesson and exams consisted of appropriate introductory concepts for desktop material extrusion. The positive overall change in AM learning shown in Table 10 and the positive change for the majority of AM learning objectives shown in Table 11 suggests that the administered lessons and questions were of educational value to first-year undergraduate engineering students. After demonstrating this overall educational value, it allowed us to evaluate participants exposed to AM technology in a traditional, physical setting and participants exposed to a functional, computer-designed virtual AM system as separate groups.

RQ2: For the majority of AM learning objectives, there was no significant learning difference between the VR and REAL groups.

Learning AM in a physical setting was assumed to be the preferable scenario over VR given that students are likely to be more familiar in interacting with physical objects and can interact more effectively with the facilitator; VR also presents the issue of model fidelity (i.e., how realistic is the virtual representation of the system) given technological constraints. However, analysis of the learning differences between the VR and REAL environments shows that the two mediums are actually rather similar in terms of educational gains made by the students. Table 12 shows that in addition to an increase in AM knowledge, there was no significant interaction between the VR and REAL groups (with the exception of Extruder Components and Functions). This suggests that there was similar AM conceptual learning between both groups and that VR is just as effective for introductory AM education as learning AM concepts in a physical setting.

RQ3: Disparities between VR and REAL groups are likely due to prior AM knowledge and/or unintended biases in test design.

The first deviation from expectation was a lack of overall AM knowledge increase for Support Generation. This can be attributed to relatively high conceptual and self-efficacy pre-test scores. Our assumption explaining this is that students are likely more familiar with support generation compared to the other AM learning objectives given its common appearance in 3D printed parts. The questions asked in this experiment revolving around support generation may not have been difficult enough to appropriately assess participants' increase in knowledge on this concept.

The second deviation from expectation was the significant group interaction for Extruder Components/Functions. Those exposed to the VR lesson seemed to have a better understanding of this AM topic, which was surprising to discover. It was assumed that if there was an interaction effect, then those exposed to the REAL lesson would perform better on these learning objectives because they are more familiar in interacting with physical objects. The fact that the VR group had a higher learning increase suggests there may have been biases hidden in the experiment's design. The obvious bias being the VR screen shots used on the examinations to identify components of the extruder and hot end. In future iterations of the administered tests, students would be provided with images paired with questions that neither group would be familiar with, to prevent unwanted biases depending on learning environment exposure.

7 CONCLUSION AND FUTURE WORK

While schools and industry programs are developing courses to teach AM skills, the scarcity of courses results in failure to meet the growing AM work force demand. Technological and financial constraints are also an issue, limiting the scalability of hands-on AM lessons. VR was proposed as a medium to effectively teach a wider audience. The work expressed in this paper suggests that VR can indeed be an effective medium for teaching introductory AM concepts. The results show that there is overall no significant difference between learning AM in a physical environment and learning AM in a virtual environment. More specifically, it was shown that there was no learning difference between the two environments for every AM topic covered with the exception of Extruder Components/Functions. From this lack of difference between groups, it may be inferred that Virtual Reality can be an effective tool for teaching introductory AM concepts.

Future iterations of this work could emulate higher-end industrial-grade AM systems. The work expressed in this paper was done with a desktop material extrusion machine that could be easily replicated in the physical and virtual space, but it would make a greater impact if applied to more advanced AM machines, since VR allows for exposure to more advanced AM systems with minimal cost and minimal operator risks (e.g., inhalation of metal powder). This work may also explore teaching more advanced AM learning objectives or make an argument for VR as a tool for Design for AM. Finally, VR has many advantages over learning in a physical setting, namely, the ability to manipulate time, gravity, geometries, and other features which are not possible in a physical setting. The research presented in this paper confirms VR to be an appropriate tool to support introductory AM education, but it merely scratches the surface of VR's capabilities and suggests a beneficial use for teaching aspects of more advanced/less accessible AM technologies.

ACKNOLEDGMENTS

This research was conducted with support from the National Science Foundation (NSF) under Grant No. CMMI-1547021, and the Penn State Center for Online Innovation Learning (COIL) through their Research Initiation Grant program. Any opinions, findings, and conclusions in this paper are those of the authors and do not necessarily reflect the views of NSF or COIL.

Copyright © 2018 by ASME

REFERENCES

[1] Wohlers Associates, 2014, “3D Printing and Additive Manufacturing State of the Industry, Annual 665 Worldwide Progress Report,” p. 276.

[2] Murr, D. L. E., 2015, “3D Printing: Opportunities, Challenges, and Policy Implications of Additive Manufacturing,” Gao-15-505Sp, (June), p. 63.

[3] Ford, S. L. N., 2014, “Additive Manufacturing Technology : Potential Implications for U . S . Manufacturing Competitiveness,” J. Int. Commer. Econ., **6**(September), pp. 1–35.

[4] Simpson, T. W., Williams, C. B., and Hripko, M., 2016, “Preparing Industry for Additive Manufacturing and Its Applications: Summary & Recommendations from a National Science Foundation Workshop,” Addit. Manuf., **13**, pp. 166–178.

[5] Baumers, M., Dickens, P., Tuck, C., and Hague, R., 2016, “The Cost of Additive Manufacturing: Machine Productivity, Economies of Scale and Technology-Push,” Technol. Forecast. Soc. Change, **102**, pp. 193–201.

[6] Williams, C. B., and Seepersad, C. C., 2012, “Design for Additive Manufacturing Curriculum: A Problem-and Project-Based Approach,” Int. Solid Free. Fabr. Symp., pp. 81–92.

[7] Go, J., and Hart, A. J., “A Framework for Teaching the Fundamentals of Additive.pdf.”

[8] Yang, Z., and Liu, Q., 2007, “Research and Development of Web-Based Virtual Online Classroom,” Comput. Educ., **48**(2), pp. 171–184.

[9] Pappano, L., 2012, “Massive Open Online Courses Are Multiplying at a Rapid Pace - The New York Times,” New York Times [Online]. Available: http://www.nytimes.com/2012/11/04/education/edlife/massive-open-online-courses-are-multiplying-at-a-rapid-pace.html.

[10] Rosenfeld Halverson, E., Imberly, K., and Sheridan, M., 2014, “Harvard Educational Review Winter 2014,” Harv. Educ. Rev., **84**(4), pp. 495–505.

[11] Pausch, R., 1993, “Three Views of Virtual Reality: An Overview,” Computer (Long. Beach. Calif)., **26**(2), pp. 79–80.

[12] Mitchell, D., 2009, “First Person: The Promise of Virtual Design,” Civ. Eng. Mag. Arch., **79**(9), pp. 50–59.

[13] Minetola, P., Iuliano, L., Bassoli, E., and Gatto, A., 2015, “Impact of Additive Manufacturing on Engineering Education – Evidence from Italy,” Rapid Prototyp. J., **21**(5), pp. 535–555.

[14] Gatto, A., Bassoli, E., Denti, L., Iuliano, L., and Minetola, P., “Multi-Disciplinary Approach in Engineering Education: Learning with Additive Manufacturing and Reverse Engineering.”

[15] Loy, J., 2014, “eLearning and eMaking: 3D Printing Blurring the Digital and the Physical,” Educ. Sci., **4**(1), pp. 108–121.

[16] Schelly, C., Anzalone, G., Wijnen, B., and Pearce, J. M., 2015, “Open-Source 3-D Printing Technologies for Education: Bringing Additive Manufacturing to the Classroom,” J. Vis. Lang. Comput., **28**, pp. 226–237.

[17] “Penn State World Campus | Courses - Additive Manufacturing and Design Master of Engineering” [Online]. Available: https://www.worldcampus.psu.edu/degrees-and-certificates/penn-state-online-additive-manufacturing-and-design-masters-degree/courses. [Accessed: 20-Feb-2018].

[18] Gibson, I., Rosen, D., and Stucker, B., 2015, *Additive Manufacturing Technologies*.

[19] Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C. B., Wang, C. C. L., Shin, Y. C., Zhang, S., and Zavattieri, P. D., 2015, “The Status, Challenges, and Future of Additive Manufacturing in Engineering,” Comput. Des., **69**, pp. 65–89.

[20] Rayna, T., and Striukova, L., 2016, “From Rapid Prototyping to Home Fabrication: How 3D Printing Is Changing Business Model Innovation,” Technol. Forecast. Soc. Change, **102**, pp. 214–224.

[21] Dorothy E. Leidner, and Sirkka L. Jarvenpaa, 1995, “The Use of Information Technology to Enhance Management School Education: A Theoretical View,” Manag. Inf. Syst. Q., **19**(3), pp. 265–291.

[22] Psotka, J., 1995, “Immersive Tutoring Systems: Virtual Reality and Education and Training.,” Instr. Sci., **23**, pp. 405–431.

[23] Bharathi, A. K. B. G., and Tucker, C. S., 2015, “Investigating the Impact of Interactive Immersive Virtual Reality Environments in Enhancing Task Performance in Online Engineering Design Activities,” *Volume 3: 17th International Conference on Advanced Vehicle Technologies; 12th International Conference on Design Education; 8th Frontiers in Biomedical Devices*, p. V003T04A004.

[24] Lesniak, K., Terpenny, J., Tucker, C. S., Anumba, C., and Bilén, S. G., 2017, “Immersive Distributed Design Through Real-Time Capture, Translation, and Rendering of Three-Dimensional Mesh Data 1,” J. Comput. Inf. Sci. Eng., **17**(3), p. 31010.

[25] Krathwohl, D. R., 2002, “A Revision of Bloom’s Taxonomy: An Overview,” Theory Pract., **41**(4), pp. 212–218.

[26] “TAZ 6 Controller Box | LulzBot” [Online]. Available: https://www.lulzbot.com/store/parts/taz-6-controller-box. [Accessed: 20-Feb-2018].

[27] “Downloads | LulzBot” [Online]. Available: https://www.lulzbot.com/content/downloads. [Accessed: 20-Feb-2018].

[28] “Two-Way ANOVA in SPSS Statistics - Step-by-Step Procedure Including Testing of Assumptions | Laerd Statistics,” Laerd Stat. [Online]. Available: https://statistics.laerd.com/spss-tutorials/two-way-anova-using-spss-statistics.php. [Accessed: 09-Mar-2018].

Copyright © 2018 by ASME

[29] Laerd Statistics, 2017, "Wilcoxon Signed Rank Test in SPSS Statistics - Procedure, Output and Interpretation of Output Using a Relevant Example." [Online]. Available: https://statistics.laerd.com/spss-tutorials/wilcoxon-signed-rank-test-using-spss-statistics.php. [Accessed: 10-Mar-2018].

[30] 2014, "The MatterHackers 3D Printing FAQ," MatterHackers [Online]. Available: https://www.matterhackers.com/articles/the-matterhackers-3d-printing-faq. [Accessed: 09-Mar-2018].

[31] Cain, P., "Supports in 3D Printing: A Technology Overview," 3D Hubs [Online]. Available: https://www.3dhubs.com/knowledge-base/supports-3d-printing-technology-overview. [Accessed: 09-Mar-2018].

[32] Lund Research Ltd, 2013, "Kruskal-Wallis H Test in SPSS Statistics | Procedure, Output and Interpretation of the Output."

Copyright © 2018 by ASME