# Influence of Virtual Human Appearance Fidelity within Building Science Storytelling Educational Applications

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**Abstract:** Building science employs student–professional interactions to increase the learning and engagement of domain topics. Although these interactions are beneficial to students, labor shortages and automation trends will create barriers to expose students to professionals in the future. One solution is to utilize virtual situated learning contexts for students to experience simulated interactions with virtual professionals. Within these simulations, virtual humans are often used as a vehicle to preserve knowledge and deliver it to students. However, the impact of the fidelity of virtual human appearance on providing knowledge to the students within the building science domain remains unexplored. This paper presents a virtual reality (VR) educational system integrated with digital storytellers and grounded in the building science electrical career path context to explore how virtual human appearance fidelity affects student learning and engagement. A between-subject study was conducted with 42 construction management participants to explore the impact of 3 virtual human appearance fidelity conditions (realistic, modeled, and abstracted virtual human) in terms of student learning, social presence, virtual human persona factors, and topic interest. The findings of this study demonstrated that successful educational outcomes could be achieved with low virtual human appearance fidelity due to the lack of significant differences observed across experimental conditions. Furthermore, the study results did not detect significant differences in students' engagement by increasing the virtual human appearance fidelity. However, students across all experimental conditions reported engagement increments in the topic learned. The increments in student engagement suggest that the virtual human's age and gender are important factors to consider when designing educational interventions. These results contribute to the understanding of how to create virtual humans for building science educational interventions.
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## Introduction

Student interactions with industry experts or professionals have proven beneficial for learning practical design and construction considerations within the building science domain (Alahmad et al. 2007). Often, professionals utilize different formal and informal venues such as workshops, field trips, or guest lectures to share their rich body of experiences, perspectives, and knowledge with students. These exposure opportunities enable students to engage in learning by connecting classroom knowledge with standard industry practices (Alahmad and Tills 2010) and gaining insights regarding new potential career paths (Beaty et al. 2014). However, it is expected that these student–professional interactions will become increasingly difficult to be offered within the building science curricula due to the rapidly aging workforce and the high automation trends in the industry. Researchers and governmental agencies have pointed to an increment in labor shortages for the building science industries in the United States (Olsen et al. 2012; US Bureau of Labor Statistics 2020) and other countries (Callejas-Sandoval and Kwon 2019; Li and Tai 2017). These workforce shortages are caused by two primary sources: (1) professionals leaving the industry once they reached the retirement age; and (2) a low influx of new professionals to replace the retiring professionals (Suryadi 2018). In addition to labor shortages, innovative technologies that help automate construction processes in the jobsite are becoming increasingly prevalent (Bock 2015). The automation of workforce tasks implies an immediate increase in labor productivity (Zhai et al. 2009) and introduces potential reductions in practicing professionals within future jobsites. Because these trends in workforce retirement and tasks automation are expected to persist, building science educators need to develop methods for enabling student exposure to industry professionals. While expert knowledge exposure is valued both in the building science academia and in industry, few investigations are available that explore the different aspects required to preserve and systematically replicate professional knowledge in building science educational applications.

One technology that has been employed to provide students learning experiences within classroom settings that mimic some aspects of the building environment—including interaction with professionals—is virtual reality (VR). Within these digital spaces, the utilization of virtual humans supports student–professional interactions that occur in simulated and contextualized built environment settings. In building science, virtual humans have been used to convey expert knowledge using verbal and nonverbal strategies, further enhancing the learning of complex information within the situated contexts (Eiris et al. 2018). One method used to deliver educational experiences in VR using virtual humans is storytelling. In building science VR environments, virtual humans have been used as a critical medium to convey narrations that connect the situated context with conceptual information (Eiris et al. 2018). Storytelling is an effective tool to deliver knowledge to the audience, because

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the narrations are memorable and entertaining (Neuhauser 1993). Particularly, achievement and transformation stories can encourage students struggling with career planning, motivation, and engagement (Rossiter 2002). Storytelling educational interventions have been shown to enable learners to internalize story contents, acquire new knowledge, and empathize with story characters, situations, and experiences (Eiris et al. 2020a). Storytelling mimics human communication that relies on indirect or tacit knowledge transfer, providing an ideal approach for expert knowledge preservation. Prior research has demonstrated that storytelling is an effective tool for knowledge preservation in academic domains, including cultural heritage (Selmanovic et al. 2018), health sciences (Bowles 1995), and engineering (Shaw and Liu 2016).

The study of virtual humans as narrators of expert knowledge within building science education is a multidimensional field of investigation that remains mostly unexplored. One area that requires immediate investigation is the appearance fidelity of virtual humans, because these digital representations are commonly used in a wide variety of building science educational applications (Eiris and Gheisari 2017). Although virtual human appearance fidelity selection introduces a critical design consideration in digital educational interventions, no evidence of effects on student learning and engagement is currently available within the building science domain. This study focuses on exploring the impact of the fidelity of virtual human appearance on student learning and engagement within highly realistic omnidirectional image-based VR environments. Leveraging the benefits of storytelling, an educational intervention was created to study student learning, social presence, and engagement effects produced by virtual human appearance fidelity within a situated context domain of building science. Different operationalized levels of virtual human appearance fidelity were introduced into an educational VR storytelling game system. Students experienced a situated context in the VR storytelling system through the narrations of an electrician apprentice, represented by a virtual human. The situated electrical career path context is traditionally challenging to access in educational settings due to difficulties in reaching remote jobsite locations and obstacles in obtaining communication opportunities with practicing trade experts and professionals. Moreover, the electrical context is a trade with a large labor shortage problem (Minooei et al. 2017), making it an ideal candidate for knowledge preservation purposes. In addition to understanding virtual human appearance fidelity impact on student learning and engagement, this research's educational intervention is expected to provide student learning opportunities through professional exposure and enhance the available techniques to preserve industry professional knowledge using virtual human-based storytelling and VR educational immersive experiences.

## Related Work

### VR Applications in Building Science Education

VR is defined as a computer-generated three-dimensional environment, in which users can manipulate objects, be immersed, and move around and see the environment from different angles (Pham et al. 2018; Warwick et al. 1993; Wen and Gheisari 2020). VR has been adopted in the building science domain to enhance learning experiences since the early 2000s (Wang et al. 2018). Within this building sciences, VR has been applied in various educational contexts, including architecture design and review (Kandi et al. 2020; Vosinakis et al. 2008), safety training (Le et al. 2015; Pham et al. 2018), equipment operation training (Su et al. 2013), and structural analysis (Young et al. 2012). There is growing evidence showing VR to be effective for providing students a better understanding and visualization of abstract concepts. Gu et al. (2009) demonstrated the use of a VR platform for architecture students to work remotely on a collaborative design project, which resulted in reports of visualization being easier to understand within the 3D medium for the design concepts. Furthermore, VR can significantly improve communication and collaboration skills by allowing multiple students, wherever they are located, to share their ideas in a dynamic 3D environment with various types of interaction tools (Anderson et al. 2014). Other researchers also highlighted that VR-based learning improves students' motivation and engagement by enabling students' interactions in active, hands-on explorations of the digital environment (Pedro et al. 2016; Pham et al. 2018; Young et al. 2012). VR can also provide students highly realistic representations of equipment, structure details, material placements, and working procedures of different construction activities on construction jobsites without exposing students to the real jobsites. Consequently, these safe and controllable exposures to jobsites support cost-effective opportunities for students to gain safety awareness on-site and learn to operate equipment (Cheng and Teizer 2013; Pedro et al. 2016; Pham et al. 2018). Although VR has been widely used in building science education applications with various learning focuses, there is very little research on leveraging VR technology in combination with digital storytelling for educational applications.

### Digital Storytelling for Learning

Storytelling is one of the oldest forms of education, because it has been widely used as a teaching tool to transmit knowledge, values, cultural beliefs, and traditions. Because of storytelling's ability to convey information across humans, researchers have considered it as an important knowledge preservation technique (Giannakou and Klonari 2019; Hamilton and Weiss 2005). Digital storytelling integrates oral and written storytelling traditions with various digital media such as images, music, recorded narrative audios, and videos (Robin 2016). In educational settings, digital storytelling is a powerful tool for both teaching and learning purposes. From the teacher's perspective, digital storytelling can be an effective tool to deliver knowledge, motivate, and engage students and raise students empathy with story characters, situations, and experiences, ultimately improving students' overall learning experience (Eiris et al. 2020b; Neuhauser 1993; Rossiter 2002). From the students' perspective, creating digital stories encourages them to conduct in-depth research and analyze and synthesize various information sources. Moreover, the creation process of stories has been found to enhance student communication skills through organizing their ideas, expressing their opinions, and crafting meaningful narratives (Robin 2016).

Digital storytelling has been popular in education since the 1990s. Humanities and social sciences have led the way using digital storytelling techniques, applying them to research areas that include culture, gender, language and literacy, social psychology, and social studies (Wu and Chen 2020). However, very few efforts in the building science domain have utilized digital storytelling. For example, Sakka and Zualkernan (2005) reported a case study of using digital storytelling in a civil engineering laboratory. Students created digital stories in a video format to explain their lab experiments and educate other students on the process. Study outcomes concluded that storytelling enhanced the understanding of specific experiment and equipment operation and improved the students' communication skills. In another study, Eiris et al. (2020b) applied embedded story narratives within 360° virtual environments to provide safety training. The study found that the digital storytelling experience provided a similar outcome to Occupational Safety and Health Administration (OSHA) safety training while reducing the required training time.

Because media is an important component in digital storytelling, many studies have been conducted to investigate the impact of various techniques (e.g., images, videos, and recorded narrations) for telling digital stories. However, little research has focused on an essential component within storytelling—the storyteller's physical existence (NSN n.d.). In a traditional storytelling experience, the storyteller and the audience are in the same space. The storyteller can easily engage the audience with their body gestures and facial expressions and build an emotional connection with the audience. However, such body gestures and facial expressions of the storytellers are not always available in digital storytelling. Although digital stories have been integrated into several educational applications, the impact of the storyteller's physical existence and appearance on digital educational stories remains unclear.

### Virtual Humans in Building Science Education

A virtual human is a computer-generated entity that replicates the human embodiment within a digital environment. Typically, virtual humans are used as a medium to interact with other objects, humans, and systems in digital spaces (Eiris and Gheisari 2017). There are two common classifications of virtual humans that depend on the different methods users employ to interact with these entities—avatars and agents. This study utilizes the definitions presented by Badler (1997) for avatars and agents: an avatar is a virtual human, operated in real time by a user, while an agent is a virtual human, operated by computer software. In building science education, virtual humans have been commonly used as avatars to explore and interact with the virtual environment. Multiple studies of virtual human applications have conducted research that involves these human representations for safety training purposes, including hazard recognition and hands-on safety training. In these applications, virtual humans are controlled by the users to observe and manipulate objects in the virtual world. For instance, Kiral et al. (2015) developed a virtual safety training tool, V-SAFE (Virtual Safety Analysis for Engineering applications), to simulate and visualize construction safety training scenarios. In this platform, the user controls an avatar through a keyboard and mouse while having a first-person view. The avatar enabled the user's interactions with 3D objects and other users. Virtual humans have been employed in other educational areas, such as design education (Yan et al. 2011), collaborative education (Arain and Burkle 2011), and project planning (Goedert and Rokooei 2016). Analogously, the users controlled an avatar to communicate with other virtual humans, objects, and systems to exchange ideas and practice project teamwork, resource management, and project optimization (Arain and Burkle 2011). Some building science applications have also used virtual humans as agents. In Eiris et al. (2020c), a virtual human is used as an agent, which is preprogrammed and controlled by the software, to act as a narrator to introduce embedded learning materials and guide students in their developed educational application. Even though virtual humans have been widely applied in various building science educational applications as both student-controlled avatars and computer-controlled agents, few studies have been conducted in building science education to understand the impact of the virtual human presence and utilization on users' learning and engagement.

### Pedagogical Problem: Virtual Human Appearance Fidelity and Its Impact on Learning

Virtual human fidelity refers to the degree to which a digital human presentation resembles a real human (Badler 1997). Virtual human fidelity spams five dimensions to characterize human representations in virtual environments—appearance (accuracy of visual representation), function (range of functions to replicate humans), time (accuracy of animations), autonomy (intelligence to react and make decisions), and individuality (personality associated with interaction with other real or virtual people) (Badler 1997). From these five dimensions, virtual human appearance fidelity is particularly important due to its impact on the creation (more technically involved and more computationally expensive for the higher end of appearance fidelity —Volonte et al. 2019) and utilization (varying effects for users in terms of experiences, emotions, and behaviors—Zibrek and McDonnell 2014) of systems that center on virtual humans. Virtual human appearance fidelity ranges from a stylized form or cartoon-like shape to a physiologically accurate model of a human (Badler 1997). The effects of virtual human appearance fidelity on the user experiences, emotions, and behaviors are well documented in the computer science domain. Previous research has shown that increasing the appearance fidelity of a virtual human does not always lead to a better user experience. In McDonnell et al. (2012), researchers found that increasing virtual human appearance fidelity increased participants' distraction behaviors due to anomalies or discrepancies in virtual human animations or actions. However, other studies have found that photorealistic representations of virtual humans can elicit significantly higher levels of positive emotions than a cartoon-like or sketch-like model. Moreover, a comparison of cartoonish and photorealistic virtual human models has pointed to significant increases in arousal for the photorealistic condition (Chaturvedi et al. 2015). Prior research in the medical science domain indicates that virtual human appearance fidelity also affects situated educational settings, improving student learning processes within the VR simulation. For example, Pence et al. (2013), in a study for practicing nurse interviewing skills, found that the appearance fidelity of the virtual humans had an indirect impact on student learning outcomes. The researchers observed that students preferred virtual humans with higher appearance fidelity, because high-appearance fidelity virtual humans produced higher satisfaction rates from participants. Satisfaction is highly correlated with engagement (Wefald and Downey 2009), which is critical in learning processes (Carini et al. 2006). However, no significant differences were found for learning outcomes across low- and high-appearance fidelity conditions.

## Research Overview and Questions

Although prior researchers in other domains outside building sciences have shown that virtual human appearance fidelity is an important factor for student learning and engagement, no studies have been conducted in the building science domain to explore virtual human appearance fidelity. However, with increasing numbers of VR applications that leverage virtual humans in the building science educational contexts, virtual human appearance fidelity is critical for study because it can affect the creation and utilization processes for systems that use virtual humans. Consequently, the goal of this study is to explore the impact of virtual human appearance fidelity on student learning and engagement in building science applications. This research goal led to the formulation of the following three research questions for this study:

- (RQ1) How does virtual human appearance fidelity affect students' learning in building sciences?

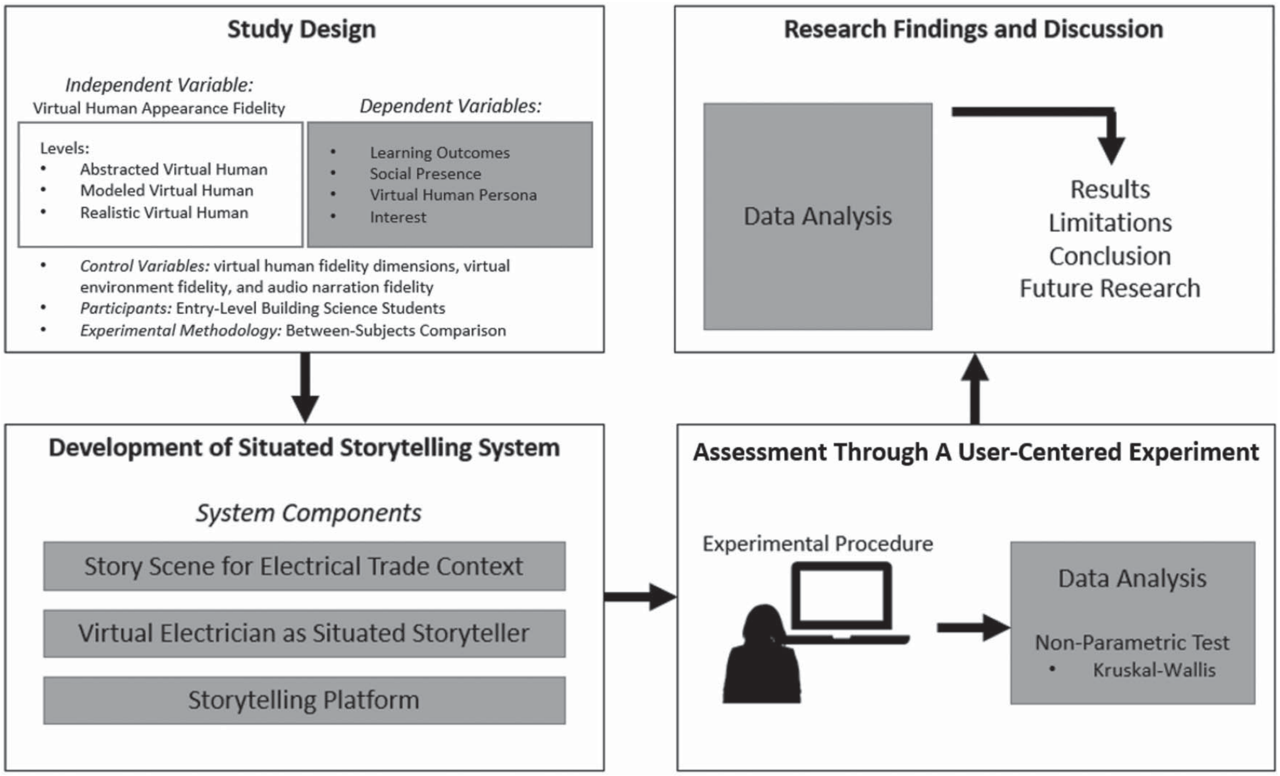


**Fig. 1.** Overview of the research study.

- (RQ2) How does virtual human appearance fidelity affect students' engagement in building sciences?

Fig. 1 shows the phases required to complete this study. To evaluate the effect of the virtual human appearance fidelity, a study design was established. Virtual human appearance fidelity was operationalized in three levels within the spectrum proposed by Badler (1997). Four dependent variables (learning outcomes, social presence, virtual human persona factors, and interest) were used to answer the two research questions described in this section. Additionally, within the study design, the target participant population was defined, and the selected experiment methodology was described. To realize the study design, a VR storytelling system was developed. The VR storytelling system was situated in the electrical trade to illustrate a typical career path in a highly realistic setting. A user-centered between-subject experiment was performed using the VR storytelling system. The study measures collected were analyzed with descriptive and statistical data analysis tools, obtaining insights regarding the influence of different levels of virtual human appearance fidelity in student learning and engagement. The study findings were reported by discussing the results observed from the student's experiences with the varied virtual human appearance fidelity conditions. Ultimately, the study limitations, conclusions, and future research directions were presented.

## Study Design

This study aimed to understand the influence of virtual human appearance fidelity on student learning and engagement within the context of the building science domain. Two research questions were formulated to investigate the influence of virtual human appearance fidelity on learning and engagement, as described in the previous section. To address these research questions, a study was designed to explore the effects of different operationalized levels of virtual human appearance fidelity within an educational storytelling system. The storytelling technique helped ground the exploration of virtual human appearance fidelity by providing a real-world context that focuses on electrical expert–preserved knowledge. The following are detailed descriptions of independent and dependent variables, the participants, and the experimental design of this study.

### Independent Variable

The independent variable of this study was centered on virtual human appearance fidelity due to its direct impact on creating and utilizing virtual human-centered systems. Typically, levels of appearance fidelity are operationalized within the appearance fidelity spectrum proposed by Badler (1997). Other research studies in the computer science domain have operationalized appearance fidelity within this spectrum, including levels such as realistic/toon/abstract (McDonnell et al. 2012); realistic/cartoon/sketch (Volante et al. 2016); and realistic/simple/sketch (Zibrek et al. 2019). For this study's design, appearance fidelity was operationalized similarly to previous efforts under three distinct levels of appearance fidelity (Fig. 2). At the first level, the virtual human appearance was abstracted to minimize the embodiment to a glowing sphere. This Level-1 condition—Abstracted Virtual Human (AVH)—offered students guidance within the situated virtual environment using a representation similar to digital assistants (e.g., Amazon's Alexa, Apple's Siri, and Microsoft's Cortana). The AVH-level condition represented the lowest end of the spectrum in virtual human appearance fidelity. In the second level, the virtual human appearance was represented by using a cartoon-like model of a human. The Level-2 condition—modeled virtual human (MVH)—offered attentional allocation to student similar to other existing VR education and training application building sciences (e.g., Yan et al. 2011; Arain and Burkle 2011; Goedert and Rokooei 2016) by using geometrical polygonal models that approximate

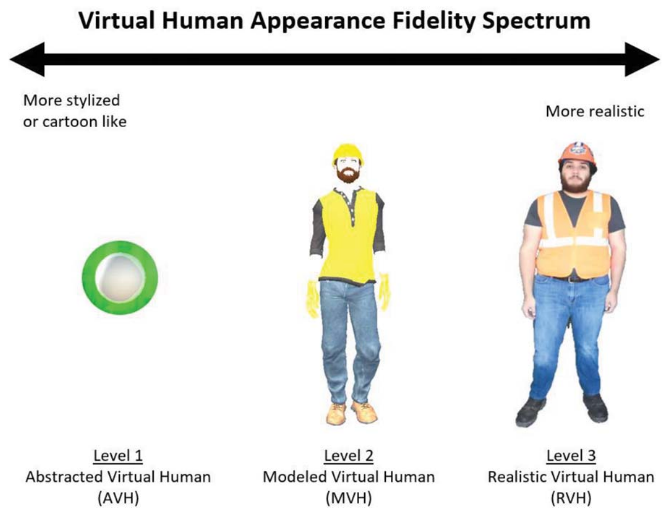


**Fig. 2.** Study independent variable—virtual human appearance fidelity levels within spectrum.

human anatomy. Within the MVH-level condition, the cartoon-like model mimicked a typical electrical trade worker with appropriate personal protection equipment (e.g., steel toe boots, reflective vest, and hard hat). The MVH-level condition demonstrated an intermediate depiction of appearance fidelity within the spectrum of virtual human appearance fidelity. In the third level, the virtual human appearance was rendered by using a realistic replica of the human anatomy. The Level-3 condition—Realistic Virtual Human (RVH)—enables attention allocation to students using a video recording of a real human. The RVH level provides a representation of the high end in the spectrum of virtual human appearance fidelity. The goal of the RVH is to replicate a typical construction worker with appropriate personal protection equipment.

### *Control Variables*

To guarantee consistency in the study design when assessing learning and engagement, three other variables of the study were controlled across the selected levels of virtual human fidelity in the appearance spectrum—virtual human fidelity dimensions other than appearance (function, time, autonomy, and individuality), virtual environment fidelity, and audio narration fidelity. For the virtual human dimensions, all variables except appearance (independent variable for this study) were kept constant in this study. The function dimension was controlled by maintaining the purpose of the virtual human as a narrator constant at all appearance levels. The time dimension was kept consistent for the conditions by providing equivalent animations appropriate for each type of virtual human appearance fidelity. The autonomy dimension was controlled for each condition by utilizing the same storytelling technique at all appearance levels. Finally, the individuality dimension was controlled by using the same male voiceover personality for all virtual humans. For the virtual environment fidelity, omnidirectional images were specifically selected to generate a high sense of presence, as found in prior studies that utilize this technology (Eiris et al. 2020a; Lee et al. 2016). Virtual environments that produce a high sense of presence have been found to significantly and positively impact learning outcomes in VR-based learning applications (Lee et al. 2010). Finally, for the audio narration fidelity, IBM's text-to-speech voiceover was selected to maintain a neutral voice tone and consistency in voice inflection across all story narrations and the same audio quality.

### *Dependent Variables*

The dependent variables of this study aimed to answer the two research questions of this study. Each dependent variable mapped to the research questions as previously outlined. The following is a detailed description of each dependent variable and how it aligns with each research question of this study.

#### Learning Outcomes (RQ1)

Learning outcomes measured the student learning within the VR storytelling system. This measure was mapped to RQ1 to assess the effect of students' learning under each level of virtual human appearance fidelity. A questionnaire was created specifically for the scope of this study, containing two multiple-choice questions and three open-ended questions. The questionnaire measured the student's ability to (1) describe the type of work an electrician performs, (2) explain the work environment of electricians, and (3) discuss electrical career paths to enter the industry. These questions aligned with the learning objectives established for the storytelling system as described in subsequent sections of this study. The question responses were graded by a building science domain expert using an established baseline rubric. Partial credit was awarded in the open-ended questions if the answers were only partially correct. Once graded, the scores ranged from a maximum score of five points and a minimum of zero points. Appendix I contains the specific questions and the grading rubric utilized for this measure.

#### Social Presence (RQ2)

Social presence refers to the extent to which students experienced the feeling of being with the virtual human throughout the story narration. The measurement of social presence was selected for study because it has been associated with engagement increments within virtual environments (Ning and Khalifa 2008). This measure was mapped to RQ2 to affect students' engagement under each level of virtual human appearance fidelity. Prior studies in computer science have mixed results in terms of how virtual human appearance fidelity affects social presence (Pence et al. 2013; Zibrek et al. 2019), but no studies are available in building science applications. The validated social presence questionnaire by Bailenson et al. (2003) was used to evaluate student social presence. This survey contained five statements on a 7-point Likert scale (ranging from 1—Strongly Disagree to 7—Strongly Agree) that evaluated social presence. Examples of such statements are "I perceive that I am in the presence of another person with me." and "The person appears to be sentient, conscious, and alive to me."

#### Virtual Human Persona (RQ2)

The student learning during the interaction with the virtual human was evaluated in terms of (1) facilitating learning, (2) credibility, (3) human-like, and (4) engagement. This measure was mapped to RQ2 to affect students' engagement under each level of virtual human appearance fidelity. These metrics were measured using the validated Agent Persona Instrument (API) by Baylor and Ryu (2003). The facilitating learning dimension describes how well the virtual human assists the students during the learning process. The credible dimension indicates the virtual human believability while the students follow the story content. The human-like dimension explores the student perception of the virtual human naturalness and personality while discussing the story. The engagement dimension indicates the student-experienced entertainment and enjoyment while interacting with the virtual human. These four dimensions' measures have been linked to positive virtual human engagement effects on learners' interactive experiences. The API employed a total of 25 questions that used a 7-point Likert scale (ranging from 1—Strongly Disagree to 7—Strongly Agree) to rank each statement.

**Interest in Electrical Trade Career Path (RQ2)**

The interest measure in this study assessed the motivational disposition of students toward the electrical career path. The motivational dimension of interest has been directly linked to positive engagement within educational applications (Hidi and Renninger 2006). The following open-ended question was used to better understand engagement effects with the story narrative. Specifically, how the story delivered by the virtual human might have sparked curiosity in students regarding electrical work and associated career paths. This measure was mapped to RQ2 to affect students' engagement under each level of virtual human appearance fidelity. To measure student interest, the following open-ended question was used: "After experiencing the story, are you more likely to find out more information about a career related to electrical work?."

### *Participants*

Building science undergraduate students in building sciences from entry-level courses were purposefully sampled for this study. Students in entry-level courses were specifically targeted for this study due to the low probability of having professional or academic exposure to electrical trades and their corresponding career paths. Consequently, the target population possessed minimal-to-no knowledge associated with the learning outcomes described in the dependent variables of this study.

### *Experimental Methodology*

For this study, a between-subjects experimental methodology was selected. Each of the three levels for virtual human appearance fidelity represented an experimental condition that was randomly assigned to the study participants: Condition 1—AVH, Condition 2—MVH, and Condition 3—RVH. This experimental methodology was chosen to reduce the learning effects produced by exposure to VR storytelling learning intervention.

## Development of the Situated Storytelling System

For this study, an educational storytelling system was developed to demonstrate domain electrical expert–preserved knowledge with a situated real-world context. The storytelling system enabled the exploration of the research questions proposed by the study. This section describes the technical procedures utilized in creating the situated storytelling narration, developing virtual human storytellers with various appearance fidelities, and implementing the developed educational intervention.

### *Development of the Story Narrative within the Electrical Trade Context*

The creation of the situated storytelling context for this study required developing a story narrative grounded in expert knowledge. To demonstrate the electrical expert knowledge, the student experience was centered on the career path of an electrical trade apprentice. This topic was selected because of the current difficulties in student–professional interactions within students' early building science careers. Often, job fairs or outreach programs (e.g., workshops, field trips, and guest lectures) are used to expose students to electrical trade careers. Although these conventional methods have helped in enabling students to interact with electrical professionals and their associated knowledge base, certain challenges hinder the opportunities for students to learn more about electricians and their career paths: (1) traditional methods cannot provide a true-to-life representation of electrical trade careers and their workplace (Walsh 2016); (2) these methods are costly and require a significant amount of time to be appropriately planned and implemented (Leece 2005); (3) there are limitations in terms of how many people can physically attend sessions in traditional methods; and (4) there are only a few of those sessions available, and only for a short period of time (hours/days) (Brennan et al. 2004). Consequently, virtual storytelling offers a method to overcome these barriers, enabling students to be immersed in the electrical trade career and workplace.

The Occupational Outlook Handbook of the US Bureau of Labor Statistics (2020) was employed to conceptualize an ideal story for students to get exposed to the electrical trade. This handbook was utilized to establish electricians' typical tasks, the characteristic of their work environment, and the suggested career paths to enter this trade. As a result of this content analysis of the report, three learning objectives were established for the students in the story narrative: (1) recognizing the type of work an electrician performs, (2) understanding the work environment of electricians, and (3) identifying electrical career paths to enter the industry.

Based on these learning objectives, a narration was created utilizing a "Day in the Life" format to describe the events occurring in an electrician's career. This storytelling technique is commonly used in video journalism to deliver thematic and cohesive narratives regarding a subject's typical daily activities (Kobre 2013). Subsequently, the narration was broken into key events to form a structured storyboard. The storyboard helped connect the narration to visual sketches that demonstrated the concepts and situated contexts targeted in the learning objectives. A storyboard was established with six scenes that described the day in the life of an electrician apprentice. The storyboard contained the following scene sequence: (1) introduction to the electrical work; (2) electrical work in an early phase of a construction project; (3) electrical work in an advanced phase of a construction project; (4) electrical work in a completed construction project; (5) electrical work and construction safety; and (6) main advantages of working in the electrical trade and story conclusion.

### *Creation of Story Scenes for the Electrical Trade Context*

The next step in creating the situated storytelling context for this study was to develop a set of realistic virtual locations that properly corresponded to the sequence of events contained in the previously developed storytelling narrative. The creation of realistic locations in virtual scenes was achieved using omnidirectional images. Omnidirectional images utilize reality capturing techniques to create immersive visualizations of real-world environments by leveraging omnidirectional camera technologies (Eiris and Gheisari 2019). The images crafted by omnidirectional cameras re-create locations in a true-to-reality manner, employing an equirectangular projection format that captures all surroundings of an environment. Prior applications in the building sciences have used omnidirectional images for interactive educational experiences, augmenting information in realistic backdrops to demonstrate difficult-to-visualize concepts, and safety training visualizations (Eiris and Gheisari 2019).

Omnidirectional scenes were used to demonstrate real-world locations and visually connect the storyboard with story learning objectives. The omnidirectional scenes and their primary purpose in this story are as follows (Fig. 3):

- *(Scene #1) Introduction to the electrical work:* The virtual electrician introduces himself as an electrician apprentice, describes

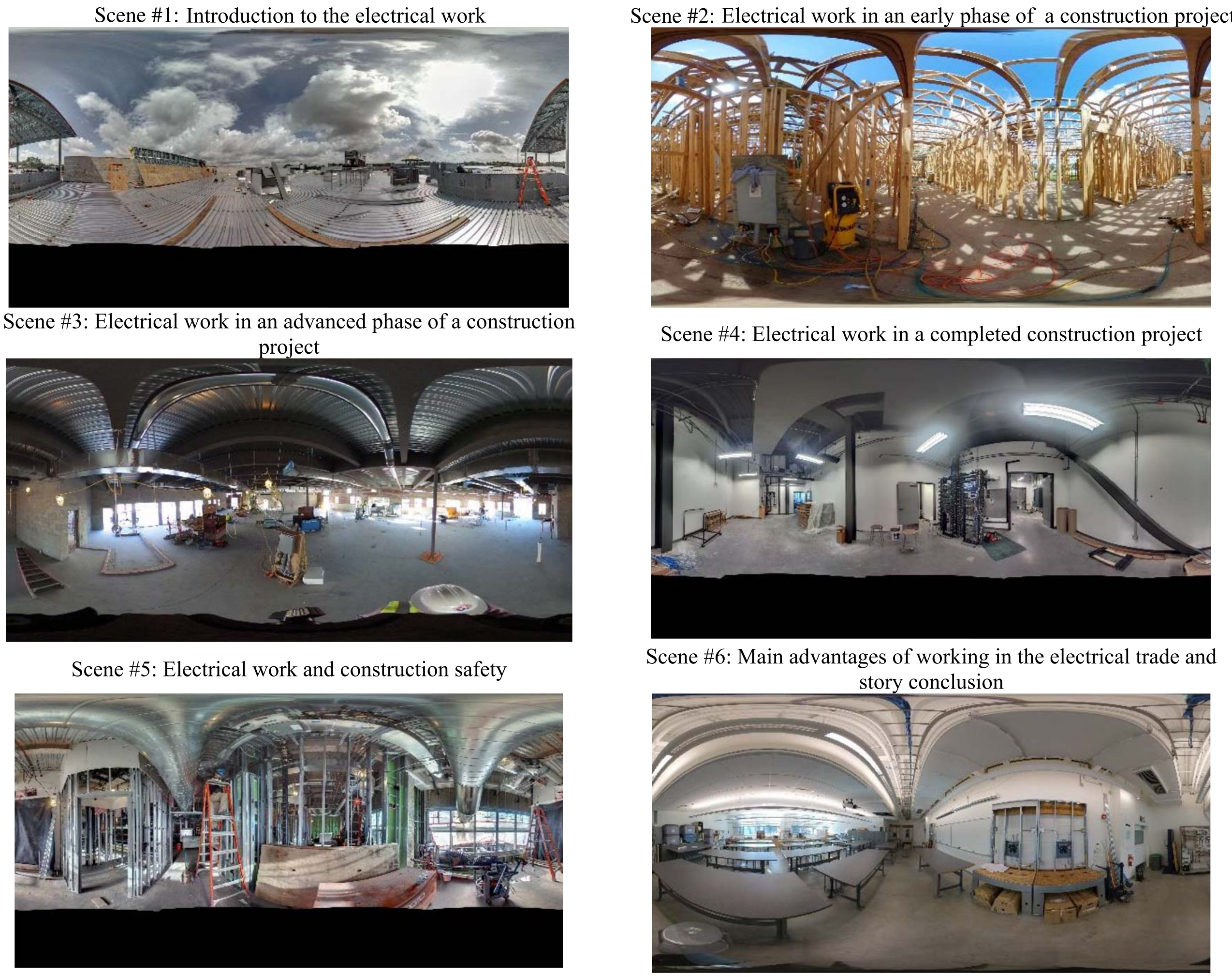


**Fig. 3.** Story scenes locations for the electrical apprentice career path.

the concept of electrical trades, and presents the type of environments electricians work in;

- *(Scene #2) Electrical work in an early phase of a construction project:* Explains the interconnection between the power grid system and temporary power in an early stage of a construction site;
- *(Scene #3) Electrical work in an advanced phase of a construction project:* Describes the need to provide temporary lights for construction tasks and the requirements for wire routing for permanent systems;
- *(Scene #4) Electrical work in a completed construction project:* Depicts the requirements for maintenance and new work within finished buildings;
- *(Scene #5) Electrical work and construction safety:* Introduces potential hazards and risks electricians are exposed to in their work environment (e.g., falls and electrocutions);
- *(Scene #6) Main advantages of working in the electrical trade and story conclusion:* Explains how apprentices attend classes and train on-the-job while getting paid. In this scene, the story concludes with a personal reflection on how the electrical career path leads to a rewarding profession.

These scenes were carefully selected from a data set of omnidirectional images to match the developed story narrations. The research team established this data set by visiting over 11 residential and commercial building construction sites and collecting approximately 900 scenes captured by advanced omnidirectional cameras (Insta 360 One X, Ricoh Theta V, NCTech Fusion, and Samsung Gear 360-2018). Using these selected omnidirectional images, the storyboard's narrations were revised to correspond to the visual information contained in the initial draft for each scene. Sections of the initially developed narrations were modified to correspond to the graphical contents within the omnidirectional images, providing a cohesive story experience to the students in terms of knowledge content and their visual representations in the virtual environment. As an example of the resulting revised narratives, Fig. 4 demonstrates electrical work in an early phase of a construction project. In this specific scene, the electrician apprentice represented by a sketched virtual human describes the apartment complex location contained in the omnidirectional scene in the Marked Spot #1. At the location, he identifies temporary panel boards used to service the site and describes the connection to the public utilities power grid. Then, the sketched virtual human transitions to the Marked Spot #2 in the omnidirectional scene once the voiceover narration is completed. A transition indicates that the virtual human moves toward Spot #2 marked in the scene by teleporting itself to that location. An arrow within the omnidirectional scene indicates to the student the new location of the virtual human. Once the virtual human reached Spot #2, the narration expanded on the concept of temporary panel boards. Finally, a description is provided explaining how apprentices help deliver temporary power to workers to support the successful completion of construction activities. The spots shown in Fig. 4 are only illustrative for this example description and do not physically show in the produced VR storytelling system.

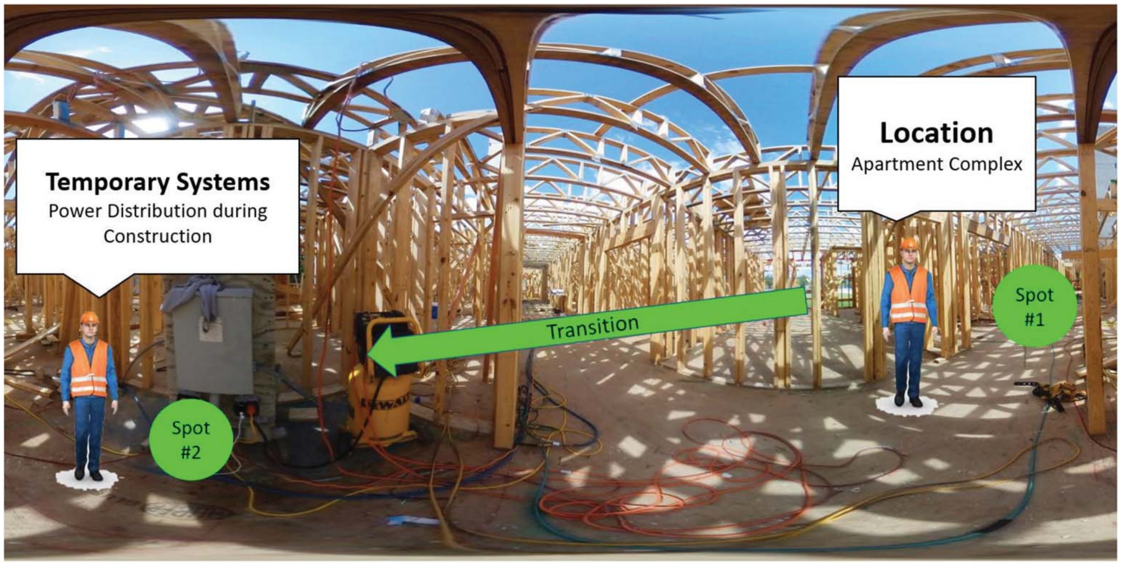


**Fig. 4.** Example of Scene #2—electrical work in an early phase of a construction project.

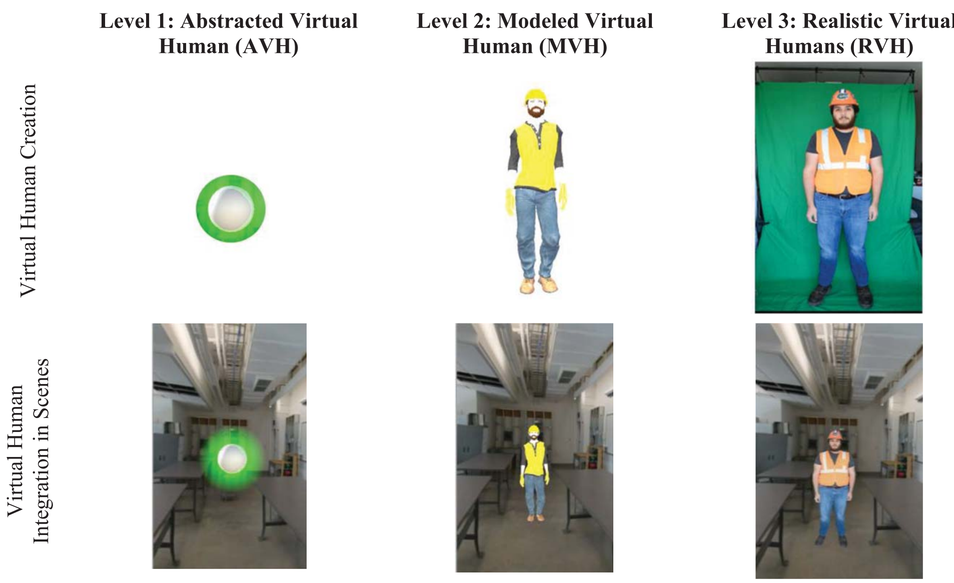


**Fig. 5.** Appearance fidelity levels of a virtual human.

Appendix II contains all the other scenes with text narrations used in the storytelling intervention.

### *Development of a Virtual Electrician as a Situated Storyteller*

An integral part of the educational storytelling system that interconnects the narrations and the situated context is the storyteller. A virtual human was used as a narrator or storyteller with three varying levels of appearance fidelity (Fig. 5). To secure that all virtual humans presented equivalent proportions and spatial positions, all the virtual humans were placed within the scene by locating the geometrical center of their bounding box. The technical development for the three levels of virtual human appearance fidelity was completed as follows:

- *Level 1:* For the AVH, the primitive geometrical shape of a sphere contained in the Unity game engine was utilized for the generation of the abstracted virtual human appearance. The glow was achieved with the existing halo shader effects contained in the scripts of the Unity game engine.
- *Level 2:* For the MVH, commercial software such as Adobe Fuse and Adobe Mixamo was utilized to model and animate the virtual human at this appearance fidelity level. The texturized and animated FBX model was introduced into the Unity game engine. The animator tool in the Unity game engine was used to seamlessly connect individual animations into a continuous and cohesive animation for each narration.
- *Level 3:* For the RVH, video recordings of a real human were used to depict the virtual human. A screen was employed to record images that allowed the removal of the background, replacing it with situated omnidirectional scenes. Adobe Premiere was used to edit and remove the backdrop, enabling a transparent alpha background using a *.WEBM format.

A set of five different base animation poses were established to maintain consistency across the Levels 2 and 3 of the virtual human appearance fidelity conditions (Fig. 6). Combinations of these five poses enabled the virtual humans to replicate realistic conversational behaviors during the delivery of a set of narrations. These sets of animations were designed to match different sections of the narrations. The Pose-(1)—Pointing Forward—was used to provide a hint to the listener to remember information previously presented in the story (e.g., "As you observed on previous sites we visited, much of my work is performed by a single electrician"). The Pose-(2)—Pointing Backward—was utilized to point the listener toward the surrounding location of the virtual human (e.g., "This is the temporary panelboard that I recently installed"). The Pose-(3)—Arms Waving—and Pose-(4)—Idle—were employed as the general cues for the listener to establish rapport during the narration delivered by the virtual human (e.g., "The temporary panelboard is a component of an electricity supply system that divides an electrical power feed into subsidiary circuits. The temporary panelboard also provides protective fuses or circuit breakers for each circuit in a common enclosure"). Finally, the Pose-(5)—Waving—was used during the introduction of the virtual human or to reinforce attention toward the virtual human (e.g., "Hello, my name is Michel. I'm an electrician apprentice"). The first level of the virtual human appearance fidelity (AVH) contained only a single blinking animation of the halo glow effect (on/off) to indicate when the virtual human was narrating in the scene.

### *VR Storytelling System Development Using Unity Game Engine*

A VR storytelling system was developed to deliver the educational intervention situated in the context of the electrical career path. The Unity game engine was employed to create the situated storytelling experience in the electrical context. Fig. 7 illustrates the creation process of the storytelling system. The storytelling system was composed of three elements: (1) story narratives, (2) virtual humans, and (3) omnidirectional scenes. The (1) story narratives represented the text contents crafted for the story scenes, described in prior sections. The IBM Watson text-to-speech services were utilized to create audio files for all these created text narrations. The (2) virtual humans contained the developed storyteller representations, including renderings and animations. The development of the virtual human renderings and animations corresponds to the processes previously discussed in prior sections. The (3) omnidirectional scenes contained the site images selected during the storyboarding process. Custom scripts were developed within the Unity game engine to interconnect the generated audio narrations with the animated virtual humans and the omnidirectional scenes. These scripts enabled students to explore the jobsite environment, gaining situated contextual information through observation and interaction. In the resulting storytelling system implementation, the students followed the virtual human's "Day in the Life" story across the six omnidirectional scenes previously discussed. The VR storytelling system was designed to be supported on desktop or laptop computers for both Windows and Macintosh operating systems. The interaction methods for advancing the story and exploring the scenes employed mouse-and-keyboard gestures such as point-and-click and drag-and-drop mechanisms. Additionally, a user interface was implemented to directly control the story's flow from the omnidirectional scenes by clicking on a directional arrow.

## Assessment through a User-Centered Experiment

Virtual human appearance fidelity was assessed by using an experimental design and protocol established for this investigation. Building science undergraduate students from Rinker School of Construction at the University of Florida were recruited at four entry-level courses. The experimental details and data analysis techniques are presented in the following subsections.

### *Experimental Protocol*

The educational interventions embedded in the storytelling system were distributed and experimentally evaluated using the Qualtrics online surveying platform. The data collection process for this study was

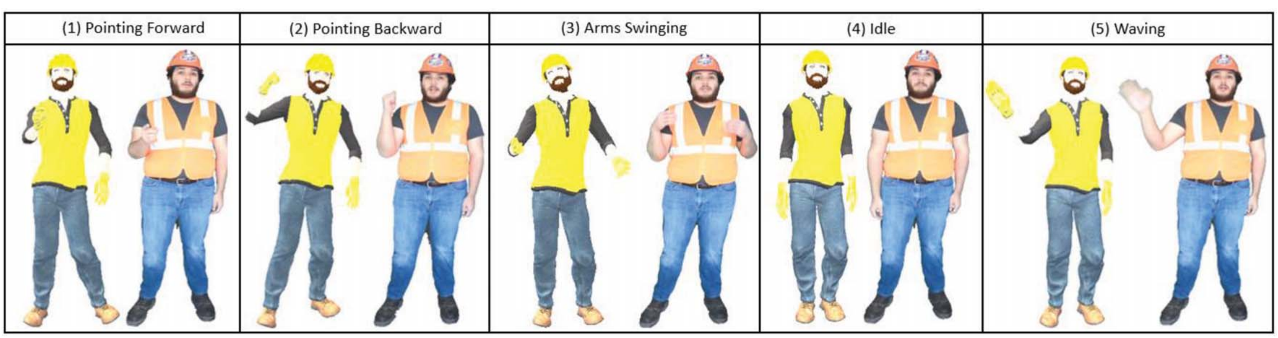


**Fig. 6.** Animation poses for modeled and realistic appearance fidelity levels of virtual humans.


**Fig. 7.** Development of storytelling system for educational intervention.



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conducted over a 5-day period. The students were randomly assigned to one of the three virtual human appearance fidelity condition levels in equal proportions, and each condition took approximately 30 min to complete 12 min in the VR storytelling system and 18 min to complete survey questions. Initially, an online questionnaire was provided that contained a consent form and a demographics survey before starting the experiment, as established in UF-IRB protocol #202000796. Subsequently, the students used their local computers (laptop or desktop) to download the platform version associated with their experimental condition and executed it. Afterward, the students were asked to complete an online questionnaire with the four different measures described in previous sections of this study.

### Data Analysis

The quantitative data collected from the study, which consisted of learning outcomes, social presence, and the agent persona instrument score metrics, were analyzed using descriptive and inferential statistics. Initially, descriptive statistics, including mean, median, and standard deviation, were computed and explored. To calculate these descriptive statistics, the questions that indicated each specific measurement were compounded into a single score that represented the variable measured following the data analysis strategies suggested by Bailenson et al. (2003) and Baylor and Ryu (2003). Subsequently, a set of Shapiro–Wilk normality tests were performed to evaluate the shape of each data distribution. All measures resulted in non-normal distributions ($p$-values > 0.05), which guided the use of nonparametric statistical tests. Kruskal–Wallis tests were used to detect any statistical differences between the three levels of the experimental conditions. The qualitative data obtained from the interest metric were coded to determine if the participants expressed curiosity in finding more information about electrical-related careers. The coding process evaluated the students' statements in the open-ended question to categorize it into positive interest as "Yes" or negative interest as "No." By categorizing these statements, the qualitative data were transformed into nominal quantitative data (count numbers of "Yes" and "No" categories). Statements with positive interest intent such as "I would consider looking more into the field of an electrical contractor" and "Yes, this is a career path I may be interested in" were categorized into the positive "Yes" interest category and statements with negative interest intent such as "No, this is not something I am interested in" and "Not at all" were categorized as "No." The resulting nominal data associated with career interest were analyzed with descriptive statistics (e.g., mean and standard deviation). The data from the dependent variables described previously were also analyzed for correlation. Nonparametric Spearman rank correlation coefficient (Spearman 1904) was formulated to assess statistically significant differences between the dependent variables. However, the analysis resulted in no significant correlations between any of the variables ($p$-values > 0.05). The overall data cleaning process and the statistical analysis on the data were performed using the IPython command shell with the Scipy and Statsmodels libraries.

## Results

In this study, the VR storytelling system was distributed to a total of 90 students across four entry-level building science courses. A total of 47 students participated in the experiment, representing a response rate of 58%. The data from 5 participants had to be discarded due to incomplete answers, resulting in 42 participants, 14 per experimental condition. The results of the analysis of this data set are presented in the following subsections.

**Table 1.** Student demographics across the three experimental conditions

| Study variable | Abstracted virtual human (AVH) | Modeled virtual human (MVH) | Realistic virtual human (RVH) |
|---|---|---|---|
| | | Age: Mean (SD) | |
| | 19 (0.72) | 19 (0.73) | 21 (7.06) |
| | | Participants: total frequency (Male—Female) | |
| | 14 (10—4) | 14 (9—5) | 14 (9—5) |
| Year within the construction program (frequency) | | | |
| Freshman | 6 | 6 | 5 |
| Sophomore | 7 | 6 | 4 |
| Junior | 1 | 2 | 3 |
| Senior | 0 | 0 | 2 |
| Years of experience (frequency) | | | |
| No experience | 5 | 12 | 9 |
| 0–6 months | 4 | 2 | 4 |
| 6 months–1 year | 3 | 0 | 0 |
| 1–2 years | 0 | 0 | 0 |
| More than 2 years | 2 | 0 | 1 |
| Understanding of VR (frequency) | | | |
| None | 2 | 1 | 1 |
| Some | 8 | 6 | 6 |
| Fair | 3 | 6 | 6 |
| Competent | 1 | 1 | 1 |
| Understanding of omnidirectional pictures (frequency) | | | |
| None | 8 | 4 | 7 |
| Some | 3 | 8 | 3 |
| Fair | 2 | 1 | 2 |
| Competent | 1 | 1 | 2 |
| Understanding of electrical career path (frequency) | | | |
| None | 10 | 11 | 10 |
| Some | 2 | 3 | 3 |
| Fair | 1 | 0 | 1 |
| Competent | 1 | 0 | 0 |

### Demographics

The demographics of the participants were analyzed to understand their background information (Table 1). It was found that the average age of the participants was 20 years old (SD: 1.15) across all conditions. Approximately two-thirds of the participants in each condition were male and one-third female. Over 60% of the participants were in their first (freshman) or second (sophomore) year of the construction management program. Most students had minimal work experience in the construction management industry—over 60% had 6 months or less across all conditions. Students reported to have a some-to-fair level of understanding of VR (over 50%) but a none-to-some understanding of omnidirectional images (over 50%). Ultimately, most students—over 70%—reported no understanding of the electrician career path.

### Learning Outcomes

The responses to the learning outcomes questionnaire were analyzed descriptively and statistically (Table 2). It was found that the AVH condition had the highest average learning score (Mean: 3.54; SD: 0.71), followed by the MVH condition (Mean: 3.14; SD: 0.93). The lowest average learning scores were observed in the RVH condition (Mean: 3.02; SD: 0.86). Although the score trends illustrated in Table 2 point to an inverse relationship between virtual human appearance fidelity and learning, the results of the Kruskal–Wallis statistical analysis indicated that there were no significant differences between conditions (statistic = 2.84, $p$-value = 0.241; $p$-value > 0.05).

## Social Presence

The responses to the social presence questionnaire were analyzed descriptively and statistically (Table 3). It was found that the MVH condition had the highest average social presence score (Mean: 4.34; SD: 0.86), closely followed by the RVH condition (Mean: 4.30; SD: 0.91). The lowest average social presence score was detected in the AVH condition (Mean: 4.16; SD: 0.56), as shown in Table 3. However, the Kruskal–Wallis statistical analysis results again indicated no significant differences across the conditions in terms of social presence scores (statistic = 0.74, $p$-value = 0.692; $p$-value > 0.05).

## Virtual Human Persona

The responses for each dimension—facilitating learning, credible, human-like, and engaging—of the API were initially analyzed descriptively across experimental conditions (Table 4). It was observed that the RVH scores for all the different dimensions of the API were consistently lower concerning the MVH and AVH scores. The MVH and AVH scores had varying differences across the API dimensions, which are all within less than 1 point of difference.

To further evaluate the descriptive results observed in Table 4, the scores for each API set of questions were averaged to represent the specific associated dimension—facilitating learning, credibility, human-like, and engaging—as demonstrated in Baylor and Ryu (2003). Descriptive and statistical analyses were performed for

**Table 2.** Learning scores across the three experimental conditions

| Study variable | Abstracted virtual human (AVH) Mean (SD) | Modeled virtual human (MVH) Mean (SD) | Realistic virtual human (RVH) Mean (SD) | Kruskal–Wallis Statistical analysis | | |
|---|---|---|---|---|---|---|
| | | | | Statistic | $p$-Value | $p$-Value < 0.05? |
| Learning score | 3.54 (0.71) | 3.14 (0.93) | 3.02 (0.86) | 2.84 | 0.241 | No |

**Table 3.** Social presence scores across the three experimental conditions

| Study variable | Abstracted virtual human (AVH) Mean (SD) | Modeled virtual human (MVH) Mean (SD) | Realistic virtual human (RVH) Mean (SD) | Kruskal–Wallis statistical analysis | | |
|---|---|---|---|---|---|---|
| | | | | Statistic | $p$-Value | $p$-Value < 0.05? |
| Social presence score | 4.16 (0.56) | 4.34 (0.86) | 4.30 (0.91) | 0.74 | 0.692 | No |

**Table 4.** Agent personal instrument responses by question At levels of the experimental conditions

| Questions from agent persona instrument | Abstracted virtual human (AVH) Mean (SD) | Modeled virtual human (MVH) Mean (SD) | Realistic virtual human (RVH) Mean (SD) |
|---|---|---|---|
| Facilitating learning | | | |
| 1. The agent led me to think more deeply about the story | 5.23 (1.12) | 5.50 (1.12) | 5.00 (1.25) |
| 2. The agent made the instruction interesting | 5.54 (0.93) | 5.58 (0.95) | 4.67 (1.76) |
| 3. The agent encouraged me to reflect on what I was learning | 5.23 (1.25) | 5.00 (1.15) | 4.89 (1.37) |
| 4. The agent kept my attention | 5.08 (1.64) | 5.42 (0.95) | 4.22 (1.99) |
| 5. The agent presented the story effectively | 5.92 (0.73) | 6.08 (0.76) | 5.22 (1.03) |
| 6. The agent helped me to concentrate on the story | 4.92 (1.21) | 5.67 (0.85) | 4.33 (2.00) |
| 7. The agent focused me on the relevant information | 5.77 (0.89) | 5.92 (0.95) | 5.33 (1.33) |
| 8. The agent improved my knowledge of the content | 6.23 (0.80) | 6.00 (0.91) | 5.56 (1.07) |
| 9. The agent was interesting | 5.77 (1.19) | 5.92 (0.76) | 4.44 (1.64) |
| 10. The agent was enjoyable | 5.62 (1.08) | 5.50 (0.95) | 4.44 (1.71) |
| Credible | | | |
| 11.The agent was knowledgeable | 6.23 (0.89) | 6.08 (0.64) | 5.67 (0.67) |
| 12. The agent was intelligent | 6.31 (0.72) | 6.08 (0.86) | 5.67 (0.67) |
| 13. The agent was useful | 5.85 (0.86) | 6.00 (0.82) | 5.67 (1.05) |
| 14. The agent was helpful | 5.85 (0.95) | 5.83 (0.69) | 5.89 (0.87) |
| 15. The agent was instructor-like | 5.85 (0.87) | 5.92 (0.86) | 5.33 (1.49) |
| Human-like | | | |
| 16. The agent has a personality | 4.31 (1.86) | 4.75 (1.01) | 4.11 (2.08) |
| 17. The agent's emotion was natural | 4.23 (1.67) | 4.50 (1.44) | 3.56 (2.01) |
| 18. The agent was human-like | 4.08 (1.77) | 4.42 (1.50) | 3.56 (2.10) |
| 19. The agent's movement was natural | 3.69 (1.86) | 3.00 (1.53) | 2.89 (1.79) |
| 20. The agent showed emotion | 3.31 (1.77) | 3.83 (1.28) | 3.22 (1.69) |
| Engaging | | | |
| 21. The agent was expressive | 4.38 (1.73) | 4.17 (1.40) | 3.67 (1.76) |
| 22. The agent was enthusiastic | 4.62 (1.44) | 4.58 (1.71) | 3.78 (1.75) |
| 23. The agent was entertaining | 5.08 (1.33) | 5.00 (1.35) | 3.78 (1.87) |
| 24. The agent was motivating | 5.08 (1.44) | 4.75 (1.64) | 4.11 (1.73) |
| 25. The agent was friendly | 6.00 (0.88) | 5.75 (1.16) | 5.33 (0.67) |

**Table 5.** Agent persona instrument variables scores across the three experimental conditions

| Agent persona instrument measurements | Abstracted virtual human (AVH) Mean (SD) | Modeled virtual human (MVH) Mean (SD) | Realistic virtual human (RVH) Mean (SD) | Kruskal–Wallis statistical analysis | | |
|---|---|---|---|---|---|---|
| | | | | Statistic | $p$-Value | $p$-Value < 0.05? |
| Facilitating Learning | 5.52 (0.90) | 5.65 (0.71) | 5.03 (1.25) | 1.51 | 0.469 | No |
| Credibility | 6.01 (0.68) | 5.91 (0.63) | 5.64 (0.81) | 0.95 | 0.623 | No |
| Human-like | 4.03 (1.54) | 3.99 (1.12) | 3.68 (1.79) | 0.12 | 0.941 | No |
| Engaging | 5.01 (1.59) | 4.81 (1.16) | 4.27 (1.84) | 1.99 | 0.369 | No |

determining the average responses for each API dimension metric, as shown in Table 5. In terms of the facilitating learning metric, it was found that the MVH condition had the highest average score (Mean: 5.56; SD: 0.71), closely followed by the AVH condition (Mean: 5.52; SD: 0.90). The lowest average facilitating learning score was seen in the RVH condition (Mean: 5.03; SD: 1.25). For the credibility metric, it was observed that the AVH condition had the highest credibility average score (Mean: 6.01; SD: 0.68), followed by the MVH condition (Mean: 5.91; SD: 0.63) and the RVH condition (Mean: 5.64; SD: 0.81). Similarly, for the human-like metric, it was observed that the AVH condition has the highest average score (Mean: 4.03; SD: 1.54), followed by the MVH condition (Mean: 3.99; SD: 1.12) and the RVH condition (Mean: 3.68; SD: 1.79). Finally, for the engagement metric, it was found again that the AVH condition has the highest reported engagement average score (Mean: 5.01; SD: 1.59), followed by the MVH condition (Mean: 4.81; SD: 1.16) and the RVH condition (Mean: 4.27; SD: 1.84). The descriptive statistic differences suggest that the AVH condition had higher credibility, human-like, and engaging dimensions. The MVH condition scores were the highest in the facilitating learning dimension. Nevertheless, the results of the Kruskal–Wallis statistical test indicated that there were no significant differences among conditions in any of the API dimensions for the three experimental conditions ($p$-value > 0.05).

### Interest in Electrical Trade Career Path

The investigation of interest in the electrical career path was done using the descriptive statistics obtained from the coding process as previously described. It was observed that on each experimental condition, approximately 20% of the participants expressed interest in finding more information about electrical career opportunities (Fig. 8). To better understand which participants were interested in an electrician career path, their demographics were carefully inspected. It was found that participants who responded positively ("Yes" coded category) to the interest question were mostly males (Male: 90%; Female: 10%), with an average age of 19 years (SD: 1.23). Moreover, these participants had no prior experience in electrical trades (no prior knowledge of electrical work: 90%) and no-to-little experience in the construction industry (no experience: 70%—less than 6 months: 30%).

## Discussion

This study's results are discussed in this section to highlight some of the trade-offs of using varying virtual human appearance fidelity in building science educational applications. This discussion aims to offer insights to help the design of future virtual human-based educational systems.

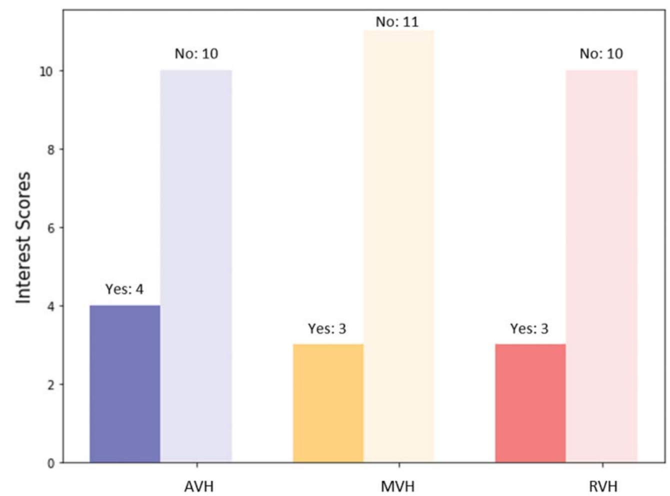


**Fig. 8.** Interest scores across the levels of the experimental conditions.

### Impact of Social Presence in Building Science Learning

The results of this study found that none of the conditions present significant differences in learning outcomes or social presence. In building sciences, student learning heavily relies on the contextual situations contained in the physical environment (Mutis 2018). Moreover, the social context of those situations is also necessary to couple human-coordinated tasks with the contextual information for effectively delivering a holistic understanding to students (Mutis 2018). In the educational VR storytelling system of this study, virtual humans served the purpose of delivering a social situation through a narrative within the context of the virtual environment. The narrative delivery method based on the virtual human required the participants to pay attention to the virtual human and simultaneously consider the surrounding environment information. This interdependence effect between virtual environments and virtual humans in building science learning applications remains unexplored. Future studies must explore how important is the contribution of each of these variables to learning. It is possible that the lack of significant differences found across all levels of virtual human appearance fidelity indicates that virtual humans are not the main variable that contributes to learning in digital interventions for building sciences, but further study must be completed to explore the interactions and relationships between these variables.

Furthermore, the lack of significant differences found in this research indicates that educational building science applications might use virtual humans within the lower spectrum of appearance fidelity to successfully deliver instructional outcomes and preserve expert knowledge properly. However, it is essential to highlight that the scope of the narrative instruction demonstrated in this paper focused on simplistic virtual humans that delivered a unidirectional story (instead of a branching story) and minimal interaction opportunities. For more interactive narrative experiences or other types of education delivery methods (e.g., project-based learning, experiential learning, and collaborative learning), higher appearance fidelity could produce a higher impact on learning outcomes. Appearance fidelity might become especially important in situations where nonverbal cues are necessary to obtain essential information (e.g., emotions, intent, and awareness) from the virtual humans, as shown in research on other domains (Daher et al. 2018; Pence et al. 2013).

### *Engagement Impact on Virtual Human Appearance Fidelity for Building Science Learning*

Previous research within the computer science domain has found that increased appearance fidelity in virtual humans enhances student engagement (Baylor and Kim 2004). However, the data analysis for the construction management students on engagement revealed no gains from increased appearance fidelity. Each of the four dimensions of the API questionnaire indicated no significant differences in perception across the appearance fidelity conditions introduced to the students. This observation potentially ties with the previously presented findings, where students rely not only on virtual humans to understand the story narration but also on the situated contextual space. Existing literature within the building science domain, specifically relating to educational content delivery using digital environments, has found positive engagement effects for students (Castronovo et al. 2014). This is potentially due to the influence on student engagement introduced by the digital environment, possibly dominating over the effects derived from the virtual human. As a result, educational building science applications should carefully consider the importance of digital environment fidelity instead of exclusively relying on virtual human appearance fidelity to increase students' engagement.

It should be noted that although no differences were detected on engagement, some students described that they would be interested in the topic covered within the narration—electrician trade career path. Over 20% of the students presented positive responses across all the experimental conditions. This finding concerning electrical careers indicates that the storytelling experience did provide engagement value independently of the virtual human appearance fidelity condition. Interestingly, most of the positive responses were young male participants, matching with the virtual human's age/gender. Research in educational technology has shown that virtual human age and gender affects student engagement while using educational applications (Dinçer and Doğanay 2017). Consequently, the effect of the virtual human's age and gender should be considered when designing educational building science systems and applications.

Ultimately, the detection of engagement effects across the virtual human conditions highlights the potential of this type of VR storytelling technique to preserve professional domain building science knowledge. In this study, the general traits of an electrician apprentice professional experience were synthesized using the Bureau of Labor Statistics Occupational Outlook Handbook (US Bureau of Labor Statistics 2020). Even though the story presented to the student was not a real account of an electrician apprentice, increments in engagement were observed. These engagement effects may become amplified if real-world electrician professional career path stories are captured and preserved using the "Day in the Life" method demonstrated in this study.

## Research Limitations

This research had limitations in four areas associated with the experimental methodology: (1) virtual human appearance fidelity operationalization, (2) sample size and composition, (3) linearity of the story, and (4) omnidirectional image exploration challenges. First, the operationalization of the virtual human appearance fidelity was exclusively presented under three conditions—realistic, modeled, and abstracted. Virtual humans exist within a spectrum of appearance fidelity, as shown by McDonnell et al. (2012), Volante et al. (2016), and Zibrek et al. (2019), in which many techniques can be potentially used to represent humans in digital environments. The inclusion of additional appearance fidelity levels within the spectrum—hyper-realistic or mannequin-like—could reveal different patterns than those observed in this study for learning and social presence. Additionally, other virtual human variables, such as virtual environment fidelity, voice characterization fidelity, animations, age, gender, and ethnicity, could further influence the results reported in this document. Second, the sample size under each experimental condition was small. This small sample size resulted from considering a between-subjects design for this study and limitations in the number of students available for sampling within our targeted population (building science students at entry-level courses). A priori power analysis was not conducted due to the sampling limitations for the targeted population of this study. Learning effects present in the storytelling narrative prevented the utilization of within-subject methodologies that would have increased the number of participants per condition. Third, the linearity of the story shown to students potentially introduced engagement limitations in the educational intervention. Participants followed the narrative of the electrical career path using the immersive VR system, but no decision making was available within in the flow of the story. By adding decision making into the narrative for student exploration, higher engagement could have been developed from the intervention. Moreover, the story narrative was limited only within the electrical career path and electrical professionals. Other types of career paths and professionals within the building science domain (e.g., mechanical, plumbing, and structure) might produce different results using the type of narrative employed in this study. Fourth, the use of the omnidirectional images limited the potential exploration of students in the virtual environment to rotation only. This was caused by the nature of the omnidirectional photography technology, because only a static vantage point was available. Other similar studies report this same limitation from omnidirectional images for training and education application in building sciences (e.g., Eiris et al. 2018, 2020a)

## Conclusion and Future Work

This study proposed to investigate the impact of virtual human appearance fidelity on student learning and engagement during simulated interactions with building science domain experts. To deliver these real-world interactions in a simulated environment, an educational storytelling system that leveraged VR was used and grounded in the situated context of the electrical trade. An educational VR storytelling system was developed to provide students with a narrative experience of a "Day in the Life" of an electrician apprentice, effectively delivering a method to preserve expert knowledge using storytelling techniques. This educational VR storytelling system was created to operationalize virtual human appearance fidelity under three condition levels: realistic, modeled, and abstracted. The virtual human operationalization was performed to explore the effect of appearance fidelity on learning outcomes, social presence, virtual human persona factors, and engagement within the context of the student–professional interactions. Within the constraints posed on this study, the results showed that low appearance fidelity virtual humans could be used to successfully produce instructional outcomes since no evidence of significant differences was found across conditions. Furthermore, it was found that there were no direct relationships between engagement and increased virtual human appearance fidelity. Although appearance fidelity was not significantly different across virtual human conditions, increments in engagement were observed independently of the experimental condition. It was observed that in the cases that student engagement increased, the age and gender of the virtual humans was a potential important factor. These findings in terms of learning and engagement for virtual humans help guide the design of educational interventions and systems that aim to target construction management student populations within building sciences.

Further work needs to be done to explore the impact of virtual human appearance fidelity on other populations, such as K-12 and vocational students (e.g., mechanical and plumbing) within the building science domain. Other trades beyond the electrical trade need to be also evaluated to better understand virtual human appearance fidelity in building sciences. The results of this study were potentially linked to the interactions between VR environments and virtual humans. These results showed that it is necessary gain a better understanding about the interconnection of the situated context and the virtual human when designing educational interventions and systems within the building science domain. Additionally, this study was limited to three particular appearance fidelity conditions of virtual humans. It would be beneficial to explore how other degrees of virtual human fidelity (e.g., function, time, autonomy, and individuality) or the removal of the physical representation of the virtual human potentially affect learning and engagement. Furthermore, other degrees of virtual environment and audio narration fidelity should also be explored in conjunction with virtual human fidelity to better understand how they affect learning and engagement. Finally, this study recognized the effects of virtual human age and gender on learning and engagement. The virtual human's age and gender, together with other factors, such as ethnicity, voice characterization, and language, should also be further explored to obtain a better understanding of virtual human effects on learning.

## Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author by request (educational intervention system assets and stories).

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## Supplemental Materials

Appendixes S1 and S2 are available online in the ASCE Library (www.ascelibrary.org).

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