Full Scale Augmented Reality to Support Construction Sequencing Education Case Study

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ABSTRACT

Providing students with hands-on construction experiences enables them to apply conceptual knowledge to practical applications, but the high costs associated with this form of learning limit access to it. Therefore, this paper explores the use of augmented reality (AR) to enable students in a conventional classroom or lab setting to interact with virtual objects similar to how they would if they were physically constructing building components. More specifically, the authors tasked student participants with virtually constructing a wood-framed wall through AR with a Microsoft HoloLens. Participants were video-recorded and their behaviors were analyzed. Subsequently, observed behaviors in AR were analyzed and compared to expected behaviors in the physical environment. It was observed that students performing the tasks tended to mimic behaviors found in the physical environment in how they managed the virtual materials, leveraged physical tools in conjunction with virtual materials, and in their ability to recognize and fix mistakes. Some of the finer interactions observed with the virtual materials were found to be unique to the virtual environment, such as moving objects from a distance. Overall, these findings contribute to the understanding of how AR may be leveraged in classrooms to provide learning experiences that yield similar outcomes to those provided in more resource-intensive physical construction site environments.

INTRODUCTION

The construction industry is facing a labor shortage (Torpey, 2018), requiring the rapid training of skilled workers and a generation of construction graduates better prepared to immediately take on roles in the field. Much of the expertise needed to successfully operate in the construction industry is tacit knowledge--which is knowledge gained through experience (Hizar Md Khuzaimah & Hassan, 2012). While this kind of knowledge is typically gained through years of experience in the workforce, the current construction labor shortage has created a sense of urgency in preparing the incoming labor force to enter the workforce with more hands-on experience, with some suggesting that graduates are underprepared when entering the workforce (Aparicio et al., 2007). Educators have introduced recent innovations to add more hands-on, authentic content to coursework in higher education (Hegazy et al., 2020). Authentic experiential learning activities place the learner in contexts that they would encounter in the real world (Herrington et al., 2014). Such experiential learning activities, like the Sacramento Municipality's Utility District (SMUD) Tiny House Competition or the Department of Energy's (DOE) Solar Decathlon are examples of activities that bring authentic, hands-on experiences to students. Activities like these have shown high potential to develop technical and professional skills for those who participate (Wu & Hyatt, 2016) and have shown that these real-world activities have significant advantages over traditional classroom experiences (Holt et al., 2012). Despite the evidence that these activities provide measurable benefits to students, these types of experiences are cost and resource-intensive (Barnes, 2012; DOE, 2017) and, consequently, most students do not experience comparable activities during their time in school. Here, augmented reality (AR) is explored as a possible alternative in situations where full-scale hands-on activities are not feasible, and this work identifies ways in which this virtual alternative compares to the physical.

BACKGROUND

AR is a visualization tool where virtual, computer-generated content is superimposed on a physical real-world environment (Milgram & Kishino, 1994), and applications for construction education, such as teaching building information modeling (Arashpour & Aranda-Mena, 2017) or for safety training (Li et al., 2018) are being explored. Although AR has shown evidence as a tool for transferring technical skills and fostering engagement, most research in AR for construction education uses AR for only display purposes or with limited interaction with the virtual elements (Shirazi & Behzadan, 2015; Bademosi et al; 2019; Vasilevski & Birt, 2020). Most of these studies relied on AR to display information that supplemented the location or content being presented, but users would typically observe the information but not interact with or change the virtual elements directly. There are some exceptions where applications are designed to have the user physically change the input of a virtual system and observe the output, such as the group who explored mobile AR applications for teaching structural analysis by having the students adjust settings on a sample model and observe structural changes (Turkan et al., 2017) or the group who created a virtual sandbox that allowed users to interact with different terrains through AR (Louis & Lather, 2020). While many of these aforementioned applications have shown potential to increase student engagement and learning in their targeted area, none have explored the possibility of utilizing this modality for authentic, full-scale, hands-on building activities, where the virtual elements are manipulatable by the user. While this kind of activity has not been studied with virtual materials, similar activities performed in the real world with physical construction materials have been shown to provide significant learning gains for construction students (Holt et al., 2012).

The point of departure for this research from past research is to utilize head-mounted AR to create an environment that simulates a full-scale, hands-on building experience—in this case, framing a wood stud wall—and to study behaviors that parallel or differ from those expected in a hands-on physical activity. By observing student behaviors during a construction activity that uses virtual building elements, the researchers seek to understand:

- What student behaviors emerge that parallel interactions with physical hands-on activities?
- What student behaviors emerge that differ from interactions with physical hands-on activities?

Overall, understanding the behaviors of students within this kind of environment will provide insight into how this kind of activity compares to hands-on learning in a fully physical environment. Ultimately, this technology has the potential to provide a cost and resource-effective alternative to a type of activity that has been proven to be extremely effective but traditionally inaccessible. Understanding where performing construction tasks within this type of visualization environment parallels or differs from reality in this context will provide researchers a springboard to target innovations or guide future strategies regarding this type of activity.

METHODS

In this study, an application was designed that allows students to interact with both physical and virtual elements to perform wood-frame construction tasks. Students had access to physical materials, such as printed plans (Figure 1) and a physical measuring tape, and interacted with virtual elements making up the building material (wood). The choice of head-mounted technology allowed for a completely hands-free experience, enabling students to utilize both hands in building and interacting with the full-scale materials. Participants were tasked with constructing a portion of a wood-framed wall using virtual wood components, paper plans, and physical tools (measuring tape and pen for document markup).

Description of Virtual Wood Framing Application

The application was designed to leverage the unique affordances of AR, using virtual elements to replace expensive and large physical elements (wood studs) and keeping physical elements where possible (measuring tape and drawings). Within the application, an initial process of registration—aligning the virtual elements with the physical environment—resulted in the placement of a designated virtual ‘floor’ area resting on the physical floor of the room and upon which the participants were instructed to build. The virtual wood studs were pre-cut to lengths that corresponded to the lengths indicated in the paper drawings provided to the students (Figure 1) and were laid out flat next to each other in no particular order regarding length. The application was designed so that as users moved the virtual wood, it would collide or ‘clash’ with other virtual objects until they become installed. The virtual wood was presented at scale and could be measured with a physical measuring tape. The wood pieces could be moved using hand gestures to grab and relocate the studs. Users could rotate wood studs in any direction using voice commands and install them (fix in place) or uninstall them (make free to be moved) using a voice command.

Subject Testing Protocol

Due to pandemic restrictions regarding contact, testing was designed to take place via videoconferencing between two on-campus rooms, where the students were alone in a test space, and the researchers were in a nearby office, giving live instructions remotely and observing participants through video and a screencast of the participants’ view through the HoloLens.

Upon entering the room, participants completed a pre-survey where they were asked about demographic information and their confidence performing wood framing sub-tasks on a Likert scale from 1 (Poor) to 5 (Excellent). Next, the researcher showed the participant the physical resources available for building, including a measuring tape, paper drawings (see Figure 1), and a pen. The participants were then provided with a head-mounted AR display (Microsoft HoloLens 1) that contained the wood framing application. The researcher guided the participant through the process of opening the application and starting the activity. After setup, the participants were trained on how to perform the tasks related to wood framing within the application.

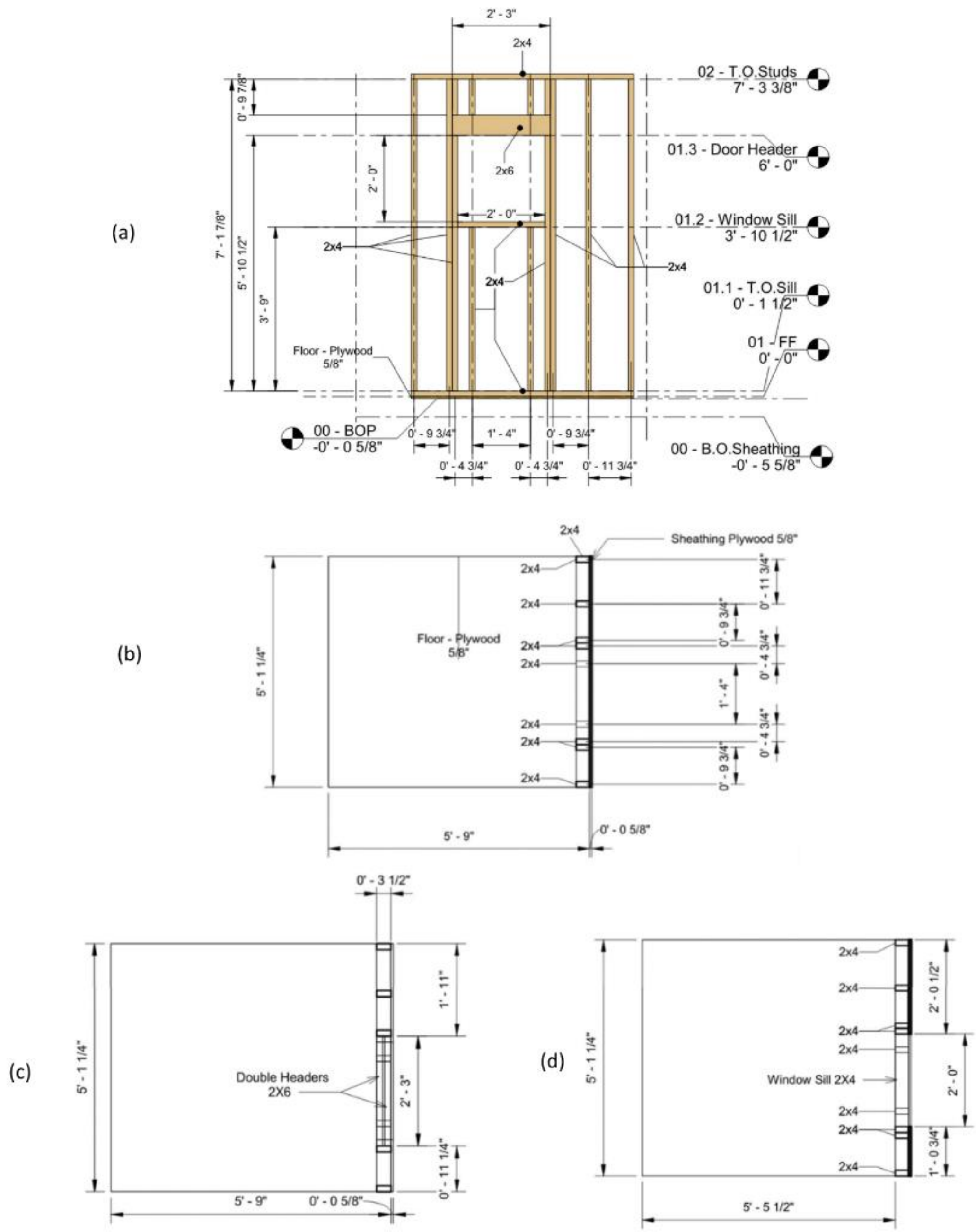

Figure 1. Set of drawings provided to the participants including (a) window elevation, (b) top-of-sill floor plan, (c) header floor plan, and (d) window sill floor plan views of the wall.

This training consisted of placing the first piece of the wall (the floor plate), by performing all possible actions (reading dimensions, measuring the pieces), voice commands (rotation and installation), and gestures (grabbing and moving the pieces) needed to build the section of wall. After training, participants performed the wall framing activity without input from the researcher, unless specifically asked by the participant. As participants completed the AR activity, they were video and audio recorded. The participants were instructed to think aloud during the process and to explain what they were doing and why they were doing it as they went through the task. Upon completion of the main activity, participants were asked to reflect about their experience framing the virtual wall in a written survey, particularly which parts of the process felt realistic and which did not.

Data Analysis Protocol

The survey data was compiled, and descriptive statistics were extracted to understand the demographics and wood framing comfort levels of the students. The video recorded data enabled analysis of emergent behaviors through observation, similar to processes other researchers have taken with video data of students using mixed realities (Alsafouri, 2017; Hartless et al., 2020). Researchers took note of student behaviors throughout the duration of the exercise, compiling a list of emergent behaviors that were added to and revised until reaching a point of saturation. The statements made by the participants, both during the activity and in their written reflections indicated thought processes behind the actions. These data of interest—observations about the wood framing process from video recordings and statements made by students about the wood framing process—provide the basis for qualitative analysis which leverages observation and supporting evidence to extract meaningful findings that address the research questions of interest (Merriam & Tisdell, 2015). This paper presents these findings in anecdotal form by describing each observation using a combination of the behavioral analysis and supporting statements from the students, similar to the case study approach used in the literature describing hands-on construction learning experiences (Gale & White, 2019).

RESULTS

Descriptive Statistics

A sample of 15 undergraduate student participants formed the dataset for this study, recruited from a traditionally upper-level construction technology course cross-listed in both the construction management and construction engineering departments. Of these students, a majority were juniors (67%), with a sample of seniors (20%), and some sophomores (13%). Of all participants, 80% were male, and 20% were female. The self-identified race and ethnicities of the group were American Indian or Alaska Native (7%), Asian (14%), Black or African American (14%), Hispanic or Latino (21%), White (43%), with 7% preferring not to answer. Besides one outlier with 21+ years of experience each, the average number of years of construction experience of the students was 1.1 (including internships, full-time, or part-time employment). Average self-reported ability regarding the following wood framing related tasks on a Likert Scale of 1 (Poor) to 5 (Excellent) are as follows; using design and construction documents to understand the design in general (mean (μ)=3.7, standard deviation (σ)=0.7), using design and construction documents to find information like sizes and dimensions (μ=3.9, σ=0.6), using design and construction documents to decide on means and methods for installing the designed structure (μ=3.0, σ=0.8), using a measuring tape (μ=4.4, σ=0.6), defining a sequence for installing wood framing components (μ=3.2, σ=0.9), installing wood framing components correctly (μ=3.1, σ=0.7), framing a wall from start to finish (μ=2.7, σ=0.9), teaching someone else to frame a wall from start to finish (μ=2.3, σ=0.9).

Observations of Interactions that Parallel Hands-On Experiences

Virtual Material Interactions and Management. First, it was observed that students typically walked around the virtual objects as if they were physically present. For example, when students had vertical studs installed, they would walk around, not through, the studs to access more material, even if it meant taking a less direct path to where the materials were stored. While students did not need to walk around the material because it provided no real physical barrier, this action showed that they treated the virtual wood as if it were actually there. Another material interaction that students exhibited was 'bumping' into other wood objects with wood that they were 'carrying'. Many students expressed frustration with this aspect, stating that "moving items and placing them was difficult because the wood would bump into other pieces and move them," but others remarked about how this made the experience more realistic, noting that "when I dragged objects into other objects that weren't locked in place then they were pushed around like real life." Material management and space constraints are realities of physical construction and this type of issue is something that could be faced in the physical world with physical resource management; however, it should be noted that the extent to which this occurred may be exaggerated due to the novelty in navigating this virtual environment. For example, virtual objects are effectively weightless, which may lead to faster motions used to move them, which may result in excessive clashes with other objects, which may have influenced this participant's reflection that "moving planks around in the space without hitting other pieces around was difficult...I knocked things around constantly when I tried to bring the object closer to me." Regarding overall material management strategy, while most participants followed a linear, single object workflow that involved choosing a wood element in the drawing, finding the appropriate piece, and installing that piece before moving on to the next, a few students differed from this process by opting to start by organizing some of the wood by length or bringing a few pieces closer to the site before installing.

Visually Detecting Mistakes. A promising behavior that resulted from this study occurred when students detected mistakes in placing virtual objects relative to other virtual objects. For example, a student had placed a piece that was the full height of the wall, then placed another piece that was slightly shorter but should have run the full height of the wall. The student looked at both virtual pieces, noticed that one was shorter relative to the other, and removed the piece that was too short. There is a level of mental recognition that is enabled when experiencing an environment in full-scale. In describing a physical building activity, Holt et al. (2012) describes students' experiences walking into a space they had built, stating that "once the home was framed, the interior design team walked through and was able to visualize the vaulted ceiling in the real perspective of the room sizes. They had an "A-Ha" moment and agreed that the vaulted ceilings made the room feel larger." This experience suggests that being physically present in a full-scale design is different from seeing the design in other formats.

Measuring Virtual Elements. During the training, students were instructed on how to utilize the measuring tape in conjunction with the virtual pieces of wood (Figure 2). Since the wood was scaled as it would be physically, this process was very similar to what would be experienced in reality. Based on the comments and survey results, most students were confident in their measuring ability and found that the process was a natural part of the experience, one even noted that "Measuring was shockingly easy." While most students found this to be one of the easiest and most natural parts of the experience, this was not without exception, and some mentioned that it was difficult to precisely measure the virtual elements, and that it was "difficult to see whether the Tape was actually lined up where I needed it to be." This kind of difficulty could be the result of the potential parallax in holograms or from holding the measuring tape 'inside' virtual objects, which have some level of transparency but could obscure the tick marks. It seemed, however, that this was not a common challenge and could be overcome, like by this student who observed "After I understood where I had to put the measuring tape to see it when I wanted to measure a plank, I had a lot of fun just measuring objects." Overall, students tended to utilize the tape measure frequently, especially when placing studs relative to each other along the length of the floor plate.

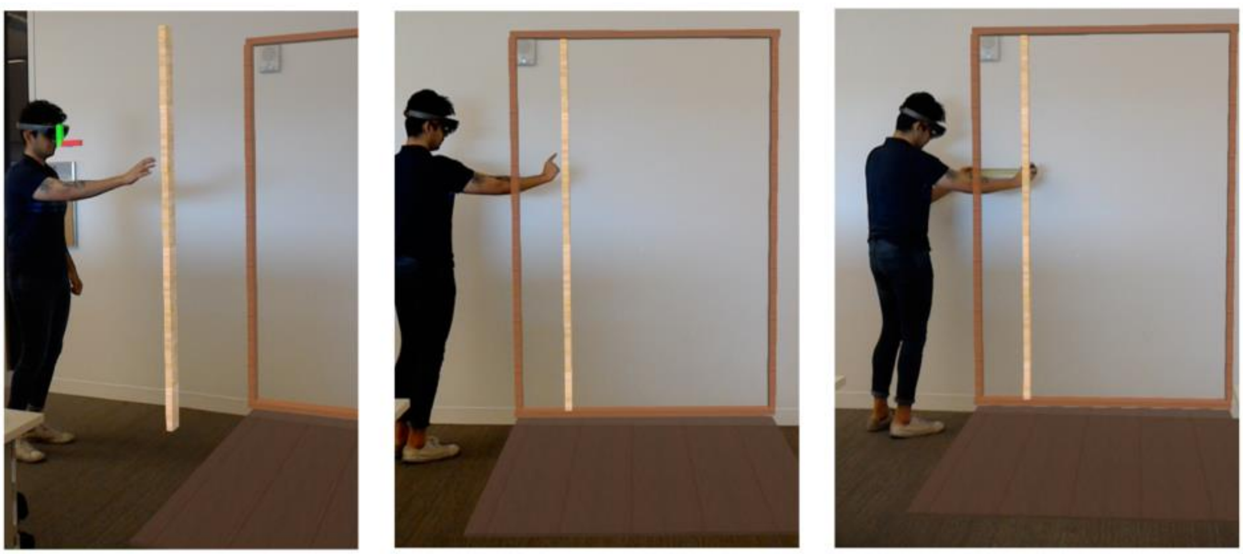

Figure 2. A student carries (left), places (center), and measures spacing for (right) a virtual piece of wood in the process ofconstructing the wood-framed virtual wall.

Referencing Plan Drawings. In addition to the measuring tape, a key physical resource provided to the students was a set of paper drawings, including plan and elevation views of the wall to be constructed. Many students took time before starting the virtual building process to analyze the paper drawing, appearing to use them to make plans for their process of construction. The researchers observed most students referencing the drawings frequently throughout the process, using them to find measurements, then measuring the pieces of wood to find the correct one. Not all students did this every time they placed a piece of wood, but most checked the drawings during their process. Most students were not perfect when choosing and installing wood studs, and this activity showed promising potential for AR to facilitate mistake recognition by leveraging both physical and virtual resources, where students were able to see when they had installed an incorrect piece and correct it accordingly. While some students noticed mistakes just by comparing virtual elements (mentioned previously), some also noticed mistakes when comparing their virtual walls to the physical drawings. For example, one student observed an error when looking at the pieces they had placed (they had placed a taller stud on the wrong side of a shorter stud), noticed that something looked awry, and referenced the drawings, looking back and forth between the virtual wall and the physical drawings. Through this process, they noticed what was wrong, said "I know what I did" and then flipped the two members to correctly reflect what was outlined in the design. This kind of behavior has been noted in physical design activities, such as a design and construction activity where “each of the students was able to identify technical issues” that emerged in a more complex interdisciplinary design (Holt et a., 2012).

Observations of Interactions that Differ from Hands-On Experiences

Relative Stud Alignment. When placing virtual wood elements next to or on each other, students often had difficulty aligning the objects to exactness, making one side flush with the other. Frequently, students would move an object near to where it should be placed, then overshoot slightly, then move it back and overshoot again. While getting things lined up in real life is certainly a necessity, this level of challenge likely would not be expected when lining up two physical studs. Many students expressed frustration at this part of the experience, stating that “trying to align the wooden member precisely would frustrate me sometimes” and that one of the most difficult parts was “making sure everything aligns”. Sometimes, users found it easier to move closer to the virtual objects to have a more accurate placement. While this helped, there was still typically some distance between the user’s hand and the piece of wood, which illuminates another unnatural virtual behavior: interacting with objects from a distance.

Interaction from a Distance. While the distance varied between users, most typically had at least a few inches of distance and up to several feet of distance between their hand and the piece of wood they were moving, likely a result of the design of default interactions in the technology used here (Microsoft HoloLens 1). The researchers noticed that some students had to try several times before successfully ‘picking up’ a piece of wood and some of the open-ended comments mentioned the process of grabbing and moving the objects did not feel realistic, like this student who remarked, “it felt as if I was actually picking up and moving the pieces, even though the workload required to move the pieces was not necessarily the same as it would be in the field.” Overall, the actual process of grabbing the wood studs, although it required a level of physicality, did not seem to directly parallel the process used to transport wood in real life.

Limitations

Because of the remote nature of the study, much of the setup and hologram registration was left to the students, which caused more difficulty and took more time in some research sessions than in others, resulting in a different amount of time allotted to students to complete the actual virtual framing task. Most students did not have time to finish the wall, so the researchers avoided analyzing quantitative task-based measures such as the number of elements placed or the time it took to build in order to avoid unreliable conclusions.

CONCLUSION

Hands-on building experiences allow students to develop tacit knowledge and prepare them for the construction field, but full-scale, physical, building experiences within an educational context are resource-intensive and available to very few. AR has the potential to replace expensive building materials with virtual holograms in providing hands-on experiences to students. To explore this modality, an AR activity was designed to enable students to perform hands-on wood framing of a wall using virtual wood and physical resources, such as a measuring tape and paper drawings. Students demonstrated a variety of behaviors in the environment, with some behaviors paralleling what would occur in a physical environment, like being able to visualize when a piece of wood has been installed that is too short, while others were unique to interaction with virtual objects, such as moving objects from a distance. The behaviors that mimic what happens in physical build tasks lend evidence to the viability of utilizing AR to simulate hands-on construction tasks. For example, the fact that students frequently utilized the physical measuring tape in conjunction with the virtual wood with general ease lends evidence to suggest that not only is this condition similar to what would be required when physically building a wall, but demonstrates some level of investment in the accuracy of the task. In addition to behaviors that parallel reality, some of the behaviors emerged that would likely not occur in a physical build, such as extreme difficulty in lining up objects and controlling objects from a distance. These observations can be useful from a developmental perspective for future work. For the authors of this work, this future work will include explorations of more advanced applications that simulate hands-on construction experiences, incorporating lessons learned from this experience to facilitate ease of use and encourage behaviors that more closely parallel hands-on experiences. For other faculty looking to implement similar types of activities in the classroom, this content can be used to strategically guide development strategies that increase the realism of the material interaction, especially as the technology continues to advance.

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