Comparing Traditional and Mixed Reality-Facilitated Apprenticeship Learning in a Wood-Frame Construction Lab

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Abstract: Mixed reality (MR) has the potential to accelerate construction workforce training and enhance college education. However, there is a lack of empirical evidence in the research literature on how effective MR may be in facilitating student apprenticeship learning in field construction activities compared to the traditional paper-based approach. This research designed an outdoor wood-frame construction lab with two parallel sessions involving paper drawings (the control) and MR mockups (the experiment) for conveying design information. The research team used video recordings and questionnaires to collect behavioral and perception data for comparative analysis. The results indicated that student teams in the two sessions exhibited comparable construction productivity. However, they demonstrated different behavioral patterns and time allocation for technology use and reported different apprenticeship learning gains. This research also identified and discussed potential contributing factors that limited the success of MR. The contribution of this work resides in presenting empirical evidence of the impact of using MR on student apprenticeship learning through outdoor construction activities. It also provides peer educational researchers with valuable insights on how to study pedagogical use of MR with consideration of potential challenges that are present in realistic construction environments. **DOI: 10.1061/(ASCE)CO.1943-7862.0001945.**

Introduction

The construction industry is becoming much more adaptive, driven by a skilled labor shortage and new sustainability regulations that urge the industry to be more efficient and nimble (McGraw-Hill Construction 2012). Companies have started to invest in technology advancements to promote workplace productivity and accelerate workforce training (Blanco et al. 2017). At the same time, undergraduate construction management (CM) education is also facing coexistent opportunities and challenges at the frontier of cultivating the next-generation construction workforce. On the one hand, the severe shortage of skilled workers implies a favorable job market and increased employment opportunities for college graduates (Karimi et al. 2016; Toossi 2013). On the other hand, it is notoriously time-consuming and resource-intensive for higher education to develop students' career preparedness with job-specific competencies. Usually, students will develop such competencies through appropriate apprenticeship learning, which refers to the process of gaining technical know-how, hands-on skills, and career awareness via professional practices or training (Bishop 2017; Daniel et al. 2019; Wu et al. 2019). Apprenticeship learning is critical because the current state of college education in the US effectively imparts technical knowledge, but it is not as effective at preparing students to integrate knowledge, skills, and affective elements as they develop into professionals. The consequence is that college graduates entering the workforce struggle to transfer what they learned in school to what is required of them as a professional (Noone 2009).

As one of the highly expected technology innovations, mixed reality (MR), or specifically wearable MR such as the Microsoft HoloLens (Microsoft Corporation, Redmond, Washington), has caught a lot of attention in both professional and educational communities for its potential to revolutionize on-the-job training and education (Bosché et al. 2016; Wu et al. 2019). Many practitioners and scholars have explored use cases and conducted proof-of-concept projects to prove the technical viability and application-readiness of MR (Rubenstone 2016; Wang and Schnabel 2009). However, most of these experiments took place in controlled lab settings with single-user experience data (Chalhoub and Ayer 2018; DaValle and Azhar 2020), and the use of MR was mostly passive to emphasize navigation, visualization, or inspection (Bosché et al. 2016; Riexinger et al. 2018). Therefore, it is difficult to infer if similar favorable results or promises of MR could hold when applied in

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real construction site settings for physical installation activities, which leaves uncertainty for the pedagogical use of MR in designing apprenticeship learning experience in the undergraduate CM curriculum.

Research Objectives and Research Questions

This research study investigates how MR may transform undergraduate CM education and improve students' career preparedness by enhancing desired apprenticeship learning in physical construction activities. Specifically, it aims to empirically assess the impacts of MR on student behavior and perception when participating in professional practices situated in an outdoor environment in comparison with traditional approaches. It also aims to identify factors and constraints that could affect the pedagogical use of MR in designing appropriate apprenticeship learning experiences in the undergraduate CM curriculum. Specifically, this study attempts to answer three research questions (RQs):

- RQ1: How will students that use MR compare with their peers who use paper drawings in behavior and outcome of performing the physical construction tasks?
- RQ2: How will students that use MR compare with their peers who use paper drawings in reporting perceived apprenticeship learning gains through the physical construction tasks?
- RQ3: What factors may limit the success of MR in this study that peer CM faculty should consider when designing pedagogical use of MR for similar outdoor construction activities?

The findings that address these questions will provide CM educators with empirical evidence of how MR may support apprenticeship learning for field construction tasks, which will fill a significant gap in the current research literature. Identifying factors that impact the success of MR in the types of learning designed in this research study will help future researchers strategically incorporate or avoid certain methodological practices to provide the highest likelihood of success when exploring further applications of MR in CM education.

Background

Apprenticeships Learning for Better Career-Preparedness of College Graduates

For a long time, evidence has suggested that graduates of engineering (and science) programs enter the workforce "ill-prepared to solve real problems in a cooperative way, lacking the skills and motivation to continue learning" (National Science Foundation 1996, p. 13). The Carnegie Foundation for the Advancement of Teaching (CFAT) proposes the notion of three apprenticeships in response to the need for more integrative learning in professional education (Noone 2009). The three apprenticeships include an intellectual or cognitive apprenticeship, or the so-called head apprenticeship; a skill-based apprenticeship related to clinical judgment and practice, or the hand apprenticeship; and an apprenticeship to the ethical comportment or behavior of the profession, or the heart apprenticeship. The apprenticeship, by definition, refers to a systematic on-the-job training process that primarily involves learning by doing (Daniel et al. 2019). Compared with traditional class learning, an apprenticeship model of learning transplants principles of apprenticeship, and is rooted in research on fundamental processes of learning and skill formation. Therefore, it focuses on how skills and knowledge are developed at and through the workplace, as opposed to designated educational settings such as classrooms (Bishop 2017). Apprenticeship learning is especially valuable because it encourages students to participate in professional practice within a community of practice, in which the working relationships and divisions of labor could generate opportunities and incentives for apprentices (students) to learn (Bishop 2017). This process ensures that students not only acquire knowledge but also improve their ways of thinking and problem-solving in the profession (Gruber and Mandl 2001). CFAT believes that the head, hand, and heart apprenticeships collectively represent the elements that are necessary for development to prepare successful professionals in the fields of engineering, nursing, law, and medicine (Noone 2009; Sullivan and Rosin 2008). For the construction industry, apprenticeship learning combines college learning with onsite experience to ensure the right balance of technical skills and practical experience (Abdel-Wahab 2012).

Recent technological innovations in the construction industry have not only reshaped its business environment to facilitate more collaborative and cost-effective project delivery but also redefined the workplace and human-technology frontiers. The widespread adoption and implementation of building information modeling (BIM), virtual reality (VR), and MR (Bouchlaghem et al. 2005; Wang and Schnabel 2009; Whyte and Nikolić 2018) urge the future workforce to develop corresponding technical skills and social-emotional intelligence to thrive in this human-technology working environment. Drastic changes in the workplace and the increasing market demand for new knowledge workers collectively impose an unprecedented challenge to educators, setting new expectations for the career preparedness of college graduates. In response, the American Council for Construction Education (ACCE) has recently revamped its accreditation process to an outcomes-oriented assessment, prompting significant changes in construction and construction engineering education (Chini 2015). The new accreditation process requires that institutions produce evidence of graduating students possessing a set of outcomes that represent behaviors, skills, and knowledge to function as construction and engineering professionals (David 2018; Leathem 2020).

Under these circumstances, construction and engineering programs in the country are reforming curricula to integrate hands-on activities and active learning techniques (e.g., experiential learning, problem-based learning, and project-based learning) (Becerik-Gerber et al. 2011; Wu and Luo 2018) to enhance apprenticeship learning. Research literature suggests that participation in apprenticeship learning promotes a better understanding of the application of content knowledge and the complexities of other nontechnical issues in professional practice (Hegazy et al. 2013; Mills and Treagust 2003). These experiences also help students develop critical skills such as collaboration, critical thinking, and problem-solving that increase their motivation, engagement, persistence, and career interest in construction and engineering (Chandrasekaran et al. 2012; Choe et al. 2019; Hegazy et al. 2013). From the faculty's perspective, hands-on and active learning modules help attain curricular goals, reach higher levels of Bloom's taxonomy in the topical areas, and meet degree programs and accreditation outcomes (Dewoolkar et al. 2009).

An emerging field of educational research explores apprenticeship learning in technology-enhanced, simulated virtual learning environments (VLEs). Studies by Kirkley and Kirkley (2005), Freitas and Neumann (2009), Chau et al. (2013), and Wang et al. (2018) provide insights on how technology such as VR/MR, gaming, and simulation could facilitate students in achieving learning outcomes through constructivist learning. Abdel-Wahab (2012) contends that exploring the application of VLEs, in particular workplace simulation, in addition to the active engagement of experienced workers and trade unions, present possible alternatives for supporting apprenticeship training in the construction industry. This research blends technology enhancement with physical

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construction activity to create a mixed learning environment and explores possible new approaches to enhance apprenticeships learning.

Challenges with Traditional 2D Communication

Part of the motivation for the blended physical and technological learning environment explored in this work stems from the recognition of limitations associated with traditional two-dimensional (2D) communication. Despite the recent increases in BIM use among building industry professionals, most formal design communication is still paper-based (Babič and Rebolj 2016). In other words, the intelligent three-dimensional (3D) models created in one project phase are typically "dumbed down" into 2D documents that serve as contract documents of record. Then these 2D documents are distributed to a project team. This practice requires individuals to reinterpret the 2D drawings back into 3D mental models, which hopefully match the design concept defined in the original BIM. In addition to inefficiencies with this drawing interpretation process, it can also be prone to errors, especially for individuals who do not have substantial experience reading construction drawings (Johnson 1998).

Prior research has demonstrated that using isometric drawings to simulate a 3D model on paper may offer efficiencies in design comprehension among industry professionals, leading to productivity gains in construction workflows (Goodrum and Miller 2016). However, with any paper-based documentation, the content shown is fundamentally 2D. It means that individuals reading drawings must still reinterpret those documents (isometric or otherwise) into mental models. This intermediate step provides an opportunity for MR to take a step further in facilitating the process of design comprehension by reducing the need for an individual to regenerate a mental model when BIM content has already been developed (Sabzevar and Gheisari 2018). This research enriches the literature through the designed experiment to directly test how MR-enhanced design communication compares with the traditional 2D approach.

Current Use of MR in the Construction Industry

The concept of leveraging MR in the building industry is not entirely novel, because some researchers have begun to explore its feasibility to leverage BIM content and improve project delivery. In the planning stage, MR has proved to help interact with prototypes (Sareika and Schmalstieg 2010) and present the required data points without interrupting existing workflows (Côté et al. 2014). It results in accelerated decision-making processes and also provides an interactive view of decisions of real-life job sites (Schubert et al. 2015).

During construction phases, MR has been used to visualize planned improvements (Thomas et al. 2000) and view hidden objects behind existing structures (Thomas and Sandor 2009). MR has also been used to monitor construction sites, collect data, and document construction processes (Golparvar-Fard et al. 2009; Zollmann et al. 2014). MR offers the opportunity of real-time comparison between as-planned and as-built building elements (Shin and Dunston 2008), which can help identify defects (Park et al. 2013). MR also leverages BIM usage and visualization onsite (Kopsida and Brilakis 2016) and can be used to reduce risk factors. Last but not least, MR enhances industrial training, namely training operators of heavy construction equipment (Wang and Dunston 2007) and teaching students by introducing job-like spatial and time constraints to enhance the understanding of complex situations (Shanbari et al. 2016). However, there is scarce literature that documents the impacts of MR on users completing authentic, physical construction tasks situated in an outdoor environment. Thus, people know little about what factors could limit the use of MR in day-to-day field operations on active construction sites. In this research, empirical data is collected to derive such factors to provide valuable insights on pedagogical design and apprenticeship training development with MR.

Method

Lab Specifications

The wood-frame construction lab was part of a lower-division Construction Materials and Basic Building Systems course at Fresno State. The lab aimed to help students develop a fundamental working knowledge and hands-on skills with material handling and wood-frame construction. Students enrolled in this course were typically freshmen and sophomores of Construction Management and Civil Engineering majors in the College of Engineering. They were assigned into teams and tasked to build a simple wood structure that consisted of a floor, three wood-stud walls, a window opening, and a door opening (Fig. 1).

The lab consisted of a series of 3-h periods (typically four to five periods depending on weather, lecture progress, and logistics) in an outdoor construction yard with designated areas for material processing and installation. During each lab period, student teams used small tools, power tools, and other necessary lab supplies to build the wood frame. Due to the lack of professional experience and relevant practical skills, two to three senior students from an upper-division Project Controls class were assigned as managers to each student team to guide the installation and help answer technical questions. These managers had gone through the same wood-frame construction lab before and were mainly playing facilitating roles only. However, they provided firsthand feedback on student experience and the use of technology via close observation. A lab technician was also hired by the department to oversee the lab operation to ensure that student teams would follow safety protocols and other lab regulations at all times. Students must pass a Red Tag Safety Examination and wear appropriate personal protective equipment (PPE) to enter the outdoor construction yard and use tools during the lab period.

Research Design

The lab was divided into morning and afternoon sessions with three teams (with four to five students per team) in each session. Teams in the afternoon session were the control group and provided with design information via paper drawings. Teams in the morning session were the experiment group, and each team was provided with two Microsoft HoloLens devices to access the wood-frame design via the SketchUp Viewer application loaded in HoloLens. As shown in Fig. 2, once students open the SketchUp Viewer version 1, the wood-frame model will be loaded and projected in front of them as an interactive MR mockup. Students can then manipulate the mockup in many ways to explore the geometric and technical details needed to install the structure. For example, students can use the Scene menu to examine a particular part (e.g., foundation, floor, wall) by isolating it from the rest of the model. They can also use Scale, Move, and Rotate to review the model at different scales, locations, and perspectives to thoroughly understand the spatial relationship between different parts of the structure. More importantly, the Measure tool allows students to obtain material sizes and positions directly from the model instead of going back and forth, as if working with paper drawings. Last but not least, with

Fig. 1. Design exhibits of the wood frame.

multiple headsets, students can inspect the design at the same time using the Collaborate function.

It is noteworthy that instead of more conventional randomized controlled trials, this research used a quasi-matched group design method informed by Solomon (1949) to form student teams to balance the demographic composition and prior experience of each team. The advantage of using a match-comparison group design in this study was that it helped to reduce the impact behavior and performance differences that could have resulted from demographic factors. This arrangement helped to isolate differences to those related to the intervention introduced (i.e., paper drawings versus HoloLens-based MR mockups).

Teams in the control and experiment session received the same lab instruction. Additionally, students in experiment teams went through a 30-min training on how to use HoloLens in the lab orientation. The training was generic and provided an overview of the pinch gesture and gaze controls of HoloLens to navigate students through functionalities of the SketchUp Viewer application shown in Fig. 2. A training model instead of the actual wood-frame design model was used to avoid unnecessary advantage to the experiment teams.

The research design integrated apprenticeship learning opportunities in the series of lab activities. Major tasks for students in this lab included handling and processing building materials such as dimensional lumber and plywood, plan reading, wood studs framing, door opening framing, and window installation. The critical intellectual challenge to students in this lab was to test if they were able to translate design comprehension and cognitive knowledge of

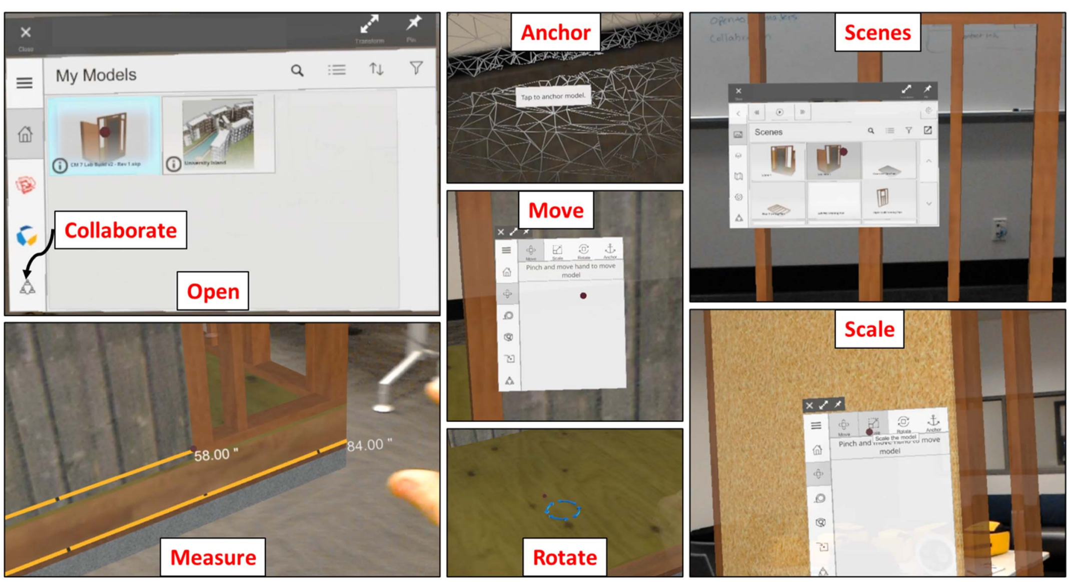

Fig. 2. SketchUp Viewer user interface and major functions for interaction. (Images by Angel Sandoval.)

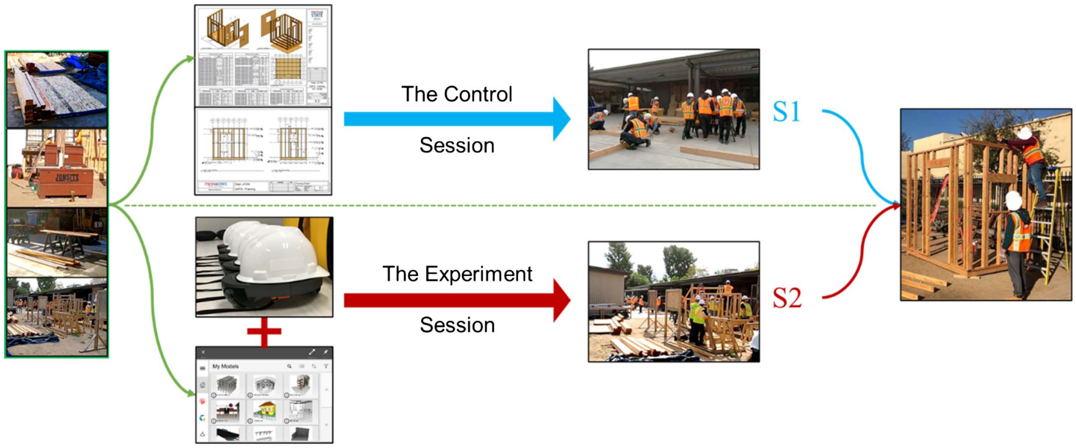

Fig. 3. Graphical overview of the proposed research design. (Images by Angel Sandoval.)

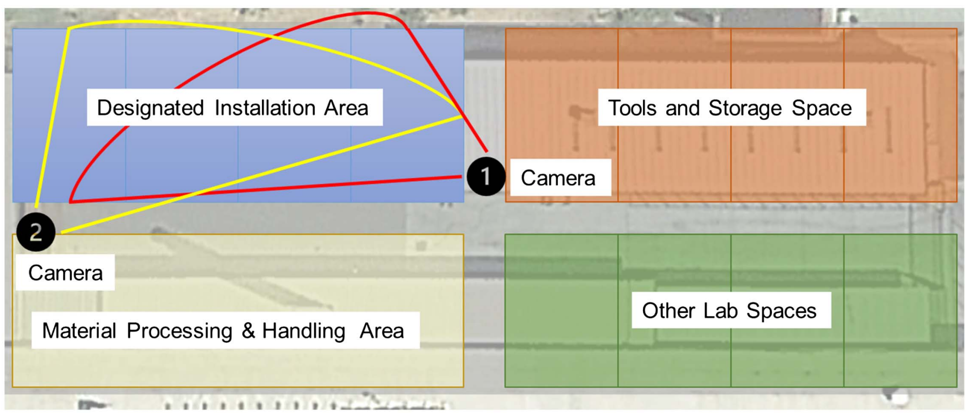

Fig. 4. Layout of the construction yard and planned data collection.

building materials, construction graphics, and spatial recognition (i.e., head apprenticeship) into hands-on skills. These skills were desirable for them to process and handle materials with appropriate tools as well as to install the required building components following proper means and methods with satisfactory quality and workmanship (i.e., hand apprenticeship). In summary, Fig. 3 depicts the overall research design and expected head and hand apprenticeship learning activities.

Data Collection and Analysis

In this exploratory research, direct observation of students while working in the outdoor lab was necessary for behavioral data collection. A pair of video recording devices (i.e., GoPro HERO6 Black, GoPro, San Mateo, California) were deployed at the construction yard to garner desired behavioral data. The two cameras were set to record activities in both morning and afternoon sessions on opposite ends of each other to ensure coverage of the whole installation area (Fig. 4). This research did not consider audio recordings due to prior experience of noted interference between teams, compounded by noises from the use of power tools and physical installation activities. It became nearly impossible to differentiate discussions among members of one team from adjacent teams. The camera recordings could help understand how students would interact with technology via direct observation of technology usage in performing specific job tasks. A graduate research assistant (GRA) and an undergraduate research assistant (URA) were involved in setting up the devices, collecting data during the lab periods, and assisting in subsequent data processing and analysis.

For RQ1, to compare the performance of student teams between the control and the experiment sessions, a production rate, or productivity of the wood-frame installation, was calculated as a percentage (%) of completion based on recorded lab progress at the end of each lab period. Table 1 below explains the particular method behind this calculation. Instead of using the more typical earned value approach by the industry, this study broke down the wood structure into work packages, parts, and building elements. It developed an earned elements approach to focus on the time and effort needed to produce the structure rather than the expenses. Specifically, each work package consisted of several parts of building elements, which added up to a total of 5 work packages and 14 parts. Based on historical lab data, an assumption was made that each of the 14 parts represented an equivalent proportion of the total workload involved to build the wood frame, i.e., 1 out of 14, or 7.14%. As a result, the daily production rate was calculated by multiplying the number of parts completed during each lab period by 7.14%, and the cumulative production rate was the product of the total number of completed parts and 7.14%. A total of 5 lab periods were planned for the fall semester of 2018 when the data was collected.

Table 1. Breakdown of the wood frame for installation production analysis

Lab period	Work packages	Parts number	Building elements (counts)	Cumulative earned elements (% of completion[a]) (%)
1	Concrete slab	1	Slab formwork (4)	7.14
		2	Slab (1)	14.29
2	Floor (base)	3	2×6 studs (9)	21.43
		4	3/4-in. plywood (1)	28.57
3	Left wall framing	5	2×4 studs (8)	35.71
		6	Insulation (1)	42.86
		7	Sheathing (1)	50.00
4	Right wall framing	8	2×4 studs (12)	57.14
		9	2×6 window header (2)	64.29
		10	Window frame (1)	71.43
		11	Window glass (1)	78.57
5	Front wall framing	12	2×4 studs (14)	85.71
		13	2×6 door header (2)	92.86
		14	Door (1)	100.00

[a]Actual installation of the work packages might not follow the exact order, but the % of completion allocated to each part remained the same, i.e., 7.14%.

For RQ2, in addition to direct observation of student behavior, the research team also administered a pair of pre and posttest surveys to understand if students' perceptions towards the wood-frame lab experience might vary with or without MR intervention. The two short surveys specifically targeted responses related to apprenticeship learning gains in the areas of plan reading, materials, and wood-frame construction. Both pre and posttest questionnaires are provided in Appendix I.

For RQ3, the research team conducted a focus group interview with upperclassmen managers who were supervising the experiment student teams. They shared their perspectives and provided critical feedback on observed student interaction with the MR technology and its impacts on student behavior and overall lab performance. The conversation was recorded and summarized for a preliminary qualitative analysis of factors and constraints that influenced the impacts of MR in this research study. Educators should consider these factors and constraints for the pedagogical use of MR in designing outdoor construction activities for apprenticeship learning. A list of interview questions was used as prompts to facilitate the discussion, and Appendix II includes a copy of these questions.

Results and Findings

The research team conducted data collection between October and November in 2018 during the fall semester. The wood-frame lab scheduled a total of five periods, but only conducted three with two canceled due to weather conditions that prohibited outdoor lab activities. The research team eventually obtained a total of 15 h of video recordings of lab activities in both the control and experiment sessions (Fig. 5).

Behavioral Data Analysis

To address RQ1, the research team was most interested in a direct comparison of performance between the control and experiment teams on the productivity of building the wood structure. Meanwhile, the research team also explored whether students in the experiment group would display different patterns of behaviors from their peers in the control group. Such behaviors included how they would obtain and apply cognitive knowledge (e.g., building materials and construction graphics) into the development of desirable psychomotor skills (e.g., 3D recognition and orientation,

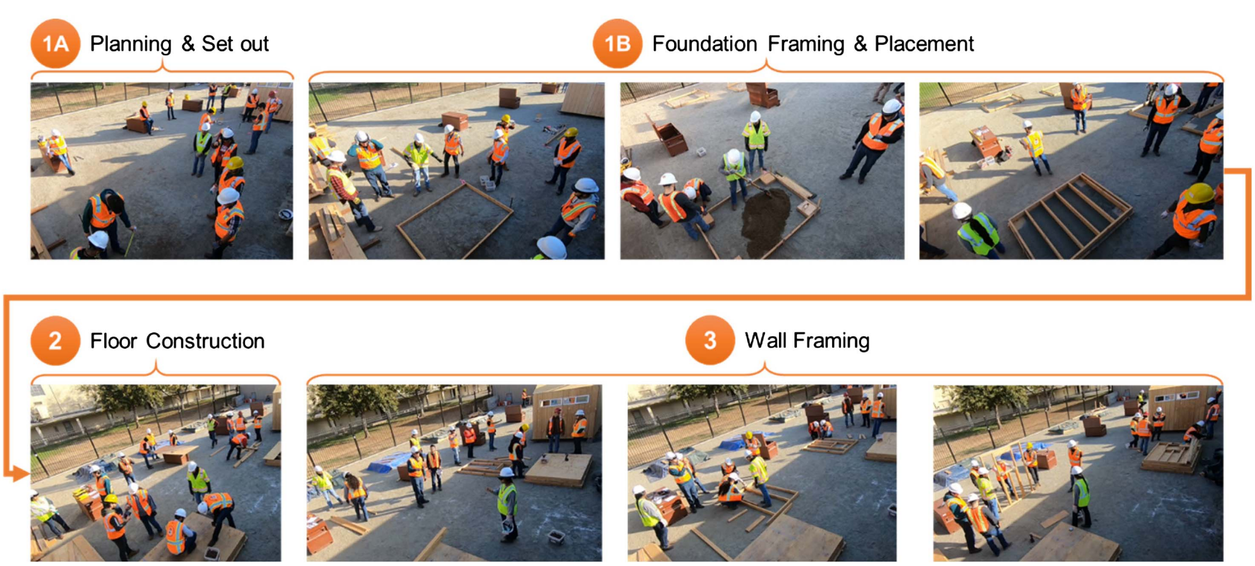

Fig. 5. Recorded lab periods and corresponding installation activities. (Images by Angel Sandoval.)

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Table 2. Time duration (unit = minute) of coded student activity per team and lab period

Lab period	Behavior category	Experiment teams (E-Teams)			Control teams (C-Teams)		
		E-T1	E-T2	E-T3	C-T1	C-T2	C-T3
1	Individual use	2.02	2.22	29.68	5.30	0	1.07
	Concurrent use	0	0	0	1.52	11.17	3.33
	Construction	30.23	67.72	52.32	45.37	33.92	47.77
	Gap	8.62	0	0	0	0	0
2	Individual use	7.70	7.70	7.70	0	0	0
	Concurrent use	0	0	0	4.75	9.55	6.97
	Construction	109.92	109.92	109.92	105.75	105.75	105.75
	Gap	0	0	0	0	0	0
3	Individual use	12.73	17.88	17.17	4.47	2.45	7.08
	Concurrent use	5.40	5.57	19.33	6.20	8.73	13.83
	Construction	77.28	94.82	93.65	81.60	113.67	93.38
	Gap	0.4	5.87	14.25	0	0	0

material handling, measuring, sequencing) needed to install the wood structure.

To conduct a quantitative analysis of the video recordings, the research team coded student behaviors into four categories, and calculated and summarized the corresponding time durations they spent on each category of these activities in Table 2. The coded categories included:

- *Individual use of HoloLens (experiment teams, or E-Teams) or paper drawings (control teams, or C-Teams)*: This refers to individual students spending time on design review to obtain wood-frame technical details.
- *Concurrent use of HoloLens or paper drawings*: This refers to concurrent design review by two or more students.
- *Construction*: This refers to the physical installation of the wood frame.
- *Gap*: This refers to the nonproduction time of gaps between design review and installation.

Productivity Comparison

Installation productivity was defined as the percent (%) completion per minute of construction. Table 2 summarizes the construction time of each student team spent in each lab period. The cumulative percentage of earned elements could be derived based on the assumptions established in Table 1 by counting the number of building elements installed at the end of each lab period according to the video recordings. Table 3 below summarizes the results of each student team's productivity for each lab period.

As stated in the preceding paragraph, none of these student teams was able to complete the wood structure due to canceled lab periods. Overall, the control teams (CT-1, 2, and 3) led in both total completion rates (average 50.00% versus 42.86% of experiment teams) and productivity (including average productivity by lab periods and overall productivity). However, the difference was marginal (see Fig. 6). It was also noticeable that productivity among control teams was more consistent than among experiment teams. In summary, MR did not seem to have an advantage over paper drawings in facilitating student teams' productivity of wood-frame construction in this study.

Time and Technology Use Pattern Comparison

The performance of student teams was a direct indicator of how much time they had worked towards building the structure and how effectively they were able to extract information from the design provided to assemble building elements appropriately. Therefore, it became meaningful and also relevant to RQ1 to understand student teams' time allocation to technology use and actual construction.

A summary of time and technology use by individual student teams has already been tallied earlier in Table 2. It was challenging to identify any particular pattern in this format when looking at individual teams. However, after aggregating and calculating the average time spent by control and experiment teams on design review and construction per lab period, some patterns of time and technology use were observed. Specifically, Fig. 7 presents the

Table 3. Summary of productivity (% completion per minute) calculation by team per lab period

Calculations	Lab period	Experiment teams			Control teams		
		E-T1	E-T2	E-T3	C-T1	C-T2	C-T3
Cumulative earned elements (%)	1	7.14	7.14	7.14	7.14	7.14	7.14
	2	14.29	14.29	21.43	14.29	21.43	21.43
	3	21.43	21.43	14.29	28.57	21.43	21.43
Total % of completion		42.86	42.86	42.86	50.00	50.00	50.00
Construction time (min)	1	30.23	67.72	52.32	45.37	33.92	47.77
	2	109.92	109.92	109.92	105.75	105.75	105.75
	3	77.28	94.82	93.65	81.60	113.67	93.38
Total construction time (min)		217.43	272.46	255.89	232.72	253.34	246.90
Individual lab productivity (%/min)	1	0.24	0.11	0.14	0.16	0.21	0.15
	2	0.13	0.13	0.19	0.14	0.20	0.20
	3	0.28	0.23	0.15	0.35	0.19	0.23
Average productivity[a]		0.21	0.15	0.16	0.21	0.20	0.19
Overall productivity[b]		0.20	0.16	0.17	0.21	0.20	0.20

[a]Average productivity is the arithmetic mean of individual lab productivity.
[b]Overall productivity = Total % of completion/total construction time.

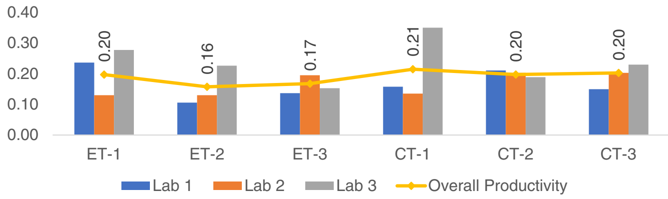

Fig. 6. Individual teams' productivity per lab period (columns) and overall productivity (line).

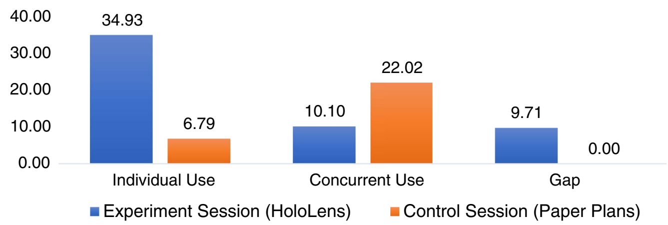

Fig. 7. Average time of each lab period spent for design review (minutes).

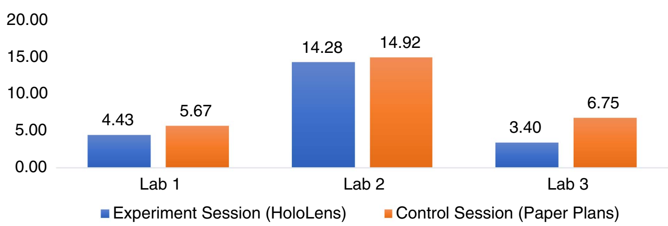

Fig. 8. Construction time to design review time ratio per lab period.

average time per lab period spent by control teams and experiment teams on design review, respectively. The experiment teams exhibited a preference for individual checks on design with the HoloLens, while the control teams tended to review design information concurrently. Even though each experiment team had only 2 HoloLens devices, one student could invite a second teammate to join the review of the 3D design model in HoloLens via the Collaborate function of the SketchUp Viewer application. However, students in the experiment teams rarely used this function according to the upperclassmen who were managing these teams.

It is also noteworthy that there was no gap time for control teams. In contrast, the gap time occurred in the experiment session due to the use of HoloLens, including switching the HoloLens with regular hardhats and charging the HoloLens. The HoloLens provided in this lab had already been integrated with the hardhats. Students found them heavy to wear when performing physical installation, so they opted to switch back to regular hardhats after reviewing design information using the HoloLens, which was not expected by the research team.

Similarly, the research team aggregated and calculated the ratio of the construction time to design review time per lab period per control teams and experiment teams, respectively. Fig. 8 presents comparable results between the two sessions, with the control teams appearing to be slightly more efficient in deriving design information because they were able to get more construction done per unit of time spent on design review, especially in Lab 3.

Perceived Apprenticeship Learning Gains

Apprenticeship learning took place in this lab project when students assessed design information through specific formats (i.e., paper drawings for control teams and HoloLens MR mockups for experiment teams) to determine technical details of the wood frame (head apprenticeship). By internally processing such cognitive gains, students then directed appropriate actions on specific building materials and tools to develop desirable psychomotor skills via physical construction activities (hand apprenticeship). Admittedly, the physical construction activity would enhance students' apprenticeship learning, regardless of whether they were using paper drawings or HoloLens. However, the research team attempted to address RQ2 by comparing: (1) if control team students or experiment team students would report bigger apprenticeships learning gains, and (2) if they would report different types of apprenticeship learning gains. A pair of pre and posttest questionnaires were used to survey students in the orientation session and after completing all three lab periods. Copies of the pre and posttest questionnaires were provided in Appendix I. The pretest established students' self-evaluated baseline understanding of plan reading, building materials, and wood-frame construction before participating in this lab project. The posttest revisited the same set of questions to assess students' perceived apprenticeship learning gains via physical construction activities. Tables 4–6 summarize the results and comparison between the control and the experiment.

According to Table 4, the most significant learning gain on plan-reading for both the control and experiment teams was the ability to "decide on means and methods for installing the designed structure." Table 5 suggests that control teams found the lab project most helpful in enhancing their knowledge about "types of wood members," while the experiment teams learned most on "basic framing design and installation." Table 6 represents a comprehensive evaluation of head and hand apprenticeships expected for students to develop through the construction activities of the wood-frame lab. The results were universally positive as both control and experiment teams reported consistent improvement in self-efficacy

Table 4. Perceived learning gains on plan-reading

Plan-reading (5-point Likert scale: 5 = Excellent, 1 = Poor)	Control			Experiment		
	$N = 14$ Pre	$N = 7$ Post	Gains (Δ = post − pre)	$N = 7$ Pre	$N = 4$ Post	Gains (Δ = post − pre)
Understand the design in general	3.9	3.9	0.0	3.7	3.8	0.1
Be able to find information such as sizes and dimensions	4.0	4.1	0.1	3.7	3.8	0.1
Be able to decide on means and methods for installing the designed structure	3.4	4.0	0.6	3.2	3.5	0.3

Table 5. Perceived learning gains on wood materials and wood framing

Wood materials and wood framing (5-point Likert scale: 5 = Excellent, 1 = Poor)	Control			Experiment		
	$N = 14$	$N = 7$		$N = 7$	$N = 4$	
	Pre	Post	Gains (Δ = post − pre)	Pre	Post	Gains (Δ = post − pre)
Types of wood members	3.2	3.9	0.7	3.0	3.5	0.5
Material handling and processing	3.5	4.0	0.5	3.5	3.5	0.0
Basic framing design and installation	3.6	4.0	0.4	3.0	3.8	0.8

Table 6. Self-efficacy on head and hand apprenticeship before and after lab project

Self-efficacy on head and hand apprenticeship (5-point Likert scale: 5 = Strongly agree, 1 = Strongly disagree)	Control			Experiment		
	$N = 14$	$N = 7$		$N = 7$	$N = 4$	
	Pre	Post	Gains (Δ = post − pre)	Pre	Post	Gains (Δ = post − pre)
Read and understand the design	2.9	4.1	1.2	2.7	3.5	0.8
Identify desired dimensions and sizes of wood framing components	2.9	4.1	1.2	2.8	4	1.2
Decide on the means and methods of installing the wood frame	2.9	4.1	1.2	2.3	3.5	1.2
Determine installation sequencing and overall installation time	2.7	4.1	1.4	3.3	3.5	0.2
Verify the quality, accuracy, and workmanship of our installation	3.0	4.0	1.0	2.8	3.3	0.5

Table 7. Compare SD of survey responses between pretest and posttest

Survey questions	Control			Experiment		
	SD			SD		
	Pre	Post	Δ = post − pre	Pre	Post	Δ = post − pre
Plan-reading						
Understand the design in general	0.74	1.36	0.62	1.11	0.43	−0.68
Be able to find information such as sizes and dimensions	0.76	1.36	0.6	0.47	0.43	−0.04
Be able to decide on means and methods for installing the designed structure	0.89	1.41	0.52	0.69	0.43	−0.26
Wood materials and wood framing						
Types of wood members	0.77	1.36	0.59	1.15	0.5	−0.65
Material handling and processing	0.82	1.41	0.59	1.58	0.5	−1.08
Basic framing design and installation	0.73	1.41	0.68	0.33	0.83	0.5
Self-efficacy on head and hand apprenticeship						
Read and understand the design	1.33	1.36	0.03	1.25	0.5	−0.75
Identify desired dimensions and sizes of wood framing components	1.36	1.36	0	1.07	0.71	−0.36
Decide on the means and methods of installing the wood frame	1.49	1.46	−0.03	0.47	0.5	0.03
Determine installation sequencing and overall installation time	1.03	1.46	0.43	0.94	0.5	−0.44
Verify the quality, accuracy, and workmanship of our installation	1.46	1.41	−0.05	0.69	0.43	−0.26

Note: SD = standard deviation.

beliefs across these apprenticeship learning metrics. For control teams, the biggest self-efficacy gain (pre and posttest Likert scale $\Delta = +1.4$) was able to "determine installation sequencing and overall installation time." It was followed by "read and understand the design," "identify desired dimensions and sizes of wood framing components," and "decide on the means and methods of installing the wood frame" (all with pre and posttest Likert scale $\Delta = +1.2$). For experiment teams, the most significant self-efficacy gains (pre and posttest Likert scale $\Delta = +1.2$) included both being able to "identify desired dimensions and sizes of wood framing components," and "decide on the means and methods of installing the wood frame." An interesting observation, according to Table 7, was that responses from the control teams were generally having increased standard deviation (SD) from pretest to posttest. In contrast, responses from the experiment teams seemed to have an opposite trend, showing an increased central tendency.

Factors Affecting Pedagogical Use of MR in Outdoor Construction Activity

Findings from both behavioral and perception data indicated that the use of MR did not show expected advantage over paper drawings in facilitating students' apprenticeship learning in outdoor physical construction activities designed in this study, which seemed to contradict the research literature. However, considering the gaps in understanding how MR would perform in the outdoor environment, the research team believes that it is imperative to address RQ3 and investigate what factors might have affected the success of the pedagogical use of MR in this and similar future research efforts.

Upperclassmen managers (hereinafter managers) played a unique role in this research. They provided managerial perspectives of and insights on students' interaction with technology without emotional biases associated with direct experience. Their observation of success and failure experienced by students in this lab project helped objectively assess factors affecting HoloLens's pedagogical usage in outdoor hands-on construction lab settings. The research team maintained regular checks with these managers at the end of each lab period and conducted a focus group interview after the last lab period for a comprehensive feedback session.

In a nutshell, the managers reported three categories of observed factors that might have contributed to shaping students' apprenticeship learning experience with MR/HoloLens:

- Technology-related factors: these included both hardware and software features of HoloLens. The managers concurred that the most significant advantage of using HoloLens over paper drawings was the ability to superimpose the 3D design mockup on top of the physical environment. They noted that even for completely inexperienced individuals, there was little to no obstacle for them to comprehend the design, navigate, and query for necessary technical details from it. Teams with the paper drawings initially had a hard time to visualize the design and mentally construct its 3D representation. However, the biggest challenge with HoloLens identified was anchoring the MR mockup in place when students were performing necessary measurements. It was cumbersome in that frequent body motion of students in physical construction activities often triggered the anchored model to shift again. Two experiment teams (ET-2 and ET-3) also had the misconception that they had to layout the MR mockup at a particular location, and then build the physical structure around it, which caused a loss of productivity in Lab Period 1. Limited field view of the HoloLens was another major drawback. The nature of the lab tasks and the limited construction space allocated to each student team forced students to project the 3D mockup close to them to ensure accurate measurement. The small field view severely hindered the efficiency of dimension reading and detail checking as only a small portion of the design was visible through the HoloLens at a time. Other technology-related factors included battery life, weight, and hand gesture detection. As mentioned previously, during productivity comparison, nontrivial gap time occurred among experiment teams because they had to charge the HoloLens and switch between HoloLens-integrated hardhats and regular hardhats. The current design of HoloLens imposed a considerable weight burden on the neck and made students feel ergonomically awkward wearing the HoloLens to perform the physical installation. Some student teams also complained to their managers that HoloLens would not detect their hand gestures with the gloves on, yet wearing gloves was a mandatory safety requirement of the outdoor lab.
- Environment-related factors: strictly speaking, environment-related factors could also be technology-oriented because the impacts of the environment were primarily on the device instead of on students. In the research literature, most testing and experiments with HoloLens were done indoors in controlled environments. This research meticulously assessed the use of HoloLens in an authentic outdoor construction site to ensure that the results would reflect real-world scenarios. The managers identified a few apparent constraints, including weather, lighting, dust, and noise. Without waterproofing features, HoloLens simply would not be applicable on rainy days. Direct exposure to sunlight, especially in summer afternoons, could incur unpleasant glare and heat the HoloLens to cause discomfort. Not only did these environmental factors impact the user experience, but they also directly affect the productivity and quality of the end product. The managers commented that field conditions could be a significant bottleneck for technology such as MR/HoloLens to completely replace traditional approaches such as paper drawings in the construction industry.
- Training-related factors: the managers unanimously voted training as the most significant factor that contributed to shaping student teams' performance, behavior, and overall learning experience. The consensus was that the 30-min training in the orientation session was far from sufficient. The managers recommended dedicating at least a whole lab period (3 h) to training. Specifically, managers highlighted the needs for both MR/HoloLens training and fundamental technical training. The managers suggested that MR/HoloLens training should be more than just familiarizing students with generic controls of the HoloLens and navigation tools of the SketchUp Viewer application. They believed that students should also be required to train with a sample model to perform tasks similar to the actual lab project, such as anchoring, measuring, verification, and team collaboration. One manager stressed the importance of training from the perspectives of a mental paradigm shift. Students understood that HoloLens allowed them to take measurements and apply markups directly on the 3D design mockup. However, the managers noticed that quite a few students would still write these measurements down on a piece of paper for cutting and installation without realizing they could directly read them from the HoloLens without going through the redundant 2D process. Managers believed that students should also be proficient with troubleshooting technical issues with HoloLens in the field to reduce gap time. Fundamental technical training referred to knowledge checks on students to make sure that they knew how to use and read a tape measure, how to use small tools and power tools, and so on. Seemingly irrelevant to the research questions, at least two managers reported that failure and frustration with the lack of necessary technical knowledge could negatively affect students' attitudes toward technology and discourage them from using HoloLens.

The managers also brought up a particular issue that did not seem to belong to the preceding categories. They noticed that a common mistake was made by both control and experiment teams when constructing the header for the window opening, where it required two pieces of 2×6 lumber to be sandwiched with a plywood spacer in between. Ideally, the experiment teams should have an advantage over the control teams because they have a direct visual of the completed 3D design mockup. In contrast, control teams have to rely on 2D information to construct the 3D representation mentally. Managers commented that the 3D mockup provided via the HoloLens was missing the details of the plywood spacer. This raised the alarm for faculty to consider quality control when leveraging MR for pedagogical uses and content development. The benefits that higher education could reap from MR heavily rely on the quality of learning design practices that demand significant preparatory work and dedicated training.

Discussion and Limitation

Incorporating new technology in higher education curriculum usually comes with a learning curve, which is evident in this research. Although it was not the intention of this research study to quantitatively assess students' acceptance of MR, their varied attitudes towards this new technology were well received. Managers noted that students were experiencing a technology shock during the first lab period. Verbal complaints due to frustration and anxiety were present until the managers intervened to assist in troubleshooting. As the lab proceeded, a clear divide among the students occurred starting at the end of the second lab period. Many students began to get excited about MR/HoloLens with a lot of positive feedback. Yet, a handful of them remained indifferent and were clearly attempting to avoid the engagement with technology throughout all lab periods. One of the three experiment teams had only two students persistently work on the project, while the other two teammates stopped attending after Lab 1. Such a divide was not observed among the control teams. Managers commented that experiment teams could have achieved better productivity had all of their students been more motivated and engaged.

Another observation, both via the video recordings and managers' feedback, was related to team dynamics and leadership. In the control session, students with some prior construction and carpentry experiences immediately became the leaders of their teams. In contrast, in the experiment session, the ones who were more technology-savvy tended to lead. Students in the control session also seemed to do a better job of involving everyone in team discussion and collaborating on installation without much idling compared to the experiment teams. Managers believed this was due to an insufficient number of HoloLens, and the lack of understanding of the collaboration function of the SketchUp Viewer application. Impacts of MR on team dynamics and leadership formation were beyond the scope of this study but certainly could be meaningful topics for future research.

This research study had several limitations. The absence of verbal communication data due to practicality considerations could be lost opportunities for gaining valuable insights on intuitive real-time reflection of students. The weather, although considered as an "act of God," also truncated possible lab periods, thus limiting empirical data collection. Finally, low response rates of the pre and posttest surveys and the limited size of control and experiment groups may influence the generalization of results and findings from this research.

Concluding Remarks and Future Research

Recent advancement in technology innovations such as MR seems to provide a viable solution to the skilled labor shortage in the construction industry. The promises to promote workplace productivity, enhance training, and education of the next-generation workforce have been touted for significant investment in MR applications from both professional and education communities. However, there are still considerable uncertainties with the practical and widespread use of MR because there is a lack of empirical evidence on how MR would perform in the field on real construction job sites. This research explores MR's potential in facilitating students' apprenticeship learning in the undergraduate CM curriculum by situating its application in an outdoor wood-frame construction lab. Specifically, the research investigates how students using MR would perform and behave in physical construction tasks, and perceive apprenticeship learning gains via the field experience in comparison with their peers using paper drawings for the same tasks. The findings suggested that students with MR did not outperform their peers with paper drawings in any of these areas. However, their behavior patterns and perceptions towards apprenticeship learning gains were different. The research also identified technology-, environment-, and training-related factors that limited MR's success in field use. This research contributes to the body of knowledge in both professional and educational communities. It fills the gaps in understanding MR's field use with empirical evidence from apprenticeship learning data in outdoor construction. It also provides peer educational researchers with valuable insights into how to study pedagogical use of MR with consideration of potential challenges that were present in realistic construction environments. The research team is interested in further exploring team dynamics and leadership formation in MR-enhanced apprenticeship learning environments.

Appendix I. Pre and Posttest Survey Questionnaires

Pretest Questionnaire

Please provide the first 3 letters of your mother's maiden name (add "x" if shorter than 3): _____

Please provide the last 4 digits of your bulldog ID: ______

Which lab team were you assigned to? Team with paper plans/Team with Microsoft HoloLens

Did you receive the pre-lab training with the Mixed Reality device (Microsoft HoloLens)? Yes/No

Have you taken any construction graphics or plan-reading class before? Yes/No

How would you rate your current plan-reading skills? (5 = Excellent, 1 = Poor)

- Understand the design in general (5, 4, 3, 2,1)
- Be able to find information such as sizes and dimensions (5, 4, 3, 2, 1)
- Be able to decide on means and methods for installing the designed structure (5, 4, 3, 2, 1)

How much do you know about wood material and wood framing? (5 = A great deal, 1 = None at all)

- Types of wood members (5, 4, 3, 2, 1)
- Material handling and processing (5, 4, 3, 2, 1)
- Basic framing design and installation (5, 4, 3, 2, 1)

Please indicate the level of concerns you have toward the following statements about the wood-framing lab (5 = Most concerned, 1 = Least concerned)

- Review and understand the design (5, 4, 3, 2, 1)
- Verify dimensions and sizes of individual wood framing components (5, 4, 3, 2, 1)
- Means and methods of installing the wood structure (5, 4, 3, 2, 1)
- Installation sequencing and time management (5, 4, 3, 2, 1)
- Quality control and workmanship of the installation (5, 4, 3, 2, 1)

Posttest Questionnaire

Please provide the first 3 letters of your mother's maiden name (add "x" if shorter than 3): _____

Please provide the last 4 digits of your bulldog ID: ______

After completing the wood-frame lab, how would you rate your current plan-reading skills? (5 = Excellent, 1 = Poor)

- Understand the design in general (5, 4, 3, 2, 1)
- Be able to find information such as sizes and dimensions (5, 4, 3, 2, 1)
- Be able to decide on means and methods for installing the designed structure (5, 4, 3, 2, 1)

After completing the CM7S lab, how much do you know about wood material and wood framing? (5 = A great deal, 1 = None at all)

- Types of wood members (5, 4, 3, 2, 1)
- Material handling and processing (5, 4, 3, 2, 1)
- Basic framing design and installation (5, 4, 3, 2, 1)

Which lab team were you assigned to? Team with paper plans/Team with Microsoft HoloLens

For teams with paper plans: please indicate your levels of agreement with the following statements when using paper drawings in this lab (5 = Strongly agree, 1 = Strongly disagree):

- I can easily read and understand the design (5, 4, 3, 2, 1)

- I can easily identify desired dimensions and sizes of wood framing components (5, 4, 3, 2, 1)
- I can easily decide on the means and methods of installing the wood frame (5, 4, 3, 2, 1)
- I can easily determine installation sequencing and overall installation time (5, 4, 3, 2, 1)
- I can easily verify the quality, accuracy, and workmanship of our installation (5, 4, 3, 2, 1)
- Overall, I find paper drawings provide sufficient information needed to complete the lab tasks (5, 4, 3, 2, 1)

Paper drawings have been used in our industry for a long time; what are some of the pros and cons using paper drawings in this lab project in your opinion? ___________

For teams using the Microsoft HoloLens, please indicate your levels of agreement with the following statements when using Microsoft HoloLens in this lab (5 = Strongly agree, 1 = Strongly disagree):

- I can easily read and understand the design (5, 4, 3, 2, 1)
- I can easily identify desired dimensions and sizes of wood-framing components (5, 4, 3, 2, 1)
- I can easily decide on the means and methods of installing the wood frame (5, 4, 3, 2, 1)
- I can easily determine installation sequencing and overall installation time (5, 4, 3, 2, 1)
- I can easily verify the quality, accuracy, and workmanship of our installation (5, 4, 3, 2, 1)
- Overall, I find the Microsoft HoloLens could completely replace paper plans and provide all necessary information for this lab (5, 4, 3, 2, 1)

Mixed reality devices like HoloLens are still very new to our industry. What are some of the pros and cons using HoloLens in this lab project in your opinion? ___________

In general, what do you think could be done to make HoloLens more helpful for lab projects like the wood framing in our curriculum? Any comments or suggestions? __________

Appendix II. List of Focus Group Interview Questions

What was your favorite and least favorite part of using mixed reality?

Do you feel that mixed reality can completely replace paper plans in construction?

What limitations were imposed on students when using mixed reality over paper plans?

How has mixed reality influenced the productivity and quality of the wood framing structure?

Would it be easier for inexperienced individuals to build a wood-framing structure with mixed reality? Yes? No? Why?

Do you feel that mixed reality will be easier to use than paper plans for certain disciplines such as Mechanical, Electrical, and Plumbing (MEP), Civil, etc.? If so, which ones and why?

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request.

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