USE OF AUGMENTED REALITY TECHNOLOGY TO ENHANCE COMPREHENSION OF CONSTRUCTION ASSEMBLIES

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SUMMARY: *The construction industry faces the incessant challenge of adjusting to a continuous fluctuation of employees. Consequently, the industry is faced with a loss of expertise and practical knowledge required to successfully deliver construction projects, especially with older and more experienced employees retiring at a rate faster than the incoming workforce can replace them. The future of the industry is dependent on the competence of this next generation of employees joining the construction workforce. Therefore, it is highly desired that new employees be equipped with the necessary skills and abilities required to manage the complexities inherent in construction processes successfully. The lack of practical exposure to on-site construction situations during a new employee's college education results in a limited spatial and temporal understanding of complex construction processes, which adversely influences these new employees' abilities to solve problems, therefore limiting their initial productivity.*

This study simulates the environmental context and spatio-temporal constraints of several construction assemblies by using Augmented Reality (AR) technology combined with a layer of simulated visualizations. The superimposition of BIM-based model elements and images on real-time site videos functions as a novel pedagogical technique which virtually incorporates jobsite experiences into the classroom. The jobsite becomes an interactive experience subjected to digital manipulation which reinforces and highlights key technique and constructability based concepts. Testing revealed that construction management students exposed to AR-enabled content were better able to identify the elements and tasks related to masonry, roof, and steel construction when compared to those students who received typical in-class instruction. The results further indicate that ART combined with typical classroom instruction provides educators with an advantage as they strive to prepare their students for successful careers in construction.

KEYWORDS: *augmented reality, construction management, construction industry, construction management education, construction assemblies, masonry, roofing, structural steel, spatio-temporal constraints.*

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1. INTRODUCTION

The people involved and the extent of their knowledge are key success factors for any construction process. Therefore, it is imperative that new employees who enter the construction industry have developed the abilities required to resolve the convoluted problems inherent in the construction process. However, institutions of higher learning customarily use passive teaching techniques, which are not very effective in teaching the spatial and temporal skills needed to meet the problem-solving requirements of the construction industry. The consequence of passive teaching techniques is that students receive inadequate exposure to many construction processes and procedures which they will be faced with as they begin their careers, thus resulting in a comprehension deficiency of the spatial and temporal constraints present during construction.

Teaching techniques which incorporate both, construction site visits and in-class media presentations are usually implemented with the aim of rectifying this lack of exposure. Although these techniques may provide some understanding, sole dependence on them would fail to deliver the contextual details required to grasp the complex nature of construction projects fully. It is nearly impossible to get a class into the field to witness the exact systems or processes being taught in the classroom at any given time, and to do so would require an unreasonable amount of site visits. Therefore, to reinforce what is being taught in the classroom site visits alone may not be enough. The resulting lack of exposure and understanding renders the students inadequately equipped to contribute to aspects of a project when they enter the workforce.

Advanced teaching techniques which can provide greater insight into the educational process are needed to enhance the educational experience of Construction Management students. This study uses a combination of Augmented Reality (AR) technology with a layer of simulated visualizations to replicate the environmental context and spatio-temporal constraints which exist during masonry, roof, and steel construction processes. The superimposition of virtual elements on real-world videos and images provides a pedagogical technique which virtually incorporates jobsite experiences in the classroom. The integration of AR allows for virtual site visits and augmented experiences that can be tailored to what is being taught in the classroom, thereby providing a more effective learning experience which is better able to reinforce classroom learning.

AR provides a potential benefit for construction management students, aiding in their understanding of complex products and associated jobsite processes through the overlaying of computer-generated (virtual) content onto real-world jobsite visualizations. As this technology continues its rise toward widespread utilization, it is of the utmost importance that its ability to enhance educational experiences be studied and analyzed. This research presents a summary of AR; investigates current AR developments; examines the potential influences of AR on the future construction industry workforce; and evaluates the impact of AR on learning outcomes in construction management education. The findings of this study offer a premise for understanding for instructors seeking to integrate a new instructional tool into their curriculum, with the goal of improving the educational experience of their students, as well as their understanding of the complex processes that they will experience during their future careers in the construction industry.

1.1 Problem statement

Construction management students are infrequently exposed to many construction processes and procedures during classroom instruction, resulting in a minimal understanding of their complex nature. Although supplementary teaching techniques, such as field trips, may provide some insight, they do not completely communicate the contextual details required to comprehend the complexity of construction projects fully. This limited exposure to unabridged construction processes leaves the students with a comprehension deficiency related to the spatial and temporal constraints which are prevalent during the construction process. Consequently, the deficiency in experience and practical knowledge may ultimately hinder the capacity of students to contribute to the workforce early on in their careers productively. It is possible for course instructors to improve this situation by making adjustments in their curriculum to incorporate advanced teaching techniques that can provide greater insights to students. In an effort to meet the needs of the industry, this study focuses on establishing how the use of AR technology improves spatial and temporal comprehension of masonry, roofing, and structural steel construction in construction management education.

1.2 Research Goals and Hypotheses

This research aims to determine the effectiveness of the implementation of AR in enhancing the learning experience of construction management students and improving their comprehension of the spatio-temporal constraints which are prevalent throughout specific construction processes. Learning assessments were conducted using visual documentation, e.g., images and video of an established test case, layered with simulated virtual visualization through AR. Evaluations were used to determine the students' baseline and gained spatio-temporal comprehension of the constraints within the given test case. A pre-test was administered to establish an initial baseline of the students' comprehension of the selected subject matter so as to determine the effectiveness of the traditional lecture and test teaching techniques in imparting students with the requisite knowledge in regards to the particular construction process. AR-enabled visualizations were developed to simulate supplementary conditions in order to increase the students' level of comprehension for the specific construction process in question. The developed AR visualizations were made available to the study participants in a video format which was convenient, easy to use, and easily accessible with standard computer technology available to students. Lastly, the hypotheses that the use of augmented reality will enhance the students' comprehension of the spatio-temporal constraints prevalent in construction processes associated with the masonry; roofing; and structural steel assemblies was tested. This study hypothesized that integration of visually documented construction site experiences superimposed with virtual enhancements in the classroom environment would result in an increase in students' comprehension of various construction processes. This paper is a continuation of formerly published work (Bademosi et al. 2017, Blinn et al. 2015, 2016), and relies on similar methodologies for the development of AR-enabled content, study methodology, and data collection.

2. AUGMENTED REALITY IN THE CONSTRUCTION INDUSTRY

Augmented reality (AR) systems enhance the real-world by combining the real-world with the virtual-world and overlaying computer-generated information onto a real-world environment (Azuma et al. 2001, Izkara et al. 2007). The Architecture, Engineering, Construction and Operators (AECO) industry has conducted research into the applications of AR in several areas including the areas of tracking as-planned to as-built progress, training, dynamic site visualization, exposure of construction defects and incorporation with diverse building information modeling (BIM) workflows (Rankohi and Waugh 2013).

While there is much effort being directed towards research with AR technology, the dominant aspect of research in AECO industry has concentrated on the utilization of AR in the field. An instance of the application of AR in the field was its use by Shin and Dunston (2009) for detecting the precise positions of anchor bolts and the alignment of steel columns during steel erection. They concluded that AR showed potential for increased productivity during the erection process of steel elements and also demonstrated the ability of users to acclimatize themselves to the use of technology that they had not been exposed to beforehand.

A comprehensive evaluation of AR-based research completed by Rankohi and Waugh (2013) observed that 8% of the 133 articles associated with AR were directed at students and their experiences. Additionally, 5% of the reviewed articles centered on the areas of application related to education or training within the AECO industry. These statistics show that the applications of AR can expand beyond the jobsite, to the education and training of students to better prepare them for joining the workforce. Gheisari et al. (2014) used a case study to show the application of AR in education and training using a building information model (BIM) and a mobile augmented reality (MAR) device to provide virtual data and information about actual building components and systems on the mobile devices of facility managers. Similarly, a comparable design can be applied as an instructional tool by tailoring the augmented experiences to what is being learned in the classroom, allowing for an improvement in the spatial-temporal skills of students and thereby providing a more efficient learning experience.

AR technology is rapidly evolving and shows possibilities of being interconnected with every aspect of the construction process. Construction processes will be distinctly enhanced by several applications fostered by AR technology, including uncomplicated field inspections and having access to localized context-aware data (Chi et al. 2013). According to Izkara et al. (2007), some of the potential benefits of AR to the construction industry include mobility of the users by reason of mobile computing devices, increased productivity as a result of automatic access to constantly updated information on-site, and detection of jobsite conditions in an uncontrolled environment improving safety in construction. AR technology demonstrates several possibilities of achieving increased profitability, sustainability, safety and security in the construction industry. Rankohi and Waugh (2013) recommended that members of the AECO industry keenly keep this area of study under observation in order to stay conversant with advancements in this technology. This suggestion is not limited to those in the industry. Educators should also bear this in mind as they train the next generation of the AECO industry workforce in preparation for starting their professional careers.

3. AR IN EDUCATION

AR, because of its vast potential and numerous advantages for the augmentation of teaching and learning settings, has been established as an innovative instruction technique that would supplement education (Yuen et al. 2011, Wu et al. 2013). AR gives learners a different point of view on concepts being taught in the classroom and is also known to increase the motivation of students for learning (Di Serio et al. 2013). Virtual objects and information that would otherwise go unnoticed are made easily visible to students with the use of AR (Kesim and Ozarslan 2012). This is particularly essential for CM students, as they would be able to spot hidden building elements, enhancing their understanding of the construction process.

Yilmaz (2016) established that beginning with early education, AR can be employed to foster communication and enhance cognitive realization in early adolescence education, which are two very important influences on knowledge transfer. Progressing to middle school education, Nincarean et al. (2013) enumerated the research papers that implemented mobile augmented reality (MAR) in a bid to enhance learning in diverse disciplines including butterfly ecology (Tarng and Ou 2012).

By incorporating AR technologies and techniques in the more complicated systems introduced in institutions of higher learning, students become more receptive to these systems thereby increasing knowledge transfer (Martín-Gutiérrez et al. 2015, Akçayır et al. 2016). Jeřábek et al. (2014) explored the instructive attributes of AR and how they can be employed to increase the standard of pedagogic systems. Ayers et al. (2016) in a case study tasked groups of students with executing a building redesign task with the use of an AR-based educational game or paper-based formats to design, visualize, and evaluate exterior wall designs to reconstruct an existing facility and improve its overall sustainable performance. They concluded that the students who used the game were able to design innovative and creative concepts with better overall performance than students who used paper-based formats. Similar educational tools help foster an active learning environment necessary to best improve the spatial and temporal skills of learners.

3.1 Challenges in Construction Management Education

A typical construction project usually consists of several complicated processes which are interconnected with one other. The inadequacies of conventional pedagogical techniques impede the ability of the instructors to adequately teach and elucidate such complicated construction techniques and processes in a classroom environment (Rojas and Dossick 2008). Sole reliance on course materials and simple in-class media presentations would fail to convey the contextual specifics that are required to comprehend the complex nature of construction projects fully. These specifics generally add immense value to the learning experiences of students, significantly impacting their learning (McClam et al. 2008). Field trips and internship programs are two approaches often used to overcome such limitations in CM academic programs. Typically, students are taken on field trips one or two times in a semester, which only provides the students with a snapshot of the actual state of affairs in the field. Furthermore, the field operations taking place at the time of the field trip are likely not related to the exact systems or processes being taught in the classroom at any given time. Thus this approach alone does not deliver a complete contextual construction jobsite experience, and to do so would require an unreasonable amount of site visits.

Alternatively, internship programs provide students with a broader perspective of construction projects. Nonetheless, not all students possess the intrinsic motivation and desire for the active learning participation required for a successful internship experience, thereby limiting the aim of the approach (Levesque-Bristol et al. 2010). Moreover, the availability of active construction projects is not guaranteed as it is often determined by geographical location and the state of the regional economy. Firsthand engagements with complex situations in education will undoubtedly result in a more significant and genuine educational experience (Kolb and Kolb 2005). However, chances of these firsthand engagements are narrow in construction management education. Therefore, the use of alternative approaches that incorporate advanced teaching techniques, which can provide greater insight to students is required to enhance the learning experiences of construction management students.

Aside from these educational challenges, the construction industry is faced with a loss of expertise and practical knowledge as a result of older and more experienced employees going into retirement at a rate faster than new employees can replace them (Jain 2015). Therefore, it is imperative that institutions of higher learning meet the educational needs of students by equipping them with the necessary skills and abilities required to make them successful in their careers. Mutis and Issa (2014) noted that a reliance on only traditional teaching techniques coupled with media limitations has resulted in knowledge gaps and inadequacies in fully developing spatial and temporal skills. Therefore, there is a need to re-evaluate construction management courses to link concepts and theories for improved reasoning and analytical abilities, and to promote better spatial and temporal skills development using AR. With the availability of mobile devices and the latest AR technologies, the possibilities of providing visually active learning environments to improve spatial and temporal skills are more abundant.

4. AUGMENTED REALITY TEST CASE

4.1 Selected Sample Project

The methodology used for the development of the AR-enabled content and data collection for the masonry, roofing and structural steel construction assemblies in this study were identical to those used in previous publications which were part of this study (Bademosi et al. 2017; Author et al. 2016, 2015). A low-rise educational and administrative building being built on the University of Florida (UF) campus was selected as the test case for the purpose of this study. The research team cooperated with the project contractor to record and document the construction project in its entirety, including the specific assembly processes, for the purposes of this study. Construction on the project site commenced in the fall of 2013, and the researchers carried out daily site visits throughout the duration of construction and turnover to acquire both image and video data. The techniques used to collect data from several viewpoints included standard imaging techniques along with unmanned aircraft system (UAS) to capture both still picture and video data. The visual data collected for purposes of the study was also accessible to the contractor for project documentation and management workflow purposes. A data management system was created whereby the entire collection of the captured data was kept on a secure computer system and was arranged in chronological order as well as subject matter, from excavation through final inspections.

Due to the location of the building in the historic zone of the UF campus, the project required special consideration for design and construction techniques which matched the historical aesthetic of that portion of campus, as well as ensured durability. The prevalent method of construction for the test case building was a steel structural frame surrounded by brick veneer concrete masonry unit exterior walls and a clay tile roofing system. Also, unconventional information technology and HVAC systems were incorporated into the building, and the installation of these systems was recorded throughout each installation phase for potential future research. Collaboration with the contractor nurtured a relationship that allowed for exceptional site access and for a great deal of data to be collected. In addition, critical installation and project milestones which needed to be documented were identified by the contractor and researchers, ensuring that fundamental construction processes were not missed. Due to the complexity of the project and the breadth of information that could be collected from documenting the entire construction process, this project proved to be an exemplary test case for this study.

Site activities and construction processes were documented on a daily basis throughout the entire duration of construction, from the excavation of the foundations through final building inspections. In order to make available a wide range of media platforms to the research team as the study evolved, both still images and video recordings were captured. Fig. 1 shows an instance of a still image capturing the progress of the project during the construction phase a year into the project. The range of construction techniques which were in focus during construction as a result of the building design and the particular building systems selected included erection of structural steel, masonry work, metal stud framing, installation of clay tile roofing, installation of stone parapet and façade elements, installation of chilled beam air conditioning system, and fireproofing throughout the building. The assortment of the building systems and installation processes documented provided the research team with a range of options to choose from, which was a critical factor for this study.

FIG 1: Overall construction progress taken with an unmanned aircraft.

4.1.1 Masonry Construction

One of the three main construction assemblies chosen as a focal point for this study is the exterior wall masonry system, which was subsequently used during the classroom testing phase of this study. The masonry system for the sample test case consisted of the concrete masonry unit (CMU) backing wall, waterproofing, insulation, brick veneer and accompanying masonry wall accessories (such as brick wall ties, flashing, etc.). Inexperienced students often find the tasks of taking off masonry quantities and calculating cost estimates arduous, and this can be partially attributed to the assembly process being unfamiliar to them. Fig. 2 shows the installation of rolled on waterproofing over the CMU backing wall, captured while documenting the construction of the masonry wall assembly. This example demonstrates the level of detail at with which each phase of the masonry wall construction process was captured.

FIG 2: Installation of waterproofing on the exterior CMU wall.

4.1.2. Roof Construction

The roof assembly was the second main construction assembly chosen as a focal point for this study and was subsequently used during the classroom testing phase of this study. The roof assembly selected for the project consisted of; a steel frame, light-gauge metal joists, metal decking, rigid insulation, plywood decking, vapor barrier, copper flashing, and clay roofing tiles. Although roofing assemblies are relatively straightforward in comparison to other construction systems, students commonly find it difficult to understand the sequencing and overlap associated with the installation of the several roofing layers. Fig. 3 shows an instance of documentation during the construction of the roof, depicting the installation of clay roof tiles over a waterproof membrane, as well as the visible installation of the copper flashing in a roof valley. A UAS was used to capture all the phases of the roof assembly construction, and the collected media were then displayed in the AR-enhanced videos to show progressive stages of completion to impart a comprehensive knowledge of the roofing construction process.

FIG 3: Installation of clay roofing tiles.

4.1.3. Structural Steel Construction

The structural steel assembly system was the third construction assembly selected for this study. The structural steel assembly for the project consisted of; concrete spread footings, concrete shear walls, structural steel columns, structural steel framing, angle bracing, and metal decking. While structural steel assemblies are less complicated in terms of the number of elements to identify, the system poses some challenges to students when it comes to an understanding the accurate sequencing involved during the erection of structural steel elements. The foundation pour and steel erection processes were captured in their entirety, including context related to material storage and staging. Furthermore, the collected documentation shows live site conditions, including equipment and sequencing, at each stage of the steel erection process. The selected sample project was an "L" shaped building on a highly constrained jobsite which increased the importance of proper planning for steel erection. An example of the structural steel assembly for the sample project is shown in Fig. 4 and focusses on the erection and fastening of structural steel elements around a cast-in-place concrete shear wall.

FIG 4: Erection of structural steel

4.2 Study Participants

The selected target population for this study was undergraduate students enrolled in an accredited construction management program at one of two Universities. The data analyzed for the purpose of this study was derived from a sampling of students enrolled at the Rinker School of Construction Management at the University of Florida (UF) and the Turner Department of Construction Management at Louisiana State University (LSU). The study was conducted after obtaining Institutional Research Board (IRB) approval at both institutions and students signed consent forms which outlined the goals and expectations of the study. The students participating in this study were enrolled in the second semester of their junior year at their respective University. This study was conducted over a period of two academic years (Fall 2014 – Spring 2016), with students from the UF and LSU providing viable data for use in this study. A total of 74 students completed the masonry assembly tests, 120 students completed the roofing assembly tests, and 55 students completed the structural steel assembly tests for this study.

A required Estimating I course was chosen for the implementation of this study and as the course from which participants would be solicited at each University. The prerequisites for the estimating course required that students had completed basic construction techniques and project management courses. The learning strategies used in the techniques course were predominantly the studying of course materials and completion of associated coursework, accompanied by trade demonstrations provided by subcontractors as well as field trips to local jobsites and material manufacturers. The students were exposed to the fundamental practices of construction estimating in the selected course, which expands on the students' prior knowledge of construction techniques. The course teaches the students how to conduct quantity takeoffs for the elements important to produce a comprehensive cost estimate and focuses on the ability of the students to identify all the elements in a given construction process which have cost implications either stated or implied in the construction documents.

However, one of the challenges in teaching students how to quantify cost items is ensuring that the students develop the ability to understand the processes and items which are not evident in the drawings or specifications but are imperative to the accuracy of the final cost estimates. Awareness of these secondary cost elements integrated in the means and methods of certain building systems is typically acquired over time and with experience. Therefore, imparting basic knowledge and recognition skills for these elements to students is a required learning objective for a comprehensive estimating course. In this study, AR is used to provide greater insights to the students, as it provides contextual visual representations of construction processes in the classroom environment without having to visit a construction site.

5. EXPERIMENTAL CONSIDERATIONS

5.1 Augmentation Procedure

The development of AR-enabled site documentation for the primary construction assemblies of the sample project was a crucial step in this research. The process of efficiently augmenting virtual models and components onto construction site visualizations was achieved with the aid of several software packages. The site images and video which were collected during the construction process were reviewed, and a subset was selected for the augmentation procedure. The content and level of visible detail were the primary factors considered in the first phase of media selection for the three building systems addressed in this study. Next, the selected images and videos were screened for quality and smooth camera positioning, which is crucial for effective AR outcomes. A camera tracking software was used to process the selected videos in order to establish the camera path and location of the objects on the construction site. Subsequently, a developed script defining the camera path was imported into the 3D modeling software in order to initiate the procedure of capturing the virtual objects appropriately for combination with the visual media. Strings of object markers were used to determine the location of several components located within the line of sight of the camera, making it possible for the virtual model to be sited in the appropriate location and visualized from the most suitable camera path and angle. Finally, the various site images and videos representing the complete masonry, roofing and structural steel assembly construction processes were merged with carefully chosen augmentation through the use of the video-editing software.

The result of overlaying virtual spread footing objects on real-world site visuals using AR is shown in Fig. 5. The computer-generated model, developed as a detailed subset of the entire project BIM model to show the segment of the building that was used in the student tests, is displayed in-situ within the as-built conditions on the construction site. All the augmentation examples were generated using the previously described process and achieved similar results to those shown in Fig. 5. In order to decide on the AR methods which would produce the most appropriate content for the entire study, previously developed augmentation content was thoroughly reviewed and edited by the project team. Multiple augmentation segments were completed for each of the three primary assemblies, and the developed AR content was combined into one continuous video for each of the three assemblies.

FIG. 5: Augmentation of concrete foundation footings over prevailing as-built jobsite conditions

The developed AR content was saved as in a standard video file format and safeguarded on a secured server at the end of the augmentation procedure. The students participating in this study were granted access to the content on the server as needed during the appropriate phases of the study. The completed AR-enabled video for the masonry construction assembly was 2 minutes and 49 seconds in length, the roofing construction video was 3 minutes in length, and the structural steel construction video was 8 minutes and 37 seconds in length. With the intention of eliminating the possibility of an unintended impact on individual student learning and comprehension, text and sound were not incorporated into the visuals in any of the three assembly videos. The only edits made to the content were completed using AR and were designed to enhance comprehension of the existing site visuals. Students, in the appropriate test groups, were allowed to watch the video during the test and were instructed to view the content whenever they deemed convenient. Except for granting students access to the video and announcing that they were free to use it whenever and as much as they deemed fit, the proctors were not involved with the learning assessment tests in any way. To guarantee overall quality and contextual accuracy of all components, all of the chosen augmentations and videos were comprehensively evaluated by the research team for accuracy and clarity.

5.1.1 Masonry Component Augmentation

Masonry wall ties and flashing were the assembly components selected as the primary focus of the AR development for the masonry assembly. By relying on the experience and expertise of the estimating class faculty, these components were singled out by the research team as the elements of the masonry assembly which students often had difficulty identifying. Both elements were enhanced in the collection of the real-world in-situ visuals through the augmentation with BIM components using AR. Fig. 6 shows a section of a brick masonry wall tie embedded in a CMU backing wall. In order to give the students an understanding of how the wall ties stay in place, the video displays a computer-generated model of the tie being visibly detached from its original location in the CMU wall, while enlarging the model to better display one of the potential forms of wall ties. The augmentation correlating to the location and installation of copper flashing within the brick veneer wall is shown in Fig. 7, which is a still image capture of a more extended video clip displaying the location and various stages of flashing installation. In addition to the brick wall ties and flashing, AR was used to highlight the installation sequencing as well as the concept of determining the number of installed bricks or blocks per square foot. The AR content was supplemented with un-edited jobsite media in the final video, which provided situational context for the masonry process.

FIG. 6: Masonry wall ties augmentation in exterior CMU backing wall

FIG. 7: Copper flashing highlighted in AR-enabled video of brick veneer installation process.

5.1.2 Roofing Component Augmentation

In regards to roofing assemblies, flashing and vapor barrier were identified as elements of roof assemblies which students often had trouble comprehending. Asides from identifying the elements, the students had a difficult time comprehending the overlap inherent when installing each component layer of most roof assemblies. For the purpose of augmentation, copper flashing and vapor barrier were singled out as the main focus for the roofing assembly ART intervention. Both elements were enhanced by augmenting the layers over the in-situ real-world visual documentation. The achieved augmentation of the vapor barrier over real-world visuals is shown in Figure 8. Based on discussions with estimating faculty, one of the common estimating errors made by students, especially by those who had limited experience in the construction industry, was a miscalculation of material due to the omission of overlap, which the installation of vapor barrier requires. If this overlap is not taken into consideration, this error can have an effect on material quantities and labor. Therefore, the augmentation was carefully presented in order to effectively demonstrate the actual overlap which occurs during the installation of the vapor barrier. Similarly, students often failed to estimate proper flashing quantities, as they are not familiar with its installation process. An augmentation of the copper flashing between the interconnection of the clay roof tiles and the masonry wall is shown in Figure 9. The overlap of material in the vapor barrier and flashing is emphasized using AR, to highlight the material installation sequencing and conditions which may otherwise go unnoticed. The final roofing video was designed to show several layers of the roof assembly throughout the entire video at various stages throughout the building. The augmentation demonstrated the installation process of the roof assembly elements according to how it would be constructed on site, from multiple vantage points, including aerial imagery.

FIG. 8: Augmentation of water barrier installation over prevailing as-built jobsite conditions.

FIG. 9: Augmentation of copper flashing over prevailing as-built jobsite conditions.

5.1.3 Steel Component Augmentation

The identification and installation sequence of individual structural steel elements were singled out as the components of structural steel assemblies that students commonly had a hard time identifying. Concrete spread footings, steel columns and structural steel framing were the assembly elements emphasized in the AR content development process. Figure 10 shows periodic images of a video sequence in which the steel structure is virtually erected in-situ on the jobsite. The virtual structure model embedded in the real world visuals shows the in-situ assembly and installation sequence, to enhance understanding of the erection process. In addition to steel erection, the video spans from concrete spread footing installation all the way to the metal deck and slab edge welding. It is presented in sequence with a focus on showing the contextual environment in which these tasks take place on a jobsite. The structural BIM model is used in various stages of completeness, and individual elements were used to produce useful AR content which enhanced the real-world visuals collected on site.

FIG. 10: Augmentation of structural steel elements over prevailing as-built jobsite conditions.

6. EXPERIMENTAL PROCEDURE

This study spanned over the course of four semesters and focused on three building systems, steel structure, masonry wall assemblies, and roofing. Prior to the commencement of the study, the rights of study participants were communicated to them in accordance with the protocols of the Institutional review boards of both the University of Florida and Louisiana State University. The purpose and requirements of the study were carefully explained to the participants, and those who were willing to be involved in the study signed consent forms agreeing to participate. During the study, developed AR-enabled videos were incorporated in the classroom with the standard lectures for masonry, roofing, and structural steel construction estimating and quantity takeoff. In this regard, careful consideration was given to ensure that no group of participants was deprived of any content which may have had an impact, or a perceived impact, on their learning experience in the course. The goal was to achieve an effective method of study participation, leading to an analysis of the impact of AR on the student's comprehension and spatio-temporal understanding of construction assemblies, while protecting the learning experiences of the student participants.

Following the acquisition of consent, the students were divided into groups at the start of each semester using a random number generator. Following the formation of the three test groups, a tracking number was given to each participant and served as the participants' identification number throughout the study. Thus their name or any other personal information was not permitted on any of the study documents that they turned in to the proctor during any phase of the study. The two documents which identified the participants, their signed informed consent and number assignment spreadsheet, were not accessible to the researchers conducting the analysis of the data in this study. In the event that a student asked for their data to be left out from the study or a name was needed for any reason, the participant's identification number could be looked up from the master list and handled appropriately. Also, the members of the research team who completed the data analysis had no access to the participants and were not involved in the proctoring of the tests.

This study was organized into two distinct phases, with the three test groups, referred to as groups A, B, and C in Table 1, performing the tasks with different information streams. Phase 1, the pre-test, was developed to accurately evaluate the base knowledge of the participants prior to any educational intervention, classroom or AR. This evaluation is based on the completion of a questionnaire prior to the intervention of any classroom learning or AR-enabled content. After this, Phase 2, the post-test, was implemented to evaluate the potential impact of the different instructional tools the students were exposed to, depending on their group designations and corresponding information streams. Both phases of this study took place in a controlled classroom environment, or computer lab for those who had access to the AR-enabled content during Phase 2, and was proctored by the actual course instructor as well as one of the members of the research team who would not be conducting any data analysis.

Phase 1, the pre-test phase, required the students to respond to the qualitative questionnaire with only a provided parametric 3D drawing of the test case building, and no supplementary information, except a prior understanding of the assemblies that they might have acquired by virtue of personal experiences. The students were tasked with answering qualitative questions in regard to material identification, construction task requirements, and task sequencing associated with the specific assembly being examined. During the pre-test phase of the study, the baseline knowledge of the participants was established, thereby enabling the research team to effectively determine variances in the comprehension and spatio-temporal understanding of the various building assemblies for each student. Thus enabling the determination of the potential impact made by AR-enabled content on a student's comprehension and spatio-temporal understanding.

Phase 2, the post-learning test (post-test), was completed at a later point of the semester when the curriculum reached the respective assembly being studied. During Phase 2 of the study, students were tasked with the completion of the same set of qualitative problems related to material identification, task requirements and sequencing as in Phase 1, as well as a quantity takeoff assignment based on the assembly being studied. A set of construction drawings for the building system of the sample project being studied, inclusive of plan views, section views and 3D parametric views, were provided to all students in each group for use in completing the assigned tasks. The three test groups were separated during Phase 2 in order to maintain the integrity of the study and avoid unintended exposure to additional information streams beyond what they were allowed. On account of this, the participants in the groups that were entitled to the video content were taken to a computer laboratory where they were granted access to the AR-enabled video content for the given building system. Authorization to view the videos was given through a web-based access portal on individual computer terminals for the duration of the phase. Furthermore, discussion between students was not permitted, and the students were also not permitted to ask the proctor questions related to the content of the assignment being completed.

TABLE 1: Group designations and corresponding information streams.

Assemblies	Group A	Group B	Group C
Masonry	Classroom Lecture Only (Control Group)	Classroom Lecture and AR-enabled Video	AR-enabled Video Only
Roof	Classroom Lecture and AR-enabled Video	AR-enabled Video Only	Classroom Lecture Only (Control Group)
Structural Steel	AR-enabled Video Only	Classroom Lecture Only (Control Group)	Classroom Lecture and AR-enabled Video

During the course of the semester, each group was exposed to a different combination of pedagogical techniques for each of the three construction assemblies selected for this study. The rotation of group pedagogical exposure within a semester was conducted in order to reduce the potential of one group skewing the results for a given assembly set. Furthermore, due to the voluntary nature of participation, each student did not necessarily complete all three assemblies in a given semester and the rotation aided in the collection of evenly distributed responses. The pedagogical exposure for each of the three groups, as well as for the three construction assemblies, is detailed in Table 1. The groups that were provided with just the AR-enabled video (A for the structural steel assembly, B for the roofing assembly, and C for the masonry assembly) were not allowed to sit in on the standard classroom lecture and were solely granted access to the AR-enabled video developed for the assembly being examined. The groups that were provided with just the lecture (A for the masonry assembly, C for the roof assembly, and B for the structural steel assembly) were considered the control groups for their respective assemblies, and as such they were present in the classrooms for the standard lectures of the assemblies being studied but were not authorized to gain access to the AR-enabled video during the study phases for that assembly. The remaining groups for each of the assemblies (B for the masonry assembly, A for the roofing assembly, and C for the structural steel assembly) were permitted to attend the regular lectures on the assemblies and were also granted access to the AR-enabled video specific to the construction assembly being studied.

In addition to the lecture and AR-enabled information streams, identical document sets for both phases of the study were made available to each participant. The Phase 1 documents included the questions being asked as well as an image of the area and assembly being studied derived from the developed BIM model of the test case building. The Phase 2 documents included a full drawing set of the test case building assembly including; dimensioned plans, sections, and 3D views. The physical documentation provided during the study was identical regardless of the group the student was assigned, with the only variant among the groups being pedagogical exposure based on their assigned group and construction assembly. The classroom lecture materials and information outlined in the course syllabus for each of the studied assemblies was made available to the students after completion of the study. Also, makeup lectures were delivered, when deemed necessary or requested, to guarantee that there were no adverse effects on the standard learning experience due to participation in this study.

The students attended classroom lectures three times a week and completed the study over the duration of two class sessions for each assembly. In an effort to guarantee that the participants in the 'Video Only' group did not miss the information provided in the classroom lecture, they were issued the Phase 2 post-test immediately after completing the Phase 1 pre-test for the given assembly. The study schedule was coordinated with the course instructor to ensure that Phase 2 was completed by the 'Video Only' group prior to any class lectures so that they could attend the regularly scheduled lecture and experience no change in the typical course structure. Additionally, the students in the 'Lecture Only' and 'Lecture and AR-enabled Video' groups were able to take part in the classroom lecture with no interruptions in the learning experience defined in the course syllabus while completing the study. The role of each group changed for each assembly so that each group experienced each type of information stream and study schedule over the course of the semester.

Completed study documents and work connected with the students' responses from both Phase 1 and Phase 2 were collected according to the designated identification numbers assigned to the students at the start of the semester. Afterwards, the responses were inputted into a database for statistical analysis by members of the research team who were not involved in the administration of the study. The submitted data were assessed for completeness, and any incomplete data sets from a specific assembly, representing a student's absence during the day of the study, was not used for analysis. Both physical and digital copies of completed study documents were stored in a secured location and on protected servers. Each one of the participants had the right to stop their participation at any point in during or after the study and to request that their data be excluded. Furthermore, participation in this study had no impact on a student's grade in the course in which the study was administered.

7. RESULTS

This study consisted of a demographic and background questionnaire, a problem-solving skills questionnaire in Phases 1 and 2, in addition to a quantity takeoff problem in Phase 2. The problem-solving skills questionnaire aimed to accurately evaluate the participants' understanding of the subject matter in order to determine if there was any change in the participant's knowledge and spatio-temporal understanding of the different construction assembly processes, as well as evaluate the impact of the multiple pedagogical techniques implemented in the study. The quantity takeoff problem was used to assess how the students' comprehension in quantity takeoffs changed due to the use of AR-enabled content. For the purposes of this analysis, the element identification portion of the problem-solving skills questionnaire was the primary focus, as it provided the best opportunity for comparative statistics of the students' performance related to their comprehension of various building assemblies.

7.1 Results of the Masonry Assembly

The responses analyzed in this section of the study provided information on the ability of the participants to identify the main elements of the brick veneer wall assembly used during the learning assessments. The various elements that constituted the brick veneer walls, which were either presented in the estimating class or listed by the students as answers to the question, are shown in Table 2. All observations were grouped according to the three test groups (A, B and C) developed in this study. The number of observations for each of the individual elements was later translated to a sample proportion according to the corresponding group. By comparing the sample proportions observed in the groups for each one of the elements, the research team was able to determine whether there was any significant difference between the groups. The sample proportions observed in the pre-test were compared to determine whether the baseline of the three groups were similar, in order to allow for more accurate comparisons in the post-test. For the masonry assembly, all the listed elements were distinctly noticeable in the AR-enabled video, however only the brick ties and flashing items were highlighted as an augmentation.

TABLE 2: Quantity of observations and sample proportions for masonry assembly elements.

Principal elements of Brick Veneer Wall assembly	**GROUP A OBSERVATIONS (CLASSROOM LECTURE ONLY) CONTROL**				**GROUP B OBSERVATIONS (AR-ENABLED VIDEO AND CLASSROOM LECTURE)**				**GROUP C OBSERVATIONS (AR-ENABLED VIDEO ONLY)**			
	n = 23				n = 25				n = 26			
Wall Elements	Pre-Test	p̂	Post-Test	p̂	Pre-Test	p̂	Post-Test	p̂	Pre-Test	p̂	Post-Test	p̂
CMU	15	0.65	15	0.65	12	0.48	20	0.80	11	0.42	19	0.73
Waterproofing	6	0.26	11	0.48	8	0.32	15	0.60	7	0.27	19	0.73
Insulation	4	0.17	11	0.48	3	0.12	9	0.36	5	0.19	7	0.27
Bricks	21	0.91	21	0.91	21	0.84	24	0.96	24	0.92	25	0.96
Mortar	16	0.70	16	0.70	17	0.68	14	0.56	18	0.69	19	0.73
Rebar	2	0.09	6	0.26	2	0.08	5	0.20	2	0.08	8	0.31
Brick Ties	4	0.17	7	0.30	9	0.36	16	0.64	11	0.42	20	0.77
Flashing	2	0.09	5	0.22	5	0.20	9	0.36	1	0.04	2	0.08
Stone Cap	1	0.04	6	0.26	1	0.04	5	0.20	3	0.12	6	0.23

The null hypothesis (Ho) postulates that no significant difference was observed between the sample proportions of the groups, while the alternate hypothesis (Ha) postulates that the sample proportions of the groups are significantly different. At a 95% level of confidence, the null hypothesis and alternate hypothesis are:

Ho: $\hat{p}1 - \hat{p}2 = 0$ (1)

Ha: $\hat{p}1 - \hat{p}2 < 0$ (2)

Minitab (2017) statistical software was used to compare the sample proportions of the pre-test and post-test observations of the various elements. The data collected showed that the control group and the experimental groups' responses regarding the elements that were not highlighted in the video were not significantly different at a 95% confidence level (p-value > 0.05). However, significant differences were observed between the groups' responses to the elements highlighted in the video. The results of the hypotheses testing for the flashing and brick ties observations in both the pre-test and post-test are shown in Table 3.

TABLE 3: Results of masonry assembly hypotheses testing.

Elements	**Test for Difference**	**Study Phase**	**p-value**
Flashing	$\hat{P}_a - \hat{P}_b$	Pre-test	0.135
	$\hat{P}_a - \hat{P}_b$	Post-test	0.142
	$\hat{P}_a - \hat{P}_c$	Pre-test	0.750
	$\hat{P}_a - \hat{P}_c$	Post-test	0.910
Brick Ties	$\hat{P}_a - \hat{P}_b$	Pre-test	0.142
	$\hat{P}_a - \hat{P}_b$	Post-test	0.010*
	$\hat{P}_a - \hat{P}_c$	Pre-test	0.063
	$\hat{P}_a - \hat{P}_c$	Post-test	0.000*

* $p < 0.05$; Ho is rejected.

For the "Flashing" element, the hypotheses testing at the 95% level of significance showed that the null hypothesis for the pre-test sample proportions between groups A and B could not be rejected (p-value = 0.135 > 0.05). This infers that no significant difference was observed in the pre-test sample proportions between groups A and B. Also, no significant difference was observed in the post-test sample proportions between groups A and B (p-value = 0.142 > 0.05). This means that groups A and B had comparable proportions before and after the assessments. Similar results were observed in the comparison of groups A and C, where no significant difference was observed in both the sample proportions of the pre-test (p-value = 0.750 > 0.05) and the post-test (p-value = 0.910 > 0.05).

Furthermore, for the "Brick Ties" element, significant difference was observed in the sample proportions of the post-test comparison of groups A and B (p-value = 0.010 < 0.05) in contrast to the pre-test (p-value = 0.142 > 0.05). Similar results were found in both the pre-test (p-value = 0.063 > 0.05) and the post-test (p-value = 0.001 < 0.05), when comparing the sample proportions of groups A and C. It can be concluded from these results that the study participants in the groups who viewed the AR-enabled video (71%) identified the "brick ties" items significantly more often than those in the group that had been exposed to only the standard lecture (30%).

7.2 Results of Roof Assembly

The responses analyzed in this section of the study provided information on the ability of the participants to identify the main elements of the roof assembly given during the learning assessments. Table 4 shows the several elements of the roof assembly that were either presented in the estimating classroom lectures or listed by the participants as answers to the question. All observations were grouped according to the three test groups. Subsequently, the number of observations for each of the individual elements was translated to a sample proportion according to the corresponding group. Similar to the masonry assembly, the sample proportions observed in the pre-test were compared to determine whether the baseline of the three groups were similar, in order to allow for more accurate comparisons in the post-test. For the roof assembly, all the listed elements were distinctly noticeable in the AR-enabled video. However, only the vapor barrier and flashing elements were highlighted as an augmentation.

The data collected showed that the control group and the experimental groups' responses regarding the elements that were not highlighted in the video were not significantly different at a 95% confidence level (p-value > 0.05). However, significant differences were observed between the groups' responses to the insulation and metal decking. The results of the hypotheses testing for the insulation, metal decking and flashing observations in both the pre-test and post-test are shown in Table 5.

The hypothesis testing at the 95% level of significance showed that the null hypothesis for the pre-test sample proportions between groups A and C could not be rejected for the "Insulation" item (p-value = 0.170 > 0.05), inferring that no significant difference was observed in the pre-test sample proportions. However, a significant difference was observed in the post-test comparison of groups A and C (p-value = 0.026 < 0.05). Similar results were found in both the pre-test (p-value = 0.148 > 0.05) and the post-test (p-value = 0.001 < 0.05), when comparing the sample proportions of groups B and C.

Table 4: Quantity of observations and sample proportions for roofing assembly elements.

Principal Elements of Roofing Assembly	**GROUP A OBSERVATIONS (AR-ENABLED VIDEO AND CLASSROOM LECTURE)**				**GROUP B OBSERVATIONS (AR-ENABLED VIDEO ONLY)**				**GROUP C OBSERVATIONS (CLASSROOM LECTURE ONLY) CONTROL**			
	n = 39				n = 48				n = 33			
Roofing Elements	Pre-Test	p̂	Post-Test	p̂	Pre-Test	p̂	Post-Test	p̂	Pre-Test	p̂	Post-Test	p̂
Roof Tiles	37	0.95	38	0.97	47	0.98	48	1.00	33	1.00	33	1.00
Vapor Barrier	21	0.54	28	0.72	24	0.50	32	0.67	18	0.55	20	0.61
Wood Nailable Decking	22	0.56	36	0.92	29	0.60	41	0.85	25	0.76	26	0.79
Insulation	8	0.21	12	0.31	10	0.21	21	0.44	4	0.12	4	0.12
Metal Decking	0	0.00	23	0.59	1	0.02	28	0.58	0	0.00	3	0.09
Light Gauge Roof Framing	28	0.72	34	0.87	36	0.75	43	0.90	23	0.70	27	0.82
Bolts/Fasteners	4	0.10	4	0.10	4	0.08	4	0.08	4	0.12	4	0.12
Flashing	7	0.18	13	0.33	13	0.27	30	0.63	11	0.33	15	0.45

TABLE 5: Results of roofing assembly hypotheses testing.

Elements	**Test for Difference**	**Study Phase**	**p-value**
Insulation	$\hat{P}_a - \hat{P}_c$	Pre-test	0.170
	$\hat{P}_a - \hat{P}_c$	Post-test	0.026*
	$\hat{P}_b - \hat{P}_c$	Pre-test	0.148
	$\hat{P}_b - \hat{P}_c$	Post-test	0.001*
Metal Decking	$\hat{P}_a - \hat{P}_c$	Pre-test	1.000
	$\hat{P}_a - \hat{P}_c$	Post-test	0.000*
	$\hat{P}_b - \hat{P}_c$	Pre-test	1.000
	$\hat{P}_b - \hat{P}_c$	Post-test	0.000*
Flashing	$\hat{P}_a - \hat{P}_c$	Pre-test	0.928
	$\hat{P}_a - \hat{P}_c$	Post-test	0.849
	$\hat{P}_b - \hat{P}_c$	Pre-test	0.722
	$\hat{P}_b - \hat{P}_c$	Post-test	0.068

* $p < 0.05$; Ho is rejected.

In addition, for the "Metal Decking" item, a comparison of the post-test sample proportions showed a significant difference between groups A and C (p-value < 0.001 < 0.05) in contrast to the pre-test (p-value = 1.000 > 0.005). Similar results were found when comparing the sample proportions of groups B and C. Lastly, for the "Flashing" element, none of the comparisons between the groups showed a significant difference, indicating a need for alternative strategies to impact this learning deficiency.

7.3 Results of Structural Steel Assembly

The responses to the test question analyzed in this section provided information on the ability of the participants to identify the main elements of a structural steel assembly. The main structural steel elements, which were either presented in the estimating class or listed by the students as answers to the question, are shown in Table 6. Similar to the masonry and steel assemblies, comparing the sample proportion observed in the groups for each one of the elements determined whether there was any significant difference between the groups. The sample proportions observed in the pre-test were compared to determine whether the baseline of the three groups were similar, in order to allow for more accurate comparisons in the post-test. For the structural steel assembly, all the listed elements were distinctly noticeable in the AR-enabled video. However, only the foundation footings, structural columns and structural framing elements were highlighted as an augmentation.

Table 6: Quantity of observations and sample proportions of structural steel assembly elements.

Principal Elements of Structural Steel Assembly	**GROUP A OBSERVATIONS (AR-ENABLED VIDEO ONLY)**				**GROUP B OBSERVATIONS (CLASSROOM LECTURE ONLY) CONTROL GROUP**				**GROUP C OBSERVATIONS (AR-ENABLED VIDEO AND CLASSROOM LECTURE)**			
	n = 19				n = 20				n = 16			
Structural Steel Elements	Pre-Test	p̂	Post-Test	p̂	Pre-Test	p̂	Post-Test	p̂	Pre-Test	p̂	Post-Test	p̂
Structural Columns	14	0.74	12	0.63	15	0.75	15	0.75	12	0.75	14	0.88
Structural Framing	18	0.95	18	0.95	19	0.95	20	1.00	14	0.88	16	1.00
Metal Deck	0	0.00	7	0.37	0	0.00	2	0.10	0	0.00	2	0.13
Concrete Footings	12	0.63	14	0.74	17	0.85	11	0.55	8	0.50	7	0.44
Connections	7	0.37	5	0.26	5	0.25	5	0.25	4	0.25	7	0.44

The data collected showed that the control group and the experimental groups' responses regarding the "structural framing" item were not significantly different at a 95% confidence level (p-value > 0.05). The results show a significant difference between the control group and the experimental groups' responses as regards the "concrete footing" item in the post-test (p-value < 0.05), however the pre-test sample proportions do not provide a comparable base line (p-value < 0.05). On the other hand, significant differences were observed between the groups' responses to the structural columns, metal deck and connections elements. The results of the hypotheses testing for the elements that indicated significant differences in both the pre-test and post-test are shown in Table 7.

The hypothesis testing at the 95% level of significance showed that the null hypothesis for the pre-test sample proportions between groups A and B could not be rejected for the "Structural Columns" item (p-value = 0.415 > 0.05), indicating that groups A and B had comparable proportions before the assessment. On the other hand, a significant difference was observed in the post-test comparison of groups A and B (p-value = 0.023 < 0.05). Similar results were found where comparing the sample proportions of groups B and C failed to show that the groups were significantly different in the pre-test (p-value = 0.500 > 0.05), but showed a significant difference in the post-test (p-value = 0.036 < 0.05).

Furthermore, for the “Metal Deck” item, a comparison of the post-test sample proportions showed a significant difference between groups A and B only (p-value < 0.001 < 0.05) in contrast to the pre-test (p-value = 1.000 > 0.05). For the “Connections” item, a comparison of the post-test sample proportions showed a significant difference between groups B and C only (p-value < 0.001 < 0.05) in contrast to the pre-test (p-value = 0.500 > 0.05).

Table 7: Results of structural steel assembly hypotheses testing.

Elements	**Test for Difference**	**Study Phase**	**p-value**
Structural Columns	$\hat{P}_a - \hat{P}_b$	Pre-test	0.415
	$\hat{P}_a - \hat{P}_b$	Post-test	0.023*
	$\hat{P}_b - \hat{P}_c$	Pre-test	0.500
	$\hat{P}_b - \hat{P}_c$	Post-test	0.036*
Metal Deck	$\hat{P}_a - \hat{P}_b$	Pre-test	1.000
	$\hat{P}_a - \hat{P}_b$	Post-test	0.000*
	$\hat{P}_b - \hat{P}_c$	Pre-test	1.000
	$\hat{P}_b - \hat{P}_c$	Post-test	0.172
Connections	$\hat{P}_a - \hat{P}_b$	Pre-test	0.002
	$\hat{P}_a - \hat{P}_b$	Post-test	0.359
	$\hat{P}_b - \hat{P}_c$	Pre-test	0.500
	$\hat{P}_b - \hat{P}_c$	Post-test	0.000*

* p < 0.05; Ho is rejected.

The hypothesis testing at the 95% level of significance showed that the null hypothesis for the pre-test sample proportions between groups A and B could not be rejected for the “Structural Columns” item (p-value = 0.415 > 0.05), indicating that groups A and B had comparable proportions before the assessment. On the other hand, a significant difference was observed in the post-test comparison of groups A and B (p-value = 0.023 < 0.05). Similar results were found where comparing the sample proportions of groups B and C failed to show that the groups were significantly different in the pre-test (p-value = 0.500 > 0.05), but showed a significant difference in the post-test (p-value = 0.036 < 0.05).

Furthermore, for the “Metal Deck” item, a comparison of the post-test sample proportions showed a significant difference between groups A and B only (p-value < 0.001 < 0.05) in contrast to the pre-test (p-value = 1.000 > 0.05). For the “Connections” item, a comparison of the post-test sample proportions showed a significant difference between groups B and C only (p-value < 0.001 < 0.05) in contrast to the pre-test (p-value = 0.500 > 0.05).

8. DISCUSSION OF RESULTS

The results for the masonry, roofing and structural steel construction assemblies reviewed in this paper indicated the potential of AR in the enhancing the personal learning experiences of construction management students. The results of the learning assessment on the masonry wall assembly indicated that the AR-enabled video helped the students understand the brick veneer wall elements better. The test group that had access to both the AR-enabled video and classroom lecture (Group B) gained more from the procedure, as the AR video helped buttress the processes and elements learned from taking the standard lecture. The visualization of the brick ties and flashing also assisted the students in remembering the elements and the system. The results also showed that the students who saw only the AR video (71%) identified the brick ties more often than the students in the lecture only group (30%), even though they were not familiar with the correct terminology.

The results also indicated that the augmentation had a greater impact on the ability of the students to identify the brick ties element than the flashing element because the level of augmentation of the brick ties was more advanced than that of the flashing element, which was simply highlighted in the video. Also, the augmentation of the brick ties appeared more times than that of the flashing element. This infers that the level at which the students can understand and recollect the information is a direct function of the level and quality of any augmentation package. Moreover, the addition of virtual models, which was the case for the brick ties in the AR-enabled video, had a greater impact on the students' spatio-temporal comprehension of the brick veneer wall construction process, as opposed to solely using the highlighting augmentation technique.

Similarly, the results of the roof assembly learning assessment also pointed to an increased understanding by the students based on their ability to correctly identify the elements of the roof assembly. Through the inclusion of the AR-enabled roof video, the students were able to recognize and recall individual elements of the roof assembly better than they would typically have in a conventional classroom setting. The elements of the assembly were highlighted by the augmentation, which drew the attention of the students to them. The results show that students in the group that viewed only the AR-enabled video (Group B) benefited more from the video than the other groups. However, the significance of the AR-enabled video on comprehension and memory remains valid.

Even though the highlighting augmentation technique was used on the vapor barrier element in the AR-enabled video, no significant difference was observed in the comparison between groups. However, students were aware of the insulation and metal decking elements which were not highlighted in the AR-enabled video but were visible in the same frame. The reason being that the elements highlighted in the AR-enabled video were not specified; therefore the students' perception of the highlighted elements was different. A large number (59%) of the students that had access to the AR-enabled video observed and identified metal decking as an element of the roof assembly. However, just 9% of the students that only sat in on the classroom lectures were able to identify the metal decking element.

Similar to the previous assemblies, the learning assessment results of the structural steel assembly showed that the augmentation video helped the students to better understand and identify the main elements of the assembly. The study group that had access to both the AR-enabled video and classroom lecture (Group C) had the highest statistical benefits from the study, as they were able to apply the knowledge from the instructor to accurately visualize how the structure was assembled. The results show that students in the group that had both the video and the lecture benefited more from the procedure than the other groups. Although the metal deck was not highlighted in the video, it was visible in the frame and was identified by 37% of the students who had access to the AR video only (Group A) in the post-test. However, only 10% of the students that sat in on the classroom lectures only (Group B) were able to identify the metal decking element.

While the connection element was also not highlighted in the AR video, the video contained a series of augmented still images of ironworkers installing and connecting the structural framing to the shear wall, which was recognized by the students who watched the video. From the results, 35% of the students who had access to the AR video (Groups A and C) in the post-test identified the connection element, whereas 25% of the students that only sat in on the classroom lectures (Group B) were able to identify the element. It can be concluded from the results of the three construction assemblies used in this study that incorporating augmentation videos and other media as a supplement in the classroom, as opposed to a complete replacement of the lectures and other instructional materials, is the best approach to enhancing the educational experience of construction management students.

Analysis of the results yielded a significant difference between the responses by the control group and the experimental group as regards the "concrete footing" item in the post-test (p-value < 0.05). However, the pre-test sample proportions also indicated a significant difference (p-value < 0.05). Therefore, the statistical inference of the post-test was not conclusive as the pre-test did not provide a comparative baseline. There is a need for further extensive testing and data analyses to be performed to investigate the underlying factors behind the observed differences. These differences may have been attributable to the different demographic and background characteristics of the participants and can only be confirmed by additional testing.

To determine the other factors that may affect the transfer of knowledge and recollection in students, some correlation tests and multiple regression analyses were conducted. On average, no significant correlation was noted between the transfer of knowledge and the level of experience students had with information technology. This suggests that being proficient in information technology did not influence the transfer of knowledge to the participants via the AR-enabled video.

9. CONCLUSIONS

Applications of AR in the construction industry have advanced over time and continue to grow in many ways. The industry is currently researching the applications for AR in areas such as tracking as-planned to as-built progress, training, dynamic site visualization, exposure of construction defects, mobile computing, and lifecycle analysis (Rankohi and Waugh 2013). AR has thus far proven to have a positive impact on the industry as witnessed in several areas of improvement, such as mobility and functionality, increased productivity, and increased safety records on construction sites (Izkara et al. 2007). There is still a lot to be done in the area of AR research in education and training in the AECO industry (Rankohi and Waugh 2013). However, AR technology has demonstrated great potential to be a solution to the pedagogical challenges of construction related education and training.

The major educational challenge many construction management students are confronted with is a knowledge gap in grasping the spatial and temporal constraints which exist during construction processes. This stems from an insufficient exposure of students to many construction processes and procedures as they are being taught in the classroom. It is difficult to facilitate site visits for students that highlight and reinforce what they are learning in class, and functionally impossible to expose them to everything in parallel through site visits. AR provides a potential solution to this by virtually incorporating jobsite visits into the classrooms in a way which reinforces the students' comprehension by providing real-world context to the concepts covered in class. In that regard, AR has the capability of becoming an advantageous academic tool in the enhancement of construction management education.

The results of this study show that the developed AR-enabled content increased the students' understanding of the three selected construction assemblies, masonry, roofing and steel structure. The AR content helped them in identifying the main elements associated with those assemblies. For the masonry assembly, only the brick ties and flashing items were highlighted as an augmentation in the AR-enable video. Significant differences were observed in the post-test comparison of the control group and the experimental groups' responses to brick ties, which was one of the elements highlighted in the AR video. Amongst the participants, 71% of the students that had access to the AR-enabled video observed and identified brick ties as an element of the masonry assembly, while 30% of the students that only sat in on the classroom lectures were able to identify the brick ties.

In the AR-enabled video developed for the roofing assembly, all the listed elements were distinctly noticeable, but only the vapor barrier and flashing elements were highlighted as an augmentation. However, none of the comparisons between the groups showed a significant difference regarding these elements, indicating a need for alternative strategies to impact this learning deficiency. Nonetheless, the participants were aware of other elements which were not highlighted in the AR-enabled video but were visible in the video frame. For instance, the metal decking was visible in the AR video and 59% of the students that viewed the AR-enabled video identified metal decking as an element of the roof assembly. However, just 9% of the students that only sat in the classroom lectures were able to identify the metal decking element.

For the structural steel assembly, the foundation footings, structural columns and structural framing elements were highlighted as an augmentation in the AR-enabled video. Significant differences were observed in the post-test comparison of the control group and the experimental groups' responses to significant differences were observed between the groups' responses to the structural columns, metal deck, and connections elements. Although the connection element was also not highlighted in the AR video, the video contained footage of ironworkers installing and connecting the structural framing to the shear wall, which was recognized and identified by 35% students who had access to the AR video. However, just 25% of the students that sat in on the classroom lectures only were able to identify the element. The findings of this study indicate that the AR-enabled video content buttressed the elements and concepts being covered in the classroom lectures.

The world is changing and progressively leaning towards immersive technology in many industries, including AECO and AECO education. This study is a first step in determining how effective ART can be in the enhancement of construction management educational experiences. The utilization of AR-enabled content as a pedagogical technique, to supplement traditional classroom techniques, for the preparation of students for successful careers in the construction industry. The results of the study show that incorporating AR-enable media as a supplement in the classroom, as opposed to a complete replacement of the lectures and other instructional materials, is the best approach to enhancing the educational experience of construction management students. Furthermore, familiarizing students with ART at all levels of education increases awareness for its use cases and increases its potential for acceptance as a tool in the AECO industry. This study provides insight into the potential impact of ART in construction management education and provides evidence that it can improve students' spatio-temporal comprehension of construction processes when used in combination with traditional pedagogical techniques.

10. LIMITATIONS OF STUDY

This study represents findings based on a sample population from two Universities. In this regard, a wider range of participants from a broader grouping of Universities would enable more conclusive findings to be reported regarding ART based content utilization in an academic setting. Furthermore, the study was voluntary, attendance and participation in the learning assessments could not be mandatory or graded, and as a result, a number of the participants missed some phases of the study. This required that their data not be used for the entire building system which they did not fully participate in, and thus the number of participants varied for each construction assembly. Also, a lack of motivation to perform well on the tests administered for each building system could lead to the potential for skewed data based on the students' effort. Further study should be conducted to capture a wider range of participants and educational institutions to more definitively determine the potential impact of ART on construction management education.

For the purpose of this study, the element identification portion of the problem-solving skills questionnaire was the primary focus of the data analysis. However, Phase 2 of the study also required the participants to complete a quantity takeoff problem. Given unlimited resources and time, this research could be extended to analyze the quantity takeoff problem. The data collected from the quantity takeoff problem would enable the researchers to assess how the students' comprehension in quantity takeoffs changed due to the use of AR-enabled content.

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