Augmented Reality for Hands-On Construction Education

by

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ABSTRACT

The country is facing infrastructure crises simultaneous with a labor shortage in fields related to construction management and engineering. These challenges necessitate better and quicker preparation of the incoming workforce so they are prepared to take on responsibilities with more skill and efficiency than has been expected previously. Educators can play a key role in equipping the leaders of this upcoming generation to deal with these challenges. If students are expected to graduate with more preparation and expertise, then educators must also adjust the ways in which they teach. There are many ways that these changes can be accomplished, and researchers play a critical role in exploring new classroom techniques and technologies that may improve the way education is delivered. This dissertation focuses on a high-impact emerging technology, augmented reality (AR), as a training mechanism for students that has the potential to play a crucial role in enhancing the way construction education is delivered. First, this research explores what skills and competencies are most frequently reported as critical needs by industry members by thematically coding open-ended responses of construction internship supervisors. Leveraging the results of this data, this research explores the viability of utilizing AR to simulate hands-on training and authentic learning in ways that target these skills and competencies. The research presented in this dissertation consists of a series of subject tests involving custom-developed augmented reality applications. These full-scale, highly interactive construction mixed reality applications are designed to expose students to simulations of high-impact learning experiences but without the recurring costs of physical materials. Student behaviors and performance during these subject tests are thematically coded to reveal student behaviors and perceptions that contribute to learning objectives. The results of this research demonstrate high potential for AR as an educational tool while also suggesting best practices for creating and implementing these types of activities based on surprising and sometimes counterintuitive student behaviors during these AR experiences.

DEDICATION

I would like to send a big thanks to my support system throughout my Ph.D. experience. I would like to especially thank my husband Taylor, whose patience and encouragement helped me through difficult times and my parents, who always make time for my calls and cheer me on. I also want to thank my advisor, Dr. Ayer, for generously and thoughtfully sharing his advice, regarding both research and life.

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INTRODUCTION

1.1 Overarching Motivation

Towns, cities, and even countries are recognizable by the buildings and structures that form them. The built environment plays a critical role in people's daily lives, influencing individual well-being as individuals interact with the built environment in every sphere of life, from home, to work, to recreational activities. In fact, people in the United States spend around 90% of their time inside buildings (US Environmental Protection Agency, 2022) and much of the rest of their time is spent traveling on human-built infrastructure such as roads, tracks, or bridges. However, despite the criticality of the built environment, the country is facing a massive infrastructure crisis, receiving the grade of C- overall for 2021, including a D for roads and a D+ for schools (American Society of Civil Engineers, 2021). The country needs professionals to grapple with this crisis by fixing existing structures and by building high-quality new structures and infrastructure products. Simultaneous with the infrastructure crisis, the country is also facing a significant skilled labor shortage, especially in construction-related industries, with over 450,000 jobs left open in October of 2021 (US Bureau of Labor Statistics, 2022a) and consistent demand for more laborers projected throughout the next decade (US Bureau of Labor Statistics, 2022b). The labor shortage, although currently significant, existed long before the additional challenges presented by the COVID-19 pandemic (CII, 2018).

These challenges necessitate more effective and efficient preparation of the incoming workforce so they are prepared to take on responsibilities with a higher skill level and more efficiency than has been expected previously. Many of the future leaders of this workforce are current or incoming students in construction management and engineering programs. These students will need to be better prepared to step into versatile and demanding roles as the current veteran workforce retires. Educators can and will play a key role in equipping the leaders of this upcoming generation to deal with these challenges. However, if students are expected to graduate with more preparation and expertise, then educators must also pedagogically adjust. There are many ways that these changes can be accomplished, and researchers play a critical role in experimenting with new classroom techniques and technologies that may improve the way education is delivered.

Perhaps the best way for students to learn to design and construct buildings is to participate in the actual processes involved with designing and building. However, providing full-scale physical design and build experiences is cost-prohibitive and resource-intensive, which results in very few students being able to have these high-value experiences in a university context. This dissertation focuses on a high-impact emerging technology–augmented reality (AR)–and explores its potential to deliver effective hands-on construction education, but without many of the limitations of its physical counterpart, like the recurring cost of construction materials or the need for large material storage areas. AR is a visualization tool where virtual, computer-generated content is superimposed on a physical real-world environment (Milgram and Kishino, 1994).

The subsequent content in this introductory section explains more of the motivation for these explorations and expands on these ideas, ultimately presenting AR as an education mechanism for students that has the potential to play a crucial role in

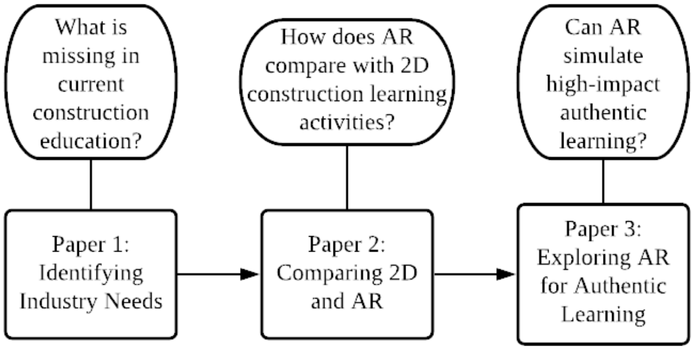


Figure 1. Flowchart Overview of the Three Papers Presented in This Dissertation and Their Motivating Research Questions.

enhancing the way construction education is delivered. The content of this dissertation takes the form of three papers, each building off the previous, and all aimed at investigating how to deliver better education to more students. In this first chapter, a summary of the motivation and methods behind the three papers will be presented, with a preview of some of the critical findings that will be explored in detail in later chapters. Figure 1 presents a preview of these papers with their overarching research question and general topic, each of which will be explained subsequently in more detail.

1.2 Overview of Papers

1.2.1 Paper 1: Identifying Industry Needs

This first paper focuses on answering the following question: what skills and competencies are most frequently reported as in-demand by construction industry practitioners? While researchers have considered this question in the past, utilizing quantitative surveys sent to industry members (Ahn *et al.*, 2012; Bhattacharjee *et al.*, 2013), these surveys required ranking or rating of predetermined categories on their importance, but did not allow for open-ended discussion of needed improvements. The work in this dissertation departs from previous work by considering open-ended data where industry members state the skills and competencies they would most like to see from graduates in the format of direct internship evaluation reviews. By utilizing an open-ended format, this dissertation is able to quantify which skills and competencies are most frequently rated as important, providing insight into what skills are most called for from industry. Additionally, while most previous research relied on industry professionals' general knowledge and opinions, the data used for this study came directly from individuals who held direct supervisory roles to current construction students. Overall, this paper provides a needed update to the body of literature regarding skills and competencies required of construction graduates using a uniquely relevant dataset. The paper considers the content of the reviews and presents the topics that occur most frequently, which may then provide guidance when creating educational interventions that are targeted to areas of most prominent industry needs.

While the findings are subsequently presented in depth in the paper, it is helpful to present some of the key results here, as they inform the work done in Papers 2 and 3. By far the most common theme within the reviews was a call for more experience from the students, specifically hands-on project experience. Thus, explorations of innovative ways to provide hands-on experience to students before they enter the construction industry would be worthwhile. Other skills that appeared frequently in reviews and helped inform the research in this dissertation include attention to detail, taking initiative, and the ability to work with plans/blueprints/drawings. Explorations of innovative ways to develop skills and competencies are addressed in the research studies that follow.

1.2.2 Paper 2: Comparing 2D and Augmented Reality (AR) Educational Outputs for Construction Sequencing Tasks

This second paper takes one perspective on answering the industry call for more experience by considering a hands-on AR activity and comparing it with a common classroom educational format, 2D, in a focused context. Since construction management and engineering students will likely be tasked in their careers with managing or planning for various trades, experience with different trade-based tasks would be beneficial, but it is not always feasible to supply the physical materials needed to learn in this way, therefore AR is explored as a method for giving future construction managers experience with the construction processes they hope to manage. As an educational tool and training mechanism, AR has been successfully used in fields such as medicine (Weidenbach *et al.*, 2000), mathematics education (Kaufmann, 2003), and military (Livingston *et al.*, 2002). Recently, interest has increased in using AR for teaching within architecture, engineering, and construction (AEC) disciplines (Noghabaei *et al.*, 2020). Within the intersection of building sciences/engineering and education, AR has been shown to provide measurable improvement in spatial abilities for engineering and construction students when used as a training mechanism (Martín-Gutiérrez *et al.*, 2011, 2010; Kim and Irizarry, 2021) and can help foster visual learning (Wang *et al.*, 2018b) and motivation (Dinis *et al.*, 2017). These are several examples of how AR has been used successfully as supplementary tools in the classroom in fields closely related to construction. However, the point of departure of this study is in utilizing

AR in a full-scale, interactive context as a direct replication of an element sequencing construction task, in this case wood framing. To provide a meaningful comparison with the type of educational experience that might be expected in a typical classroom, this study also explores the same task, wood-framed construction element sequencing, but in a 2D format. Specifically, this paper presents two educational interventions that tasked students with element sequencing of a wood-framing window structure. In the first intervention, students completed a 2D worksheet where they assigned a sequence to wood studs of predetermined lengths by stating or writing the sequence order. In the second intervention, students entered an interactive, full-scale AR environment and assigned a sequence to wood studs of predetermined lengths by virtually placing the pieces on a designated build area. For both of these educational experiences, students utilized 2D drawings that showed a wood-framed design of a wall with a window, which enabled this research to target that industry-requested skill of plan reading along with the hands-on component. The researchers conducted subject testing, where students tested the AR applications, for both of these interventions, and student approaches and behaviors during these tasks were observed and thematically analyzed.

The findings are presented in depth in this paper's section. As a preview, it was observed that students were able to engage in self-remediation when engaging with this activity via AR. This observation shows that not only do students learn how to better interpret plans and drawings, a skill highly demanded by industry, but also that AR can facilitate students taking initiative on their own to pay attention to details and fix their own mistakes during a simulated hands-on process.

1.2.3 Paper 3: Exploring AR as a Simulation of Authentic Learning Experiences

Exploring AR in a focused context revealed potential for the tool to help encourage self-remediation as students participated in a convergent activity, where the goal is to correctly sequence a series of construction elements using a predetermined design. In order to explore the potential of AR to a fuller extent, the next study presents this tool as a simulation of authentic learning, where students are presented with a full-scale design and build experience based on a real-world context, where multiple solutions are possible and there is no correct 'answer' (Herrington *et al.*, 2014). Experiential learning activities in AEC domains, like the Sacramento Municipality's Utility District (SMUD) Tiny House Competition or the Department of Energy's (DOE) Solar Decathlon are examples of activities that bring authentic, hands-on experiences to students (Figgess and Vogt, 2017). Activities like these have shown high potential to develop technical and professional skills for those who participate (Wu and Hyatt, 2016) and have shown that these real-world activities have significant advantages over traditional classroom experiences (Holt *et al.*, 2012). This kind of learning has the potential to target many of the skills and attributes called for in Paper 1 of this dissertation. However, these experiences are cost and resource intensive (Figgess and Vogt, 2017; Barnes, 2012; Department of Energy, 2017) and, consequently, most students do not experience comparable activities during their time in school despite their well-known benefit. This paper proposes AR as a simulation of this type of authentic learning activity. Understanding the behaviors and processes of students within this kind of simulated environment provides a basis for how this kind of activity compares to authentic learning in a fully physical environment. While AR does require investment of time and money, once created, it can be used without needing to purchase and repurchase physical materials. Therefore, if AR can replicate authentic learning to even some degree, it could potentially provide a cost and resource-effective alternative to a type of activity that traditionally is not accessible to many. Additionally, understanding where this type of visualization environment may fall short in this context will provide researchers a springboard to target innovations or guide future strategies regarding the utilization of AR for this type of activity.

While some researchers have explored AR in construction classrooms, most of the experiences were either as non-interactive visual supplements (Shirazi and Behzadan, 2015; Vasilevski and Birt, 2020; Webster *et al.*, 1996; Behzadan and Kamat, 2005, 2013; Bademosi *et al.*, 2019) or with minimal interactions, where students were limited in which parameters of the experience they could modify in AR (Turkan *et al.*, 2017). While most research regarding the utilization of AR in construction education has shown positive potential, there is a clear opportunity to explore utilizing this modality for authentic, full-scale, hands-on activities, where the virtual elements are manipulatable by the user and the task is situated in a real-world context. When performed in the physical world, these types of highly interactive activities have been shown to provide significant learning gains for construction students.

This paper presents an environment that simulates a full-scale, hands-on building experience. This work explores the viability of using AR to deliver hands-on experiences grounded in situations with real-world applicability. For this paper, an application was designed and created that allows students to interact with both physical and virtual elements to perform all tasks involved with the evaluations, redesign, and renovation of an existing structure. The choice of head-mounted technology allowed for a completely hands-free experience, enabling students to utilize both hands in building and interacting with the life-size materials. Authentic learning theory guided the analysis of the behaviors and perceptions observed within student subject testing in this AR environment. As a preview of the findings, strong evidence of the viability of AR to simulate authentic learning components was evidenced in many of the authentic learning categories considered. Others had counterintuitive evidence or conflicting results, which led to specific suggestions for future implementation, explained in detail within the paper.

The subsequent chapters present each of these papers in full detail, with their respective front matter, methodologies, and findings. The final chapter presents a summary of key themes and overarching findings.

Chapter 2

IDENTIFYING INDUSTRY NEEDS

2.1 Publication Information

The text presented in this chapter was submitted for publication, accepted, and published in the International Journal of Construction Education and Research under the title "Construction Education Needs Derived from Industry Evaluations of Students and Academic Research Publications" (McCord *et al.*, 2021).

2.2 Abstract

In recent years, the American Council for Construction Education (ACCE) has shifted to outcomes-based accreditation standards for higher education construction programs, allowing greater customization of educational strategies. Past research efforts have analyzed the demands of industry and strategies used in academia, but these studies occurred before the shift to outcomes-based accreditation. This paper presents an updated analysis of construction industry needs and academic priorities and aims to provide insight into the status of industry and academia in the context of this outcomes-based focus. Thematic analysis of five years of direct evaluations of student performance during industry internships provides insight into industry demands. Parallel analysis of construction education research publications from a corresponding time period is leveraged to understand developments within the academic research community. Results suggest that both sectors recognize the need

for experiential learning and software competencies among construction graduates. However, differences in trends were observed with a greater industry focus on personal attributes and a greater academic emphasis on sustainability learning competencies. The contribution of this paper is in providing an up-to-date evaluation of industry and academic trends in order to guide subsequent developments in construction education while addressing the needs of industry.

2.3 Introduction

Professionals have historically developed construction expertise through years of experience in the industry. Unfortunately, the construction industry is rapidly approaching a major labor shortage, which will mean that much of the collective expertise in the industry will exit as the current generation of experienced professionals retire, leading to 'faster-than-average employment growth' for the next several years, according to the Bureau of Labor Statistics (Torpey, 2018). Additionally, while the full effects of COVID-19 are yet to be seen, the pandemic has had a much greater impact on older members of the community, with many wary of returning to work (Eisenberg, June). For the construction industry, this may further emphasize the need to more effectively prepare the future workforce to efficiently develop the same skills and expertise as those who exit the industry due to this pandemic.

In recognition of the need to evolve the way that construction management (CM) and construction engineering management (CE) students are educated, the American Council for Construction Education (ACCE) began a shift in the mid-2010s to adopt outcomes-based learning for accreditation. The requirements to become an accredited program traditionally included a prescriptive list of courses in various subjects, such as math and science, construction skills, and communication. This shift toward outcomes-based learning enables universities to define their own strategies for educating their students, allowing programs to 'emphasize specialties' as they see fit (American Council for Construction Education, June). The ACCE specifically states that this approach may enable universities to "respond to emerging subject matter areas" (American Council for Construction Education, June). When considered in conjunction with the impending labor shortage, the shift to outcomes-based learning places universities in an ideal setting to leverage innovative technologies and teaching strategies to provide new formats of education that may provide better learning experiences for their students.

While construction education researchers have been exploring innovative teaching strategies for many years, the critical workplace competencies related to knowledge, skills, and abilities (subsequently referred to as industry "needs" or "demands") have not always been considered when defining high-impact practices for educating construction students. This work explores recent trends in the key competencies targeted by academic research and the key competencies reported most frequently by the construction industry. More specifically, it addresses the following research questions:

- What learning outcomes have been most frequently demanded by the industry in recent years?
- What learning outcomes have been targeted most frequently in recent years by academic research publications?
- How would the comparison between the two sets of high-priority learning outcomes inform better and more aligned practices in enhancing college CM/CE students' career preparedness?

The results addressing these three questions provide evidence to illustrate trends related to the learning outcomes demanded by the industry that are already being targeted by researchers and also the learning outcomes for which there is an opportunity for researchers to address emerging needs reported by industry. The contribution of this conceptual review is in systematically documenting these trends to illustrate current learning needs and strategies to support near-term learning gains, as well as documenting needs for which there is a demand for researchers to improve construction education in the future. This understanding will guide educational researchers to better prepare their students to meet the evolving demands of the construction industry.

2.4 Background

This paper provides an up-to-date review of trends in educational research and in professional competencies that are expected from CM and CE college graduates. Analysis of industry needs has precedent in publications from the last several decades. For example, in the 1980s, Warszawski (1984) reviewed the competencies relevant to construction management personnel. Later, others took a more holistic approach, focusing not only on managerial qualities, but also other relevant technical competencies, personal attributes, or interpersonal skills. For example, in 1998, a research team interviewed engineering professionals to see what expectations the industry had for engineering graduates (Back and Sanders, 1998). There is also a precedent of comparative analysis between industry and academic learning initiatives. For example, in 2012, researchers surveyed the industry to find out the key competencies that were most desirable and, using the old ACCE requirements, drew comparisons to how well these traits were being emphasized and found several instances of differences between industry and academic foci (Ahn *et al.*, 2012). This prior work generally found that academics focused more on imparting technical skills, while industry sources frequently sought professional skills, such as 'interpersonal skills'. Around the same time, researchers in the Midwest and Mid-Atlantic regions of the United States compared student and industry perceptions of what skills graduates needed to succeed in the industry (Bhattacharjee *et al.*, 2013). They found that a general understanding of required skills was shared between industry and students, but the two groups often ranked the items differently in order of importance.

While there are some similarities in the conclusions drawn by these types of comparative analyses, they also illustrate some differences that may be based on the needs of the industry at the time of their analyses. An updated version of this type of comparative analysis research has not been published since 2013. This current understanding of educational trends is especially necessary because accreditation agencies shifted to outcomes-based learning objectives, which could impact how universities prepare their students. Concurrently, changing construction workforce needs that have been recognized in the past few years (Torpey, 2018; CII, 2018) may also impact the human resource demands of the industry. This paper contributes to the body of knowledge by providing an updated analysis of recent trends in academic research and industry perspectives that illustrate how industry demands for students are changing, and how academic researchers are evolving to meet these shifting needs.

2.5 Methods

Data were collected from industry and academic sources to develop an understanding of the expectations of industry and the emerging strategies used in academia to equip construction graduates with skills needed for career success. Student internship evaluations were analyzed from industry, and educational research publications were collected and analyzed from academia. The following subsections describe the specific methods used for conducting these analyses.

2.5.1 Data Collection and Analysis—Industry Reviews

First, to gather information regarding the current status of construction industry workforce demands, information was collected directly from practicing industry professionals in the form of feedback on student internship evaluations. Researchers have historically used various methods to gather information regarding industry opinions about what they want to see from graduates of higher education construction programs. For example, some studies surveyed owners, contractors, and other project personnel (Ahmed *et al.*, 2014; Arain, 2010; Bhattacharjee *et al.*, 2013; Love *et al.*, 2001), and others have focused on surveying recruitment specialists from U.S. construction companies (Ahn *et al.*, 2012). Typically, these personnel rated significant skills, often referred to as "key competencies" (Ahn *et al.*, 2012), on Likert scales according to importance. These studies presented key competencies to industry members and asked them to draw on their general knowledge and experience and conceptually rank the skills.

By contrast, the method implemented in this work aggregates and analyzes internship evaluations based on in-depth work experiences that industry practitioners have had with specific students for three or more months. This method presents distinct benefits and a unique perspective. First, similar to previous literature, it illustrates the opinions of current industry practitioners; by nature, those who complete the evaluations are industry practitioners. However, this work stands apart from most literature in that those completing the evaluations hold direct supervisory roles to the interns, making these evaluations based directly on specific student performance rather than hypotheticals. The large number of reviews allows the desires and opinions reflected by industry to be compiled in an informative and detailed dataset and considered in aggregate. The trends that emerge through this analysis provide insights into the current status of the industry's direct evaluation of student performance.

Most construction engineering and management programs encourage their students to complete an internship during their academic matriculation. Often, after students complete these internships, employers complete evaluation forms for students to assess their performance. A large sample of these evaluations was obtained from internships completed by students at Arizona State University's Del E. Webb School of Construction. The portion of the form that provides the basis for this analysis is an open-ended section where the employers are asked to reply to the following two prompts (for analysis of the numerical ranking portion of this form, see El Asmar *et al.* (2020)):

- Please identify three (3) areas in which the student intern is most improved.
- Please identify three (3) areas in which the student is in greatest need of skill development.

While these questions are aimed at eliciting feedback about strengths developed and areas where further skills are needed, both questions ultimately provide data about the learning needs demanded by industry. This form of open-ended question has been used in other research that aims to elicit emerging topics reported by a population without limiting their responses to indicate one or more pre-determined outcomes (Allen, 2017). Furthermore, when a sample of responses to this type of open-ended response question is analyzed, it offers insights into the trends where there is the

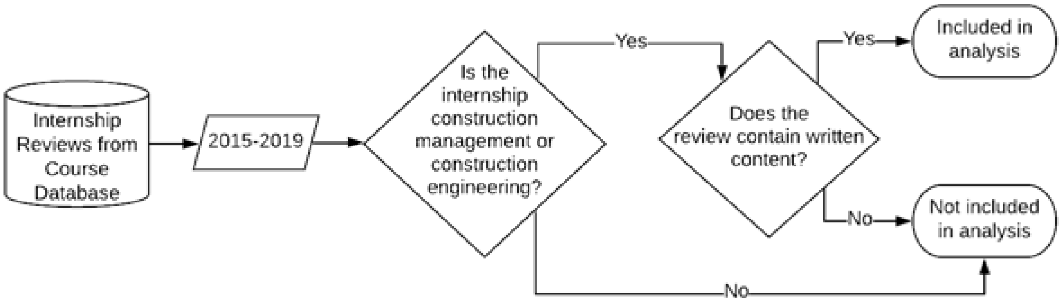


Figure 2. Flowchart Outlining the Steps Taken to Collect Industry Evaluations for the Analysis.

greatest frequency of needs reported by a population (Weller *et al.*, 2018). These questions provide an ideal source of data to not only illustrate what learning needs are demanded by industry based on an in-depth knowledge of a specific student, but also the broader trends that emerge to illustrate common learning needs demanded by industry.

These industry evaluations from 2015 to 2019 were digitized, and the content of these two write-in categories was thematically analyzed. Student names were removed from the data per the Institutional Review Board (IRB) requirements[1]. The years of data chosen correspond with the implementation of ACCE's shift to outcomes-based learning in 2015 (American Council for Construction Education, 2015) and a five-year period following. The process for obtaining and filtering this data is found in Figure 2. From this dataset, the industry responses were analyzed and coded based on themes founded in previous literature and refined by the data. In particular, the organizational structure proposed by Ahmed *et al.* (2014) was used as a guide, as it aimed to "identify the key skill set and categories required by today's construction industry from graduating construction management undergraduate students". This research combined an extensive literature analysis with an industry survey to identify seven major categories for demanded skills and attributes: Personal Attributes, Professional Attributes, Technical Skills, Managerial Skills, Industry & Business Skills, People Skills (Interpersonal Skills), and Legal & Contractual Skills. Each of these categories contains a list of subcategories delineating different components of the group. For example, the Personal Attributes category includes characteristics like dependability, time management and willingness to learn, among others. A total of 95 subcategories fall within each of these major categories. This prior work (Ahmed *et al.*, 2014) provided a starting point for organizing the new findings generated in this current paper (see Table 1).

A descriptive qualitative analysis was conducted where emergent themes were observed by a thorough reading of each of the evaluations. This resulted in an additional three categories to the 95 categories defined by Ahmed *et al.* (2014). Table 1 lists these categories, many in abbreviated form (for expanded descriptions, see Ahmed *et al.* (2014)). These 98 themes were quantitatively supported by performing a textual analysis using the text search function in 'The R Project for Statistical Computing' (R), an open source software environment used for statistical analyses. A custom script was authored using the grepl() function with a set of descriptors for each of the subcategories. This function performs a comprehensive keyword-based search of a textual database, in this case the digitized reviews. The custom script used this function for each of the categories and searched to see if any were included in either subsection of each evaluation. If any of the keywords were present, the search would return a value of TRUE for that category. This process was iterated for each of the 98 categories. Figure 4 presents this process in graphical format. The results of the analysis produced a table where each of these categories contained a count for the

Table 1. List of Construction Industry Attributes and Skills Based on Prior Work by Ahmed et al (2014) and Emergent Categories in This Study.

Personal Attributes	**Professional Attributes**	**Technical Skills**	**Managerial Skills**
Listening ability*	Hands-on experience	Plans/Blueprints/Drawings	Health/safety mgt.
Attention to details*	Teamwork capabilities	Knowledge of operations	Quality assurance
Time Management	Values/ Work ethics	Computer proficiency	Quality control
Dependability	Planning and goal setting	IT/ software	Organizational
Adaptability/Flexibility	Long term commitment	Sustainability/LEED	Document control
Desire to learn	Problem solving	Scheduling	Project management
Assertive attitude	Result orientation	Closeout and handover	Cost control
Promptness in actions	Critical path thinking	Estimating	Leadership
Comprehension ability	Decision making skills	Cost accounting	Team building
Ability to learn	Forecasting	Materials knowledge	Site planning and mgt.
Innovative/Creativity	Ability to follow up	Equipment knowledge	Personnel/resource mgt.
Willingness to travel	Risk taking	Economic/financial analysis	Risk planning, control
Taking initiative‡	Multi-tasking	Knowledge of design	Productivity mgt.
Attitude (general)‡		Constructability review	Managing labor issues
		Scope review	Knowledge/info. mgt.
		Bldg. Inf. Mod. (BIM)‡	Financial management
Industry/Business Skills	**People Skills**	**Legal/ Contractual Skills**	
Health/safety regulations	Communication (overall)†	Interpreting contract docs.	
Bldg. codes/regulations	Written communication	Law and legal environment	
Environment impact	Verbal communication	Contract administration	
Client relations	Diversity	Bidding knowledge	
Permitting knowledge	Trade coordination	Dispute avoid./resolution	
Trade knowledge	Multilingual	Project delivery/Contracting	
Procedural issues	Meetings	Change management	
Cultural issues	Relationships/Collab.	Understanding labor laws	
Other fields/disciplines	Motivation capabilities	Claims prep/presentation	
Awareness of ind. trends	Negotiations/Conflict res.	Claims defense skills	
Con. supply chain	Coaching		
Geographical issues	Mentoring		
Business Management			
Entrepreneurship			
Partnering			
Global con. environment			
Lean culture			

*these two items were originally listed as a single category but split into two distinct categories for this study
†the written and verbal categories were also analyzed in an aggregate 'communication' category that was not explicitly included in the original list
‡these three categories were added to this study

number of times the concept was mentioned in the internship reviews. The data are presented as a percentage, representing the number of reviews in which the concept emerged in proportion to the total number of reviews. Additionally, the data were separated into the two categories guided by the open-ended questions: ‘Greatest need of improvement’ (Needs) or ‘Most improved’ (Improved) categories. After the findings were organized according to the previously defined and emergent categories, they were compared to those observed in recent publications from educational researchers, a process defined subsequently.

2.5.2 Data Collection and Analysis—Academic Research

The learning outcomes most frequently targeted by educational researchers were identified by surveying research publications regarding teaching and learning within construction education. By analyzing a representative selection of literature, this review considers the procedural and technological innovations explored within academia, with special attention to the key competencies that these advancements target. The authors acknowledge that not all educators actively publish research, and some are solely focused on teaching, so this paper does not claim to represent the opinion of all higher education instructors. Additionally, this paper does not seek to provide a detailed review of CM curricula, as it is assumed that the programs that receive accreditation provide coursework that meets each of the student learning outcomes (SLOs) required for accreditation. In light of this, academic research publications are targeted in this analysis to understand where researchers see a need for development and areas of interest or focus that emerge above and beyond traditional curricula. Trend analysis of these publications provides insights on both the strategies used to enhance construction education and the underlying learning topics most frequently targeted by educational researchers. Literature from the Associated Schools of Construction (ASC), the American Society of Civil Engineers (ASCE), and the American Society for Engineering Education (ASEE) were searched to produce a representative sample of literature dealing specifically with construction education. ASC and ASCE publications

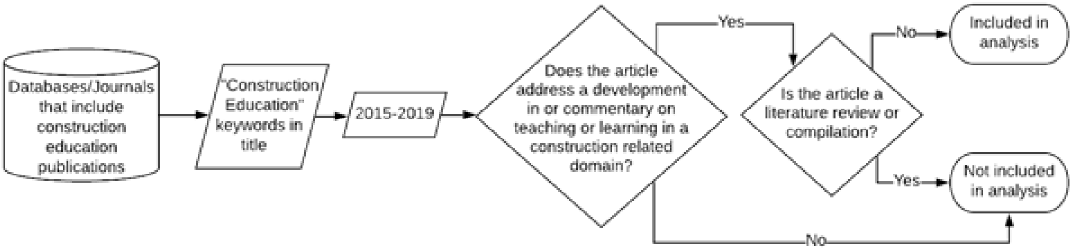


Figure 3. Flowchart Outlining the Steps Taken to Collect Articles for the Review.

alone account for more than 75% of the construction education research in the past several decades (Zheng *et al.*, 2019). Additionally, research from the International Journal of Engineering Education (IJEE) and Journal of Information Technology in Construction (ITCON) was included in the search, as these venues regularly include publications relevant to innovative construction education strategies. These databases and journals were searched using the term 'construction education' or, where possible, using the Boolean AND search with the terms 'construction' and 'education' in the title to produce a representative sample of research within the targeted scope of this review, as shown in Figure 3.

From the repositories of each of these organizations, construction education articles were filtered to include research only from the past five years (2015-2019). The resultant list of publications from this time period aligns with ACCE's shift to outcomes-based learning and also with the internship data collected from the industry, in order to support the comparison of data. To filter relevant literature, the abstracts were manually sorted based on the following question: Does this article address a development in, or commentary on, teaching or learning in a construction-related domain? If the answer was no, such as an article on the construction of higher education buildings, the publication would not be included. If the answer was yes,

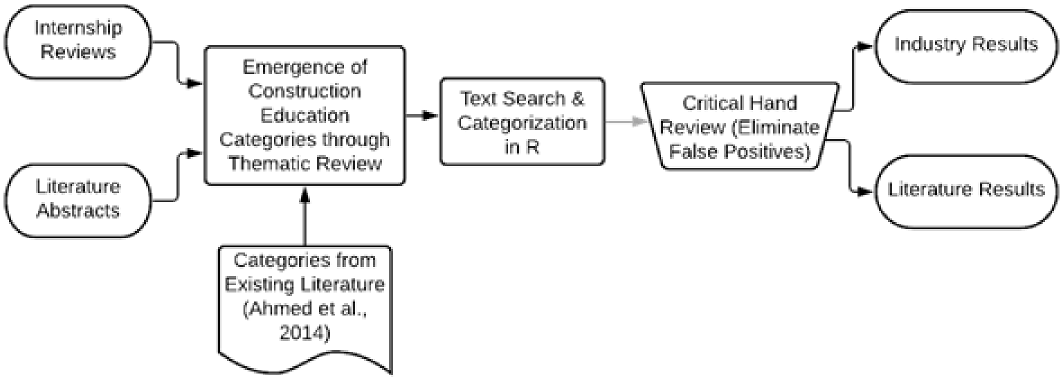


Figure 4. Process for Categorizing and Processing the Data from Both the Industry Internship Evaluations and the Literature Sourced from Academic Research.

then the next filter was applied: Is the article a literature review or compilation? If the answer was no, then the article was included. Literature reviews were not included to avoid duplicate articles and to reach construction education research at the primary source.

A review of these abstracts provided information about which key competencies were targeted. These abstracts were compiled into a database that was manually thematically analyzed to extract relevant patterns. It was also searched with the same text analysis function as the industry data. The same 95 categories defined by Ahmed *et al.* (2014) and three emergent categories that were used for organizing the industry data were applied and themes were extracted. The data resulted in percentages of reports for each category. This consistent method of data organization supported the comparison of the industry evaluation data to the reports from academia, presented in Figure 4.

2.6 Results and Analysis

2.6.1 Description of the Data

From the internship evaluations between 2015 and 2019, inclusive, a total of 993 evaluations were included in the dataset shown by year and semester in Table 2. These evaluations included students enrolled in the undergraduate sophomore construction management (CM) internship class (48%), the undergraduate junior CM internship class (37%), the undergraduate junior Construction Engineering (CE) internship class (8%), and the graduate CM internship course (7%). Typically, the enrolled course indicates the student's year in school (sophomore, junior/senior, or graduate) and their major (construction engineering or construction management). While demographic information was not solicited on the internship evaluations that form the dataset, parallel data regarding the general demographic makeup of the students is available through the university based on enrollment in construction internships. This dataset (n=1122) includes a data point for each internship completed during this time period, regardless of whether an evaluation was completed, and can be reasonably expected to represent the demographic distribution of population of interest. The dataset includes a gender distribution of 87% male and 13% female and representation from a variety of racial and ethnic backgrounds, including American Indian/Alaska Native (2%), Asian (2%), Black or African American (1%), Hispanic/Latino (24%), White (58%), Two or More Races (2%), and Other or Not Reported (11%).

The evaluators came from a variety of industry sectors and leadership roles within their company. Data on the project role of each evaluator and the industry sector for each evaluation was collected from 2017 to 2019. Exact titles and roles within a

Table 2. Number of Industry Evaluations Collected by Semester and Year.

	2015	2016	2017	2018	2019	2015-2019
Fall	10	10	16	6	13	55
Spring	9	30	16	4	8	67
Summer	111	139	154	241	226	871
Total	130	179	186	251	247	993

company varied greatly, so in order to present a coalesced and meaningful description of the supervisor roles, the most frequently occurring words or word combinations within the title description were compiled to illustrate trends. The resultant data included evaluations from individuals with the following titles (and percentage of responses): Senior Manager (13%); Manager (35%); Assistant Manager (2%); Superintendent (9%), Assistant Superintendent (1%); President (3%); Vice President (3%); Director (7%); and Estimator (5%). The students reviewed in this work completed internships in various types of companies, including Sector analysis of the companies involved revealed a high percentage of reviews coming from the commercial sector (55%), followed by heavy civil (15%), subcontractors (11%), residential (8%), owners (4%), engineering (2%), consulting (1%), and 3% in other categories or unknown.

In order to understand the topics most frequently mentioned in academic literature regarding construction education, a search for construction education-related journals, conference proceedings, and books is presented here. The breakdown of documents after applying the filters described in the methodology is presented in Table 3.

2.6.2 Emergent Themes

Figures 5, 6, and 7 summarize the frequency with which each skill or attribute was mentioned in industry evaluations or academic literature. Within the extensive

Table 3. Number of Articles Included in the Literature Analysis from Each Publisher/Journal.

	Source	#
Journals	International Journal of Construction Education and Research	18
	Journal of Civil Engineering Education formerly: Journal of Professional Issues in Engineering Education and Practice	10
	International Journal of Engineering Education	4
	Journal of Computing in Civil Engineering	3
	Advances in Engineering Education	1
	Journal of Information Technology in Construction	1
Conferences	ASCE Proceedings (various years and conferences)	10
	ASC Proceedings (various years and conferences)	9
Books	ASCE Book Chapters from: Transforming Engineering Education: Innovative Computer-Mediated Learning Technologies	3
	Total	59

collection of internship evaluations, nearly all construction-related skills and attributes were mentioned at least once. A higher frequency of skills or attributes in these reviews suggests broader recognition of the need for these learning concepts among employers. Similarly, a higher frequency of research reports targeting specific learning outcomes illustrates a broader interest in specific educational improvements. Of the 98 categories used to organize the data, only those that met a threshold of 10% or higher in at least one category (Greatest Needs, Most Improved, Total Mentions, or Literature Results) were considered. This enabled the researchers to focus their discussion on the topics for which there were common reports on the need for a specific learning category from industry and academia.

The frequency results generated from the R scripts were manually reviewed to limit false-positive categorizations. For example, the attribute of 'results orientation' produced an overinflated count in the academic literature count since most articles will state that they present research 'results', even if these are unrelated to the 'results orientation' of their students. After the data were collected and cleaned, they were compiled for analysis. What follows is a discussion of emergent themes, categorized by three groupings: Personal Attributes, Technical Skills, and Professional Skills.

For the discussion of industry results, the 'Overall Mentions' category will be emphasized. In the industry reviews, it was observed that many skills or attributes were mentioned in both the 'Greatest Needs' and 'Most Improved' categories, sometimes even within the same review. For example, one review explained that a student had 'Most Improved' in "communication skills…when tasked with scheduling a subcontractor", and that their 'Greatest Need' was "communication skills between more than one subcontractor". The researchers noted that the two categories seemed to be presenting the same information, so a correlational analysis was performed to understand the statistical difference between the two categories. The Pearson correlation coefficient was produced for the two categories with the unit of analysis being the number of reviews mentioning a category, with n=98 skills/competencies. The results of this analysis indicated that the two categories were indeed highly related (Pearson's $r(97) = 0.911$, $p < 0.001$), indicating that neither category presents unique information relative to the other and that both vary together. The average difference in percentage between the two categories was 1.7%. For example, 12.3% of reviewers mentioned scheduling as a greatest need and 11.9% mentioned scheduling in the 'Most Improved' category. Of the categories presented here for analysis, the one with the greatest difference—and the only with a difference above 10%–was Experience/Hands-on, with 36.7% of reviewers mentioning this as a 'Greatest Need' and 24.9% mentioning it as a 'Most Improved' skill. Because of the strong correlation

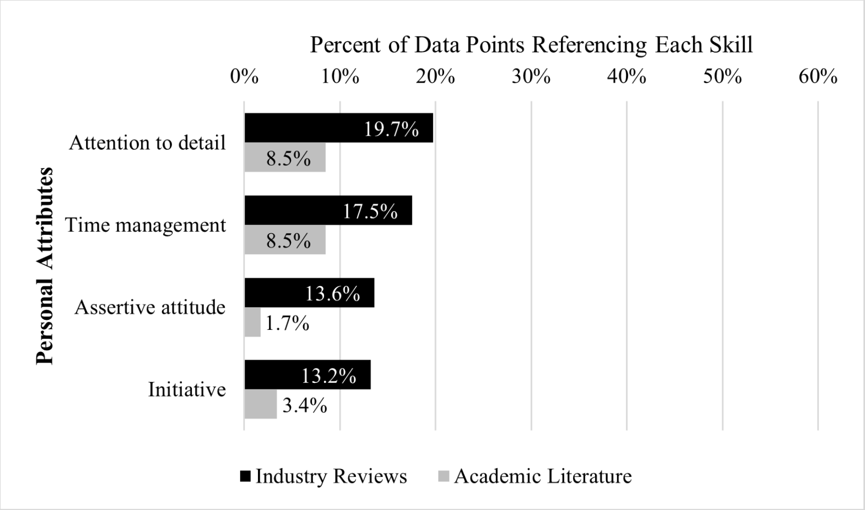


Figure 5. Bar Graph Comparing the Frequency of Personal Attributes Mentioned in Internship Reviews to the Frequency of Mention in Academic Literature. A Range from 0% to 60% Was Selected to Scale the Image for Comparison with Other Categories.

between the two categories, only the overall mentions are discussed, in depth, with percentages presented in Figures 5, 6, and 7.

Within the industry evaluations, a variety of personal attributes appeared in the reviews, with attention to detail (19.7%) and time management (17%) leading in mentions. While these may seem like small percentages, the fact that more than 1 in 6 employers mentioned these characteristics in an open-ended response is notable. Examples of content from the reviews regarding each personal attribute above the 10% threshold are included below:

- attention to detail: the intern "could use work maintaining attention to fine details in highly repetitive tasks."
- time management: the student "needs to learn to prioritize tasks and improve focus on tasks at hand."
- assertive attitude: the intern "will have to be assertive with their peers during

their career to ensure that other people's actions do not impact their quality of work."

- initiative: "I appreciated [the intern]'s initiative to check in with me frequently on their assignments, even when I was out of the office."

In general, there were many personal attributes that industry evaluators noticed and wanted to see in interns.

Overall, personal attributes were much less frequently mentioned with granularity in academic literature, but some reports suggested that students develop positive attributes in general. For example, one article suggested that a collaboration between the Design-Build Institute of America (DBIA) and ASC would help cultivate student attributes, both in personal and in interpersonal capacities (Washington, 2015). Another article referenced a personal attribute development when talking about developing the whole student through global stewardship and service-learning (Songer *et al.*, 2018). While these examples illustrate some level of interest among academic researchers in supporting the development of these skills, very few articles focused specifically on these skills with enough granularity to organize them into specific categories.

Industry demands for the development of personal attributes outweighed the academic emphasis in each specific attribute category. However, it should be noted that it is common for an educational innovation or approach to discuss the possibility of personal attribute development in the general sense while not detailing specific attributes or skills. Therefore, rather than drawing conclusions about academia not meeting industry demands for personal attribute development, it would be more appropriate to conclude that this evidence indicates the potential for greater focus on specific attributes and skills that may be more in demand than others. Researchers using technology or curriculum design to improve the student experience can specifically target personal attributes that are most in-demand, like attention to detail and time management. These two attributes have appeared in high demand in past literature about industry needs (Ahmed *et al.*, 2014). Many educators may be practicing these concepts already, but presenting them here provides a broadly applicable, and industry-backed, reasoning for emphasizing these skills and highlights the importance of reporting on the effectiveness of novel teaching strategies that support the development of these skills.

Regarding the relevance of these findings to the ACCE student learning outcomes (SLOs), most SLOs do not specifically cite personal attributes, except for possibly one—SLO 6: Analyze professional decisions based on ethical principles. This particular SLO could be considered a personal attribute (ethical behavior), but does not touch on individual work ethic and related principles, such as attention to detail, time management, assertive attitude, and initiative. Here is an opportunity for the academic realm to innovate and find creative ways to address industry demands, while exceeding accreditation requirements. For example, teaching strategies that have been studied in the business domain such as self-analysis, student-conducted interviews, or inviting guest speakers (Anthony and Garner, 2016) could be replicated in the construction domain to address the needs reported by the industry. As educational researchers explore novel ways to target and measure students' development of these personal attributes, it will enable construction educators to address accreditation SLOs, while enhancing their students' industry preparedness.

Experience/Hands–on – By far, the most common industry reports were that the intern should have more "in-field" or "onsite" experience or simply "experience" in general, with nearly half of the reviews (47.6%) mentioned that the intern either

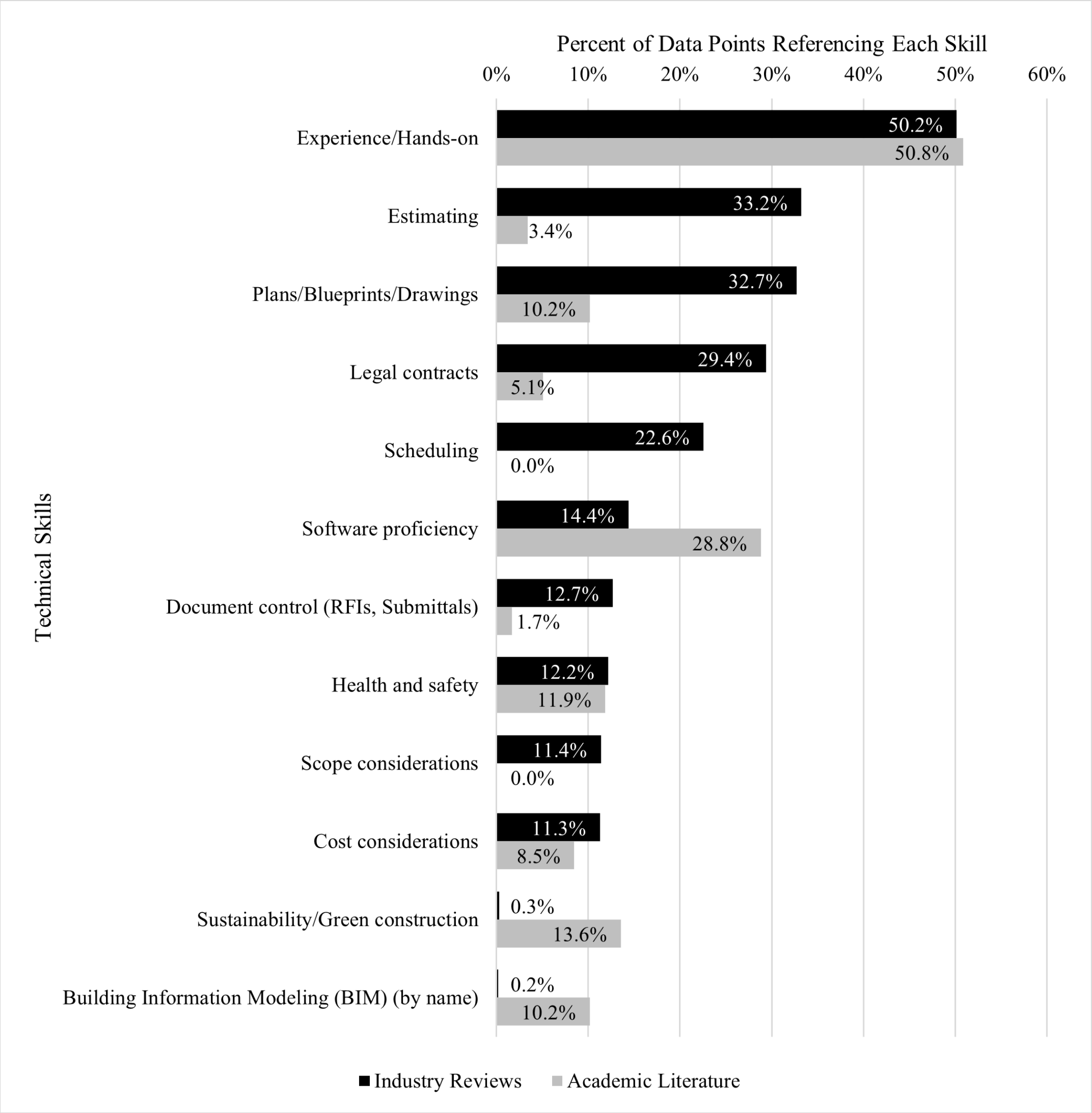


Figure 6. Bar Graph Comparing the Frequency of Technical Skills Mentioned in Internship Reviews to the Frequency of Mention in Academic Literature.

needed some kind of experience or that they had improved in this area during the internship. For example, one employer stated that a student's greatest need was, "experience - being so young, [the intern] just needs to gain experience in construction but [he or she] seems to have a passion for it and is willing to learn." Correspondingly, academic construction education literature places a high emphasis on experiential learning, including hands-on experiences in the construction field, with half the articles mentioning experience in at least a general sense. For example, researchers have been exploring the viability of providing a site visit experience through virtual reality (Pham *et al.*, 2018). With COVID restrictions on universities and a shift to remote experiences, this topic bears relevance to recent situations and likely great relevance to the new normal—which may include a blend of in-person and virtual elements—that will follow as institutions ease out of the pandemic crisis. Overall, there is a prevailing theme in this sample that experiential learning is a critical success factor that can deliver desirable skills. As one of the most prominent themes, special attention should be given to this category.

Software proficiency and BIM – Employers would frequently refer to software and technology in their responses (14.4%). Comments ranged from mentioning software skills in general to specific, well-known software producers such as Autodesk, to company-specific software applications that are proprietary to specific companies. Correspondingly, much of the literature (28.8%) mentioned software in general or specific software by name. Notably, more than 10% of the articles discussed building information modeling (BIM), a term that relates to many of the software applications mentioned, but "BIM" was far less commonly found by name in the internship reviews (<1%). Much of the academic research in the past few years has focused on the implementation of BIM in the classroom as it has become more ubiquitous in the industry. Several researchers have proposed methodologies for incorporating BIM into the classroom through intentional curriculum design (Zhang *et al.*, 2019; Lucas, 2017; Ghosh *et al.*, 2015). Additionally, researchers recognize the utility of BIM not only as an end itself, but also as a facilitator to learning other concepts such as safety education (Clevenger *et al.*, 2015) or contract management (Zhang and Gao, 2019). The strong presence of software and BIM in the academic literature indicates an understanding of its importance and of the need to educate students on its use. While academic reports list BIM far more frequently than industry, this is likely due to the granularity with which industry employers discuss BIM concepts, with many stating specific software skills as desirable, such as Revit, instead of discussing BIM as a general concept. On the other hand, in the academic realm, educators must prepare students for a wide range of experiences, necessitating more generalizable terms. In summary, findings indicate that industry and academia use different terms, but both broadly recognize the necessity of technology competencies within the construction industry. This recognition aligns closely with ACCE's SLO 10: Apply electronic-based technology to manage the construction process. This indicates a need for continued exploration of novel strategies and best practices for preparing students with these skills to meet high industry demands. For example, in addition to teaching basic technologies to students, the evidence collected in this work would suggest value for educators to focus on processes related to this implementation (i.e. 3D coordination) to improve the professional value of achieving these ACCE student learning outcomes. While this work does not suggest specific new methods for educators, the findings may guide future research, based on the current technical skill needs of industry.

General construction skills – The ability to work with plans, blueprints, or drawings was heavily emphasized in the internship reviews (32.7%), with employers stating their appreciation of an intern's "ability to read and understand construction drawings" or that the intern "needs to improve their understanding of drawings and how they relate to field conditions." Other general construction skills were mentioned throughout the reviews such as estimating (33.2%), scheduling (22.6%), and legal and contractual competencies (29.4%). Additionally, document control (12.7%), scope considerations (11.4%), and cost considerations (11.3%) were mentioned in a significant amount of the reviews. Overall, nearly all construction competencies were mentioned somewhere in the reviews and this section presents those that fell above a 10% threshold of frequency of mention. It is likely that these specific reports came from individuals who are focused on these specific topics in their work based on the nature of the data collected. While this in-depth knowledge may be necessary by practitioners fulfilling related roles, most of these skills received infrequent mentions in the sample of construction education literature. Despite the comparatively low reports on these basic technical construction skills in academic research publications, these skills are encompassed within several ACCE SLOs, which suggest that academic institutions that adhere to ACCE accreditation requirements are indeed targeting them. For example, ACCE SLOs include: SLO 4: Create construction project cost estimates; SLO 5: Create construction project schedules; and SLO 17: Understand the legal implications of contract, common, and regulatory law to manage a construction project. Because these topics are covered by ACCE accredited institutions, this could indicate an opportunity for increased focus and innovative teaching strategies by academia to more thoroughly target these technical skills to address the nuanced skills demanded by industry; however, it may also simply indicate a limitation of academic environments that aim to prepare all students to be capable of growing into any construction role. In other words, to accomplish the breadth of teaching construction topics to all students, the depth of understanding of specific technical competencies that may be of particular interest to certain construction positions may be limited. To avoid drawing speculative conclusions about how all educators should evolve in their teaching, the authors recommend that future educators consider these findings in conjunction with their own curricula to determine if they can add educational experiences to support more technical development without compromising other topics that are being covered effectively.

Sustainability – Academic literature had a much higher emphasis on sustainability than the industry reports. The prominence of the sustainability agenda in academic research is consistent with the results found by Zheng et al. (2019), who, after performing an extensive bibliometric analysis of construction education research from 1982 to 2017, found that sustainability (and building information modeling) have emerged prominently as hot topics since 2006. These findings indicate that academic researchers are actively exploring innovative strategies to support their students' education on sustainability topics. However, the frequency of mention is much lower in the industry reviews. This disparity may be due in part to the barriers that the construction industry faces to implementing sustainable design and construction, such as profit, demand, and procedural barriers (Häkkinen and Belloni, 2011). However, as these barriers evolve and ideally diminish over time, the authors envision a continued need for the kind of education that is happening regarding sustainability in conjunction with SLO 18: Understand the basic principles of sustainable construction.

Health and safety – Safety is mentioned in a significant portion of industry reviews (12.2%) as well as in much of the recently published construction education research literature (11.9%). This has been especially evident in research aimed at advancing safety education through technologies like serious games (Din and Gibson, 2018) or virtual reality (Pedro *et al.*, 2016). In addition to the academic reports on novel safety education strategies, this learning content is also directly targeted in ACCE's SLO 3: Creating a construction project safety plan. This offers further evidence that academic institutions are already targeting this learning content with some success. For a learning topic where poor decisions can lead to catastrophic life consequences, there may always be a need to improve in how students are prepared with this skill until injuries and fatalities are no longer a part of the construction field. This sentiment was indicated by an industry response that stated a need for continued improvement to safety education for students "no matter how good they are". While other responses worded this sentiment differently, this was a common type of response. Similarly, in many of the academic publications targeting this learning topic, authors would often recognize the improvements that have been made regarding construction safety, but also the continued problems that persist to motivate the work of emerging researchers. Therefore, the findings related to this topic suggest that continued work should be pursued related to safety education, as it is highly demanded by industry and still relevant based on the construction safety incidents that continue to be recorded.

Communication – One of the most ubiquitous skills mentioned in the dataset was the need for improved communication, with 39.4% of reviews mentioning communication skills in some form. The content of the comments about communication included a call for improved communication in general as well as the subcategories of written communication and oral communication. Within these two categories, reviewers mentioned both formal and informal contexts, such as formal report writing, formal oral presentation, informal email writing, or information phone conversations. For example, one evaluator addressed informal, written communication in the form of emails to clients, stating that the student "writes technical information correctly, but could

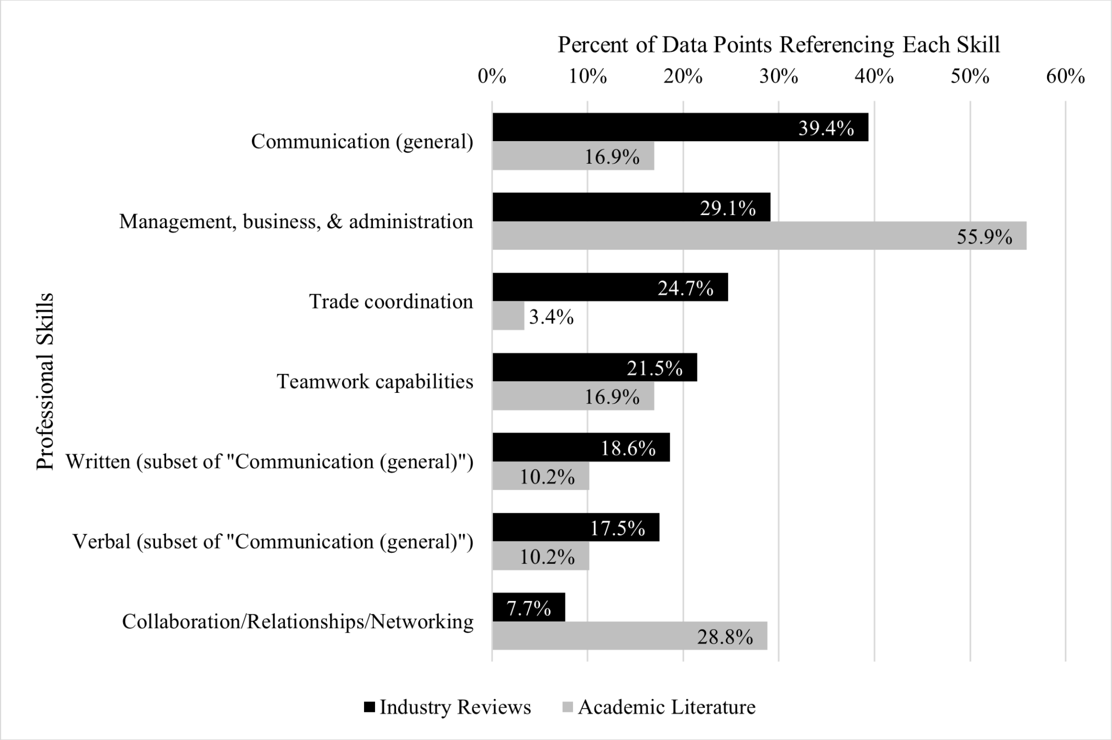


Figure 7. Bar Graph Comparing the Frequency of Professional Skills Mentioned in Internship Reviews to the Frequency of Mention in Academic Literature.

work on [his/her] ‘voice’ when emails will interface with clients”. Many emphasized the importance of students being able to recognize their areas of inexperience and articulate questions they have to enable them to improve. Overall, communication is broadly recognized to be a critical success factor in the industry reviews. While not as ubiquitous as in the industry reviews, communication was still mentioned frequently in academic literature (39.4%), suggesting a clear emphasis. For example, some researchers explored BIM as a vehicle for developing communication skills (Zhao *et al.*, 2015). Others explored how to use coursework, such as capstone projects, to foster communication (Zhang *et al.*, 2017). Within the ACCE SLOs, the first two address communication, both written and oral—SLO 1: Create written communications appropriate to the construction discipline and SLO 2: Create oral presentations appropriate to the construction discipline. These two SLOs define specific skills that were brought up several times by the industry reviewers. One form of written communication that may be overlooked in an academic setting is informal written communication, such as emails. This form of communication is certainly "appropriate to the construction discipline" and for many roles more common than formal reports. Effectively and earnestly incorporating something seemingly simple into the course curriculum could require creativity but ultimately would benefit students, many of whom need guidance on digital communication in a more professional setting. For targeting SLO 2 regarding oral presentations, many professors organically involve oral presentations in their class, providing a valuable opportunity for public speaking experience. In addition to formal settings, educators can consider the opportunity of teaching students appropriate verbal communication in professional settings. For example, many industry reviewers indicated that they wished students asked more questions, fewer questions, or simply better questions. Others wished for more effective phone communication from their interns. Developing effective verbal communication in both of these informal settings are certainly appropriate to the construction discipline and would benefit from creative application in the academic realm.

Trade coordination – While communication, in general, was acknowledged by both industry and academia, one specific area that emerged more strongly in industry results was trade coordination. This topic was not mentioned by name in most of the academic literature while more than 1 in every 5 industry reviewers cited working with "subs", "subcontractors", or "trade partners" in various forms as a crucial part of the job expectation for the student interns. The strong emphasis placed on this concept by industry suggests that academic researchers and curriculum developers can use this need to craft student experiences that meet SLO 9: Understand construction management skills as a member of a multidisciplinary team through the lens of integrating building systems with various specialty contractors and design professionals in order to prepare students for those interactions in the field. While this SLO is undergoing a wording shift from “apply” to “understand”, effectively lowering the student expectation by one level on Bloom’s taxonomy, educators can still consider ways to implement collaboration strategies in the classroom in novel ways since working with others is critical to daily work in industry. This is an area where advancements in novel teaching strategies could offer near-term value to students entering the industry.

Collaboration and teamwork – Collaboration was strongly represented in the recent construction education literature (28.8%), often in conjunction with the aforementioned communication skill. For example, researchers have addressed collaboration within interdisciplinary teams and with problem-based learning tasks (Scott and Ghosh, 2016). The intersection of several topics with teamwork, such as sustainability (Valdes-Vasquez and Clevenger, 2015) and BIM (Zhao *et al.*, 2015) presents itself in recent academic literature in the field. Researchers have also explored barriers to collaboration and the effectiveness of incentives to fostering teamwork (MacLaren *et al.*, 2017). Overall, within the recent body of academic work within the construction education fields, there is a general understanding of the importance of collaboration and a desire to improve the way this concept is delivered to students. While the concepts of collaboration and networking did not appear as frequently in the industry reviews, several employers mentioned these qualities (7.2%), showing a general understanding of the importance of collaborative skills in industry. Teamwork was also highly represented in literature (16.9%) and also in the industry reviews (21.5%). Semantically, some may argue that these two categories are inseparable. The topic group with collaboration includes networking and relationships and seems to imply a longer-term investment in some sort of interpersonal interaction while the teamwork category is more task-based. Despite the difference, the two terms are often used interchangeably in the literature, so differences in frequency should not be used to decisively conclude that one term or type of relationships is preferred over the other. Both collaboration and teamwork are recognized across industry and academia as critical success factors.

2.7 Limitations

It is recognized that the factors that motivate a direct evaluation of a specific student may differ from the factors that motivate peer-reviewed publications. For example, company needs and culture may motivate a student evaluation, while topics more likely to attract funding or to be accepted by the peer-review process may motivate publications. Therefore, the focus of this work is on offering qualitative insights into similarities or differences between the types of topics explored, as opposed to suggesting this as evidence to illustrate how academia is or is not failing to address the needs of the industry.

The authors aimed to identify trends reported about the professional attributes of students at an ACCE-accredited institution in recent years. Due to the data collection and cleaning processes involved, the authors were not able to define sub-trends specifically based on demographic information of individuals included in this study. It is theoretically possible that some trends may have emerged based on demographic group but since this was not a focus of this study and was not facilitated by the data, all reported trends and claims are not stated based on specific demographic group relationships.

In pursuing this research, the aim was to understand the trends in the U.S. construction industry on what skills construction institutions should focus on fostering in their students. The authors recognize that their set of industry data came from evaluations of students attending a university in one region (i.e., the American Southwest), which could theoretically create a geographic bias to the responses. Even so, the students enrolled at this institution complete internships across the country. Furthermore, the authors were careful to avoid including comments that explicitly refer to skills associated with only one particular region. For example, while the Southwest may require construction with sun-resistant materials and the northwest region may require more water-resistant materials, professionals in both regions need to use estimating tools and concepts to predict the cost of constructing with these materials. As a result, the authors maintain that their results can be generalized to apply across the U.S. construction industry, but how future researchers use these results may need to be tailored to their specific regional needs.

2.8 Conclusion

The construction industry's need for better-prepared professionals calls for educational improvements. The shift to outcomes-based learning goals in construction education accreditation provides the needed flexibility to implement innovative educational strategies. In order to guide educators to target learning strategies and topics that are frequently demanded by industry, this research coalesced findings related to student learning needs from industry and academia. The major findings provided by this research include a discussion of skills and competencies that are both highly emphasized by industry and academia, including technical skills that result from hands-on experience and software proficiency as well as interpersonal skills such as communication. It was also found that industry more frequently mentioned specific professional skills, such as attention to detail and time management, than academic publications. On the other hand, the concept of sustainability was mentioned much more frequently in academic literature than it was by the industry representatives. Overall, several skills and competencies, involving personal attributes, technical skills, and professional skills, were analyzed for frequency of mention and compared between industry and academic realms.

The contribution of this work is in systematically organizing and comparing recent reports from both industry and academia related to necessary competencies needed for students pursuing construction careers. In the near term, this knowledge will allow future educators to more specifically understand what learning outcomes, and what professional contexts related to those outcomes, are in the highest demand from the industry. This can guide their educational strategies for addressing student learning outcomes required for accreditation. In the longer-term, the analysis approach used in this work offers a repeatable strategy based on a wealth of firsthand industry-to-student direct feedback that would allow future researchers to update and compare findings to this paper in order to identify shifts in demands for new competencies from the industry. These methods use forms of data that are likely to continue being collected and accessible to academic researchers in institutions of higher education.

Chapter 3

COMPARING 2D AND AUGMENTED REALITY (AR) EDUCATIONAL OUTPUTS FOR CONSTRUCTION SEQUENCING TASKS

3.1 Publication Information

The text presented in this chapter was submitted for publication to the Journal Education Sciences under the title "Student Approaches to Element Sequencing Tasks in 2D and Augmented Reality Formats" and is awaiting peer feedback.

3.2 Abstract

In civil and construction engineering education research, a focus has been on using 3D models to support students' design comprehension. Despite this trend, the predominant mode of design communication in the industry relies on 2D plans and specifications, which typically supersede other modes of communication. Rather than focusing on the presentation of less common 3D content as an input to support students' understanding of a design, this paper explores more common 2D inputs, but compares different visualization formats of student output in two educational interventions. In the first intervention, students document a construction sequence for wood-framed elements in a 2D worksheet format. In the second, students work with the same wood-framed design, but document their sequence through an augmented reality (AR) format where their physical interactions move full-scale virtual elements as if they were physically constructing the wood frame. Student approaches and

performance were analyzed using qualitative attribute coding of video, audio, and written documentation of the student experience. Overall, results showed that the 2D worksheet format was simple to implement and was not mentally demanding to complete, but often corresponded with a lack of critical checks and a lack of mistake recognition from the students. The AR approach challenged students more in terms of cognitive load and completion rates but showed potential for facilitating mistake recognition and self-remediation through visualization. These results suggest that when students are tasked with conceptualizing construction sequences from 2D documentation, the cognitive challenges associated with documenting a sequence in AR may support their recognition of their own mistakes in ways that may not be effectively supported through 2D documentation as an output for documenting and planning a construction sequence. The results presented in this paper provide insights on student tendencies, behaviors, and perceptions related to defining construction sequences from 2D documentation in order for educators to make informed decisions regarding the use of similar learning activities to prepare their students for understanding the 2D design documents used in industry.

3.3 Introduction

Accurately understanding a building design is critical for making effective decisions. The Architecture, Engineering, and Construction (AEC) domains require teams of professionals to collaborate to effectively design and build infrastructure. This collaboration has traditionally involved communication of complex three-dimensional (3D) concepts using two-dimensional (2D) plans (i.e., “blueprints”). This 2D mode of communication has been used for hundreds of years and continues to be used as the format for contractual deliverables to enable stakeholder communication (Babič and Rebolj, 2016; Gould and Joyce, 2013; Sears *et al.*, 2018).

Recently, educational researchers have focused on how 3D modes of communication can lead to effective design comprehension by construction students. Some have explored using emerging visualization tools such as augmented reality (AR) as resources for performing various construction-related tasks (Chalhoub *et al.*, 2021). Augmented reality is “any case in which an otherwise real environment is "augmented" by means of virtual (computer graphic) objects” (Milgram and Kishino, 1994). Some have even compared student performance between 2D and AR conditions, where users relied on one modality or the other as a design resource for performing construction-related tasks (Chen *et al.*, 2011). Others have explored the advantages of enhancing 2D documentation with AR content for field-based tasks with industry practitioners (Foroughi Sabzevar *et al.*, 2021). These studies illustrate some of the ways that AR may offer benefits compared with 2D documentation to support design comprehension, but they focus on the use of AR as an input or resource to support this understanding. In this paper, an activity ‘input’ is any resource provided to inform a student’s under-standing of a design concept and an ‘output’ is the resultant product that students deliver upon completion of the activity. In this case, the output constitutes the student’s defined means of creating and documenting their actual construction sequence.

This study focuses on student behaviors and perceptions when given 2D plans as a design input or resource used to define a sequence for each piece of wood required to construct a section of a wood-framed wall. In this study, each intervention explores a different mode of visualization output that students may use to see the results of their process: either a 2D worksheet (Intervention 1); or an AR-based model (Intervention

2). While 2D materials are common classroom educational tools, AR is an emerging tool that is much less commonly used and has not been the subject of extensive study in a classroom context. This work identifies ways in which students' construction sequencing processes and perceived experiences compare and contrast when they view their defined processes in these differing formats, leading to the following research questions:

- RQ1: What behaviors and perceptions do students exhibit that indicate learning when utilizing 2D documentation as an input to perform element sequencing activities in a 2D output format?
- RQ2: What behaviors and perceptions do students exhibit that indicate learning when utilizing 2D documentation as an input to perform element sequencing activities in an AR output format?
- RQ3: What comparisons regarding potential impact on student learning can be drawn between using 2D and AR learning formats for defining construction sequences based on 2D documentation?

The unique contribution of this work is to provide context to the broader learning community of educators who are considering leveraging various modalities to teach relevant construction skills. While several modalities could be considered as outputs for the student work, 2D was chosen to replicate a typical classroom situation and AR was chosen to explore an emerging technological tool with the potential to bring authentic, active learning into the classroom. While 4D BIM is another realistic tool that could be considered as an alternative to 2D worksheets, AR was favored because it more closely mimics kind of experiences that may happen on an actual jobsite, introducing aspects of authentic learning like movement and physicality that are not facilitated in other methods. Presenting the task virtually through AR and not physically with real materials was chosen to explore the viability of AR as a low-cost, reusable alternative to using and discarding real construction materials. The results presented here provide insights to allow more informed decision making when considering AR and 2D methods for teaching construction sequencing tasks based on 2D documentation.

3.4 Literature Review

Building information modeling (BIM) and other advanced 3D visualization tools have become increasingly common in the construction industry (Kamat *et al.*, 2011). Advanced immersive visualization techniques, such as virtual reality (VR) or AR, have been proposed to complement 3D modeling (Sampaio *et al.*, 2010) and help in the visualization process, such as for assembly tasks (Chalhoub and Ayer, 2018) or for enhancing spatial cognition in construction practitioners (Alruwaythi and Goodrum, 2019; Goodrum *et al.*, 2016). Much of the literature discussing visualization of construction documentation explores the possibilities of advanced technology such as mixed reality, with the assumption that these more interactive models offer superior features, such as flexibility and communication clarity (Hamzeh *et al.*, 2019). Overall, interest in 3D advanced visualization tools is seeing a steady increase in the AEC domains.

In addition to exploring 3D and more immersive modalities, some researchers have looked at ways to leverage traditional 2D drawings, exploring ways to facilitate the process of drawing interpretation, such as using AR as a supplement to traditional drawings (Foroughi Sabzevar *et al.*, 2021; Côté *et al.*, 2014). Other researchers have explored the conversion of 2D drawings into 3D models with varying levels of automation (Gimenez *et al.*, 2015; Horna *et al.*, 2007; Lewis and Séquin, 1998; Ruwanthika *et al.*, 2017; So *et al.*, 1998; Yin *et al.*, 2019). These works focus on the relationship between 2D and 3D documentation, but not necessarily on the impacts to the users or their learning.

In addition to industry-based research, extensive research has gone into exploring the integration of BIM in higher education (Wang *et al.*, 2020). Other research has aimed to identify the best approach to incorporating BIM into the construction engineering curriculum, comparing 3D to 4D and 5D (Lee *et al.*, 2013). These advanced, and 3D, modes of communication have been shown to support learning gains such as increasing participation, interaction, and motivation (Wang *et al.*, 2018a), and teaching specific skills and competencies (Wang *et al.*, 2020; Abdirad and Dossick, 2016). Many studies have explored the use of emerging visualization technologies like AR as resources for helping students learn or demonstrate skills, with some researching AR alone, and others comparing AR performance with 2D resources. For example, researchers have studied how AR as an input can affect spatial reasoning (Chen *et al.*, 2011), cognitive load (Dadi *et al.*, 2014), deviation detection (Chalhoub *et al.*, 2021), and drawing interpretation (Foroughi Sabzevar *et al.*, 2021). These studies explored AR as an input to support users' design comprehension rather than an output, or a means of design creation for those users. This work departs from these prior studies by utilizing AR as the means by which students experience the process of visualizing their construction sequence outputs, based on their understanding of traditional, 2D documentation for design information.

Other construction-adjacent fields, such as architectural design, have begun producing research that indicates value in exploring AR and 2D as outputs. In this field, researchers have compared virtual reality and paper-based design as educational design tools, finding that the virtual environment led to higher enjoyability and likelihood of use (Özgen *et al.*, 2021). In another study comparing AR and 2D, researchers explored differences between students completing a 2D design activity and an activity based in AR and found that enjoyment and interest levels were similar between the two formats, but the 2D activity led to design fixation (Ayer *et al.*, 2016). These prior works demonstrate how AR outputs can impact students' learning processes in design contexts, but a similar study is missing from the literature for construction contexts.

The prior works presented in this section illustrate the range of studies that have been related to 2D and 3D documentation, and their role in supporting students in AEC domains. Many studies explore the use of 3D modes of communication as inputs to provide to students to support their design comprehension in order to complete a learning task, but far fewer studies explore how 3D mixed reality modes of communication as outputs may impact students' learning. The studies that do explore how 3D mixed reality learning outputs impact students' behavior focus on learning related to design, not construction. Given the need for construction professionals to be able to define effective construction sequences, and also the prevalence of 2D documentation in the construction industry, a better understanding of how 2D and 3D outputs impact student learning based on traditional 2D inputs would enable educators to purposefully use these tools to prepare their students for success.

3.5 Materials and Methods

3.5.1 Overview

This paper presents a study, where students utilize 2D design documentation to determine the element sequencing of wood studs within a wall section. In this exploratory, uncontrolled experiment, two groups of students participated in an intervention, with the first group of students documenting their results on a 2D worksheet, and the other group in AR. The task was selected to resemble a type of carpentry work that is common on jobsites. The scope of the design was limited to a single section of wall to enable participants to understand and perform the task within a single session and within one hour. An elevation view from the 2D documentation provided to students is shown in Figure 8, and the other drawings are included in the Appendix.

Both interventions studied began with a pre-activity survey that targeted students' prior experience and demographic information. Then students were tasked with interpreting the 2D documents provided in order define a construction sequence in either a worksheet or AR. After completing the sequencing activity, students were asked to complete a post-activity survey to understand their perceptions of their performance. The processes involved in this work are displayed in Figure 9.

Participation in these learning exercises was offered as extra credit for a construction course and took place over two years, with Intervention 1 (2D Output) implemented first and Intervention 2 (AR Output) implemented the following year. Both interventions were impacted by the COVID-19 pandemic, which necessitated some form of videoconferencing for supporting interactions between student partici-

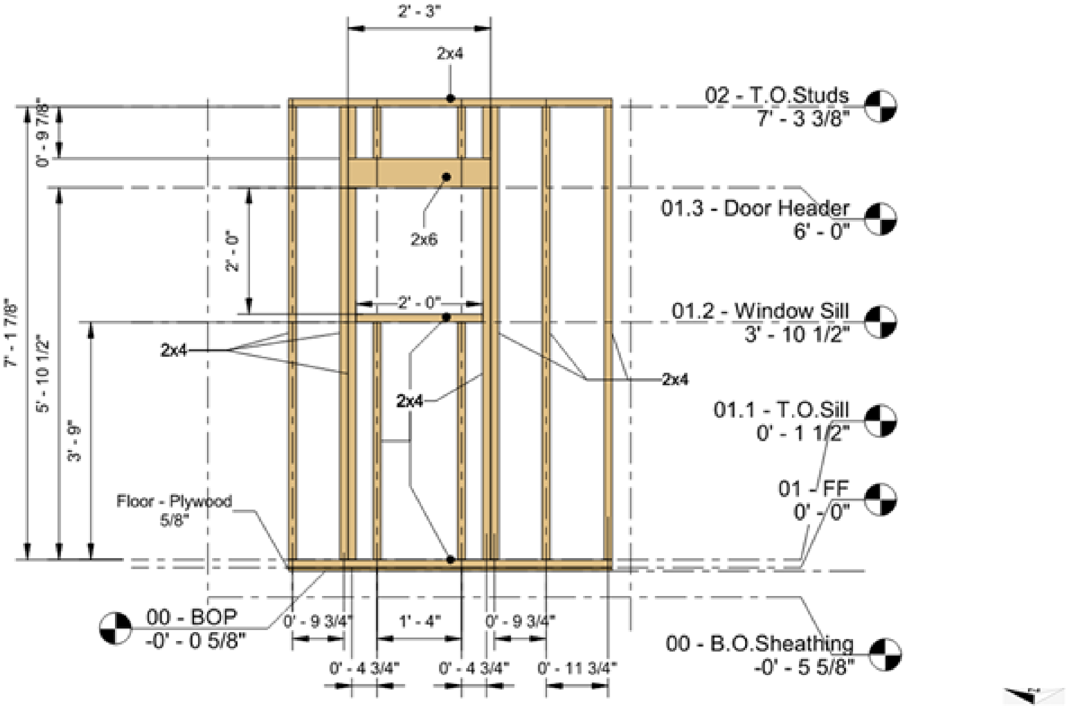


Figure 8. Example of One of the Drawing Sheets Provided to Students: A Window Elevation View of the Framed Wall. See Appendix for the Full Set of Drawings.

pants and researchers. Intervention 1 involved students defining their construction sequences on a 2D worksheet via a videoconferencing and screen-sharing application. Intervention 2 involved students defining their construction sequences while using the head-mounted AR device alone in a room on campus with a researcher interacting via videoconferencing, in accordance with health and safety restrictions.

3.5.2 Pre–Activity Survey and Reception of Design Documentation

Before completing the activity, students in either intervention took a survey that collected demographic information and asked them to evaluate their skill level regarding

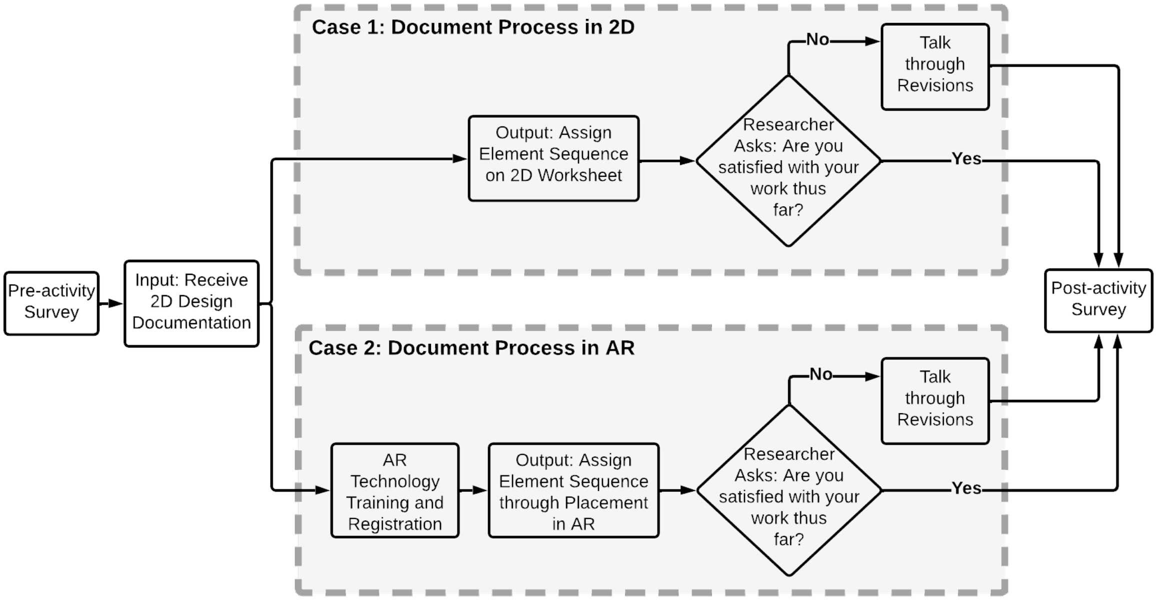
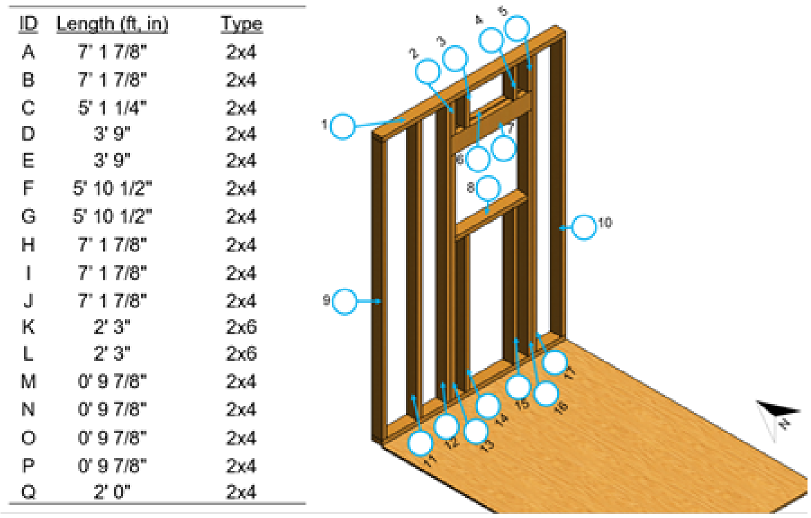


Figure 9. Flowchart Outlining the Steps Involved in the Two Learning Activities.

various wood framing related tasks on a 5-point Likert scale. The skills students were asked to self-evaluate included:

- Understand design and construction documents
- Find information (sizes and dimensions) on design and construction documents
- Decide on means and methods for installing a structure based on the documents
- Define a sequence for installing wood framing components
- Install wood framing components correctly

After the pre–activity survey, students were given the set of drawings shown in Figure 8 and the appendix, and then instructed on what to do for each of the activities.



ID	Length (ft, in)	Type
A	7' 1 7/8"	2x4
B	7' 1 7/8"	2x4
C	5' 1 1/4"	2x4
D	3' 9"	2x4
E	3' 9"	2x4
F	5' 10 1/2"	2x4
G	5' 10 1/2"	2x4
H	7' 1 7/8"	2x4
I	7' 1 7/8"	2x4
J	7' 1 7/8"	2x4
K	2' 3"	2x6
L	2' 3"	2x6
M	0' 9 7/8"	2x4
N	0' 9 7/8"	2x4
O	0' 9 7/8"	2x4
P	0' 9 7/8"	2x4
Q	2' 0"	2x4

Figure 10. The Worksheet where Students Assigned Items on a List of Pre-Cut Wood Studs (Left) to the Numbered Spaces on an Isometric View of the Completed Wall (Right).

3.5.3 Intervention 1: Construction Sequence Documented Via 2D Worksheet

Students were given a worksheet and told that the drawings corresponded to the design on the worksheet, which contained a list of pre–cut lengths of wood and an isometric view of the built wall, with empty spaces for assigning the pre–cut pieces (Figure 10). For the students to know the lengths of the pieces on the worksheet, they needed to cross reference the design drawings. They were asked to verbalize their sequence, think aloud about their process, and annotate the page if they wanted to keep track of any relevant decisions or notes. After completing the sequence, they were asked if they were satisfied with their work and given the opportunity to make any changes.

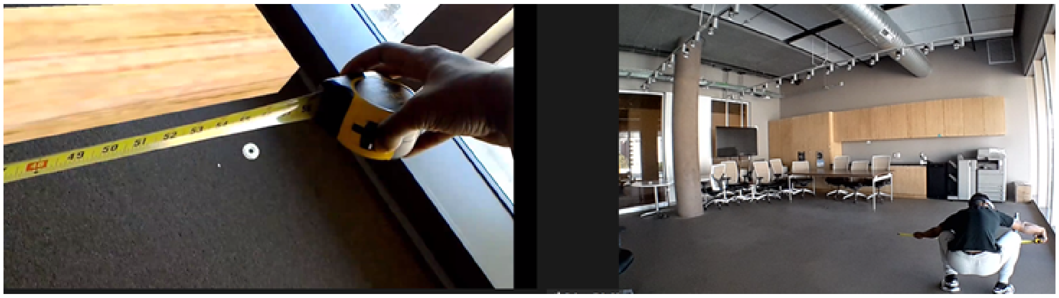


Figure 11. (Left) A Piece of Virtual Wood Being Measured with a Physical Measuring Tape and (Right) a Third Person View of the Student Measuring the Virtual Wood (the Wood is Not Visible Unless Wearing the AR Device)

3.5.4 Intervention 2: Construction Sequence Documented Via AR

For the AR experience, an application was developed utilizing both physical and virtual resources, as shown in Figure 11. All wood components were presented to the students virtually through AR via a Microsoft HoloLens 1. The wall model was designed in Revit and the components were imported into Unity. Scripts within Unity were designed to enable users to move pieces with hand gestures and install them with voice commands.

Students were instructed on how to wear and use the AR device by the researchers who joined via videoconferencing. Students were guided through the process of opening the application, registering AR content in the room, and interacting with virtual building materials. More specifically, the researchers instructed the students on how to measure the virtual floor plate using a physical measuring tape and verify that it matched the design dimensions, then move it to its appropriate location with a hand gesture, and install it with a voice command. This training enabled students to successfully learn and demonstrate each technological interaction that would be required during the AR construction process. As they participated in the training, students were aware of the upcoming task and how these actions would prepare them for their anticipated task.

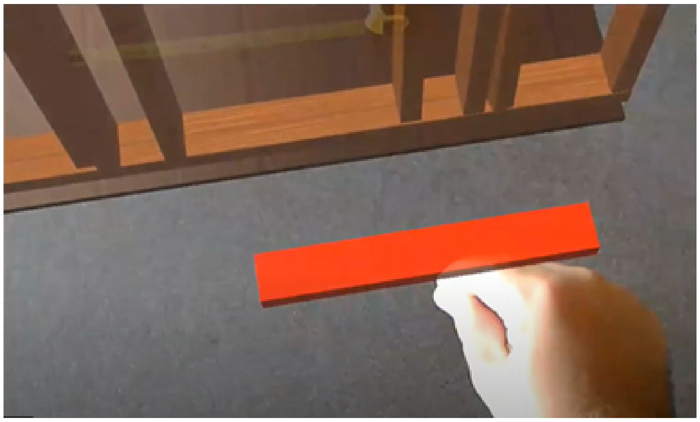


Figure 12. A Student Moving a Piece of Virtual Wood Toward a Partially Assembled Wall.

After the AR training was completed, students were tasked with defining a construction sequence for the virtual wall elements to correspond with the drawings (See Figure 12). After the placement of the initial piece during training, the researchers allowed students to complete the activity on their own and did not provide any guidance to the students on how to read or otherwise interpret the 2D documents provided to them for completing the construction sequencing task. To complete the task, students relied on the provided set of 2D drawings, a measuring tape, and a pen to mark the drawings. Additionally, students could access a virtual array of wood laid on the ground. The virtual building materials were not placed in any particular order, similar to how materials are often found on real construction sites. As students completed the construction sequencing task, they were asked to think out loud during their process. Each student had one hour to complete the task. When only 10 minutes remained, the researcher stopped the students and asked them if they felt that the work they completed was correct thus far. At this point, students were also asked if they believed that their progress thus far was done correctly and given the opportunity to explain any changes they might make if they had more time to build.

3.5.5 Post-Activity Survey

After students indicated satisfaction with their construction sequence in either of the interventions, all students were provided with a post-activity survey to reflect on the process. They were asked about the cognitive load of the activity using a selection of questions derived from the NASA-TLX questionnaire (Hart and Staveland, 1988) including their mental demand, their level of frustration, and their perceived success in the activity. In the second part of the survey, students were also asked open-ended questions for each activity. For the worksheet activity, they were shown a video demonstrating use of the AR activity tested in Intervention 2 and asked to think about the worksheet activity they did, then about the AR activity they saw, and to reflect on how they think their experience and process might differ if they performed the same activity in the other environment. For the AR activity, they were asked an open-ended reflection question regarding what they learned from the virtual building experience.

3.5.6 Analysis

The pre- and post- survey responses were saved and the students' behaviors and performance were observed in situ and video and audio recorded for later analysis in accordance with the Institutional Review Board (IRB) approval[2]. The survey results, open-ended question answers, and video recordings served as the basis for analysis. Following models of qualitative coding from similar studies in this domain (Hartless *et al.*, 2020), a triangulation of participant think-aloud statements, survey responses, and researcher observations provided an understanding of the overall experience. The videos were coded using qualitative descriptive and attribute coding with the method outlined by Miles, Huberman, and Saldaña (Miles *et al.*, 2014). During this process, a series of codes or descriptors are developed that help in extracting meaning from participants' words, actions, and characteristics. Multiple researchers worked together on creating and validating the codes to ensure consistency in the process. For example, some codes that emerged in the 2D activity were 'length mistake' and 'visualization', where these referred to when students placed a wood piece of the wrong length, or mentioned visualization in their reflection. Then, these codes were considered together to see what patterns or meaning could be extracted from the experiences. For example, the 'length mistake' and 'visualization' were considered together in the thematic category of visualization difficulties. The major patterns that emerged through this process are described in the following section along with resulting descriptive statistics. Some basic statistical analyses are added to complement the qualitative analysis described above for the pre-activity questions regarding wood framing experience and the post-activity questions from the NASA-TLX survey regarding frustration, mental demand, and perceived success. An independent samples t-test was conducted for each of these parameters between the two groups, where the unit of analysis was the student response. Given the preliminary nature of these analyses and this study, we chose a smaller sample size that would focus on the qualitative aspects that emerged while still sufficiently meeting the qualification of normal distribution for an independent samples t-test. The statistical explorations were undertaken to augment the qualitative exploration that forms the basis of the paper.

3.6 Results and Discussion

3.6.1 Results of Intervention 1 (2D Output): Behaviors and Perceptions

3.6.1.1 Descriptive Statistics: Intervention 1 (2D Output)

The worksheet activity involved 38 undergraduate student participants with varying levels of experience in both school and industry. The dataset included 1 Freshman, 5 Sophomores, 15 Juniors, and 17 Seniors. Self-reported racial and ethnic backgrounds included the following: Black or African American = 1, Hispanic or Latino = 11, White = 23, Other = 2, Prefer Not to Answer = 1. Finally, 31 participants self-identified as male and 7 as female. Regarding wood framing abilities, the average self-rated scores for participants on 1-5 Likert scales were 3.8 for 'understand design and construction documents', 3.9 for 'find information such as sizes and dimensions on design and construction documents', 3.0 for 'decide on means and methods for installing a structure based on the documents', 3.3 for 'define a sequence for installing wood framing components', and 3.2 for 'install wood framing components correctly'.

3.6.1.2 Emergent Themes: Intervention 1 (2D Output)

The participant think-aloud statements and reflections are combined with researcher observations from the videos to identify components of the activity that may impact the potential for classroom implementation and learning and are presented thematically. Two major themes of interest emerged from the analysis of the student approaches and performance using the 2D worksheet format for outlining their sequencing process: Visualization Difficulties and Extemporaneous Approach.

Visualization Difficulties: In the 2D worksheet format, a common theme that emerged was visualization difficulties, where students struggled to maintain an accurate mental model of the process they were planning. One prominent indicator of visualization difficulties was mistakes made and left unfixed. A mistake in this context refers to when a student chose a piece from the schedule of materials and indicated their intention to place it in a specific labeled location where the item length did not match the dimension indicated by the drawings. It was observed that over half of the students (53%) made at least one mistake when determining their sequence.

Examples of commonly occurring mistakes include when students chose the wrong length for a vertical stud, when they selected the wrong dimension for the top plate, and when they selected the wrong type of piece for the double header, or did not realize there was a double header (see Appendix for drawings). For some of these mistake types (the top plate and the double header), the students would have to refer to the plan views in addition to the elevation view to obtain a complete understanding of the elements. The dimension of the top plate is indicated on all the plan views, but not on the elevation view. The size of stud for the double headers is 2"x6", where all other studs are 2"x4". This designation and the back-to-back placement of the double headers are only shown on the "Floor Plan-Header" view of the wall design. The visual representation of the double headers is partially occluded in the worksheet isometric view and fully occluded on the first sheet of drawings. While all drawing sheets were provided to students as a set, it appears that there was some difficulty in utilizing all drawings together, evidenced by the abundance of errors on the worksheet. Difficulty accessing information that can only be found by accessing multiple drawing sheets has been reported as a potential issue even for industry practitioners (Foroughi Sabzevar *et al.*, 2021), and this issue seems to be fully present in student learners when using a 2D visualization format. While some students eventually corrected their mistakes during the process or in their final review, they still noted visualization difficulties in the process. Furthermore, more than half of the students who made mistakes (29% overall) finished the exercise with at least one error remaining unfixed and unrecognized upon completion.

In the activity reflection, where students discussed how their process might differ if they performed the AR task, visualization difficulties were a common theme. In fact, 29% of students mentioned visualization challenges in their reflections. Many suggested that keeping track of pieces and installation order was difficult. For example, one student said "on paper it was hard to remember what I had put in place and what was still in the lay down" providing evidence that keeping track of an updated mental model of the defined construction sequence was a challenge for students. Many students also recognized their own propensity for making mistakes in the 2D worksheet format, suggesting that in AR, "I would be able to see the errors I was making instead of guessing if I was on the right path" and that "I would physically be able to install each piece and see where it goes. I would also be able to visualize where I made a mistake and why I made that mistake. This would be able to provide immediate feedback." One student summarized their perceptions on the struggles of the 2D worksheet and the potential for AR using their personal industry experience as a factor, stating "With an augmented reality experience the activity would be much less conceptual. Without the experience I have in architecture and construction it would have been difficult to correctly identify which pieces go where in the activity as well as what order to install them in. The augmented reality allows you to have a hands-on experience and visualize the construction process which is incredibly useful when learning about construction." These comments and ideas principally served to illuminate the difficulties students had in forming and updating mental models, but also provide ideas of what themes and evidences may emerge in the AR intervention.

Extemporaneous Approach: Most students who completed this exercise did so quickly, and typically without second-guessing or making critical checks. Notably, all students completed the activity well within the allotted timeframe. The average time students spent actively completing the activity was 9 min 8 sec, with a range from 2 min 47 sec to 21 min 40 sec. Considering the average time and the fact that all students placed all pieces, the average time spent per piece was 32 seconds. The high speed of completion provided extra time for students to reflect, identify errors, or fix mistakes, but despite this time, no students revised their final sequence when provided the opportunity. This may indicate either low ownership in the task, high confidence in the correctness of their selections, or the inability to identify their mistakes. Based on post-activity survey data, this decision was likely tied to high confidence, with most students perceiving their work as highly successful, regardless of errors (Figure 14). For example, one student—who still had mistakes in their process—when given the opportunity to review and revise their work, either did not notice or decided not to change the errors and stated "I think I'm good." In addition to the speed and lack of revision, the researchers noted that most students did not reach out during the process to ask questions, choosing to complete the task independently, even though the facilitator was available at all times. Even among industry practitioners, failure to make "critical checks" and to pay attention to details (Varma, 2008) has been reported as a challenge with traditional documentation and 2D formats, and these results provide evidence that a 2D output does not remedy these challenges.

Based on Thorndike's 'trial and error' theory of learning, learners are motivated to continue performing actions that lead to success and avoid actions that lead to failure (Thorndike, 1927), suggesting, as many researchers have since, that there is value in encountering and learning from failures (Pozzi *et al.*, 2015). This is only possible when learners understand when they are succeeding or failing, and this 2D worksheet approach did not provide evidence to suggest the self-awareness that leads to valuable learning.

3.6.2 Results of Intervention 2 (AR Output): Behaviors and Perceptions

3.6.2.1 Descriptive Statistics: Intervention 2 (AR Output)

A total of 15 undergraduate student participants successfully participated in the outlined protocol, including 2 Sophomores, 10 Juniors, and 3 Seniors. The racial and ethnic responses to the survey included American Indian or Alaska Native = 1, Asian = 2, Black or African American = 2, Hispanic or Latino = 3, White = 6, Prefer Not to Answer = 1. The self-identified genders of the students included 12 male and 3 female. Regarding wood framing abilities, the average self-rated scores for participants on 1-5 Likert scales were 3.7 for 'understand design and construction documents', 3.9 for 'find information such as sizes and dimensions on design and construction documents', 3.0 for 'decide on means and methods for installing a structure based on the documents', 3.2 for 'define a sequence for installing wood framing components', and 3.1 for 'install wood framing components correctly'. Notably, these averages were very similar to the average abilities reported by the group involved in Intervention

1 (2D Output), with no statistical difference in any of the categories in independent samples t-tests, demonstrating comparability between the two samples.

3.6.2.2 Emergent Themes: Intervention 2 (AR Output)

The two major thematic categories that emerged regarded the approach and the visualization process, with students exhibiting a more self-regulated approach in AR and with evidence that this format facilitates critical checks through a virtual model that students self-update as they build, aiding in the formation of a mental model.

Visualization: From the observational data, it was noted that the AR process seemed to facilitate student visualization in order for them to recognize and fix their mistakes. For example, one participant placed a stud on the wrong side of one they had already placed. When the participant reviewed the piece compared to the drawings, the individual immediately recognized and fixed the issue, stating "I accidentally installed the wrong piece... so I had to uninstall and move it. I should have measured first, but I didn't". This comment illustrates a lesson learned by this student, recognizing an error in their process that could potentially inform future work. Other students made similar length errors and corrected them, either by gazing at pieces they had already placed that showed a mismatch in length or by comparing their built model with the paper plans (Figure 13). In addition to recognizing mistakes made during the process, some also recognized mistakes at the end of their building time while evaluating everything they had built. For example, one participant, when asked if they were satisfied, said that they noticed a stud they had placed was not the correct length. The vast majority of students in Intervention 2 (AR Output) recognized their mistakes at some point in the process, with only one student (7%)

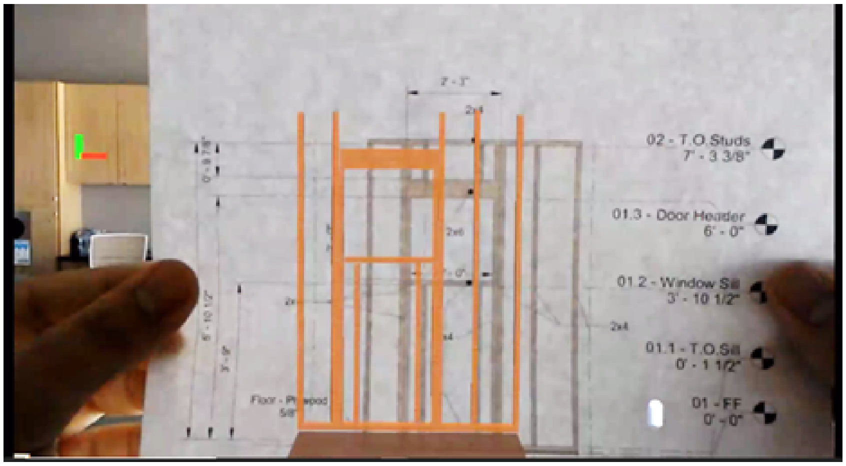


Figure 13. A Student Compares the Paper Elevation View Drawing With Their Partially Constructed Virtual Wall.

leaving unrecognized length errors. Two students (13%) left the exercise with one or two pieces rotated incorrectly, which should be noted but cannot be compared to the mistakes made in the worksheet (Intervention 1) since orientation was unchangeable in the 2D format.

In addition to inferential evidence of visualization enabling mistake recognition, students also made comments regarding how the activity explicitly enabled learning through visualization. One student suggested that this activity may have direct real-life applicability, stating “I learned what it looks like to frame a wall. . . I learned that the process is a lot easier to understand with all of the moving pieces in front of me. Seeing the moving parts with the plans all together made the whole thing make more sense. I can actually picture in my head what those plans would make in real life, and have a better picture of how I would go about developing those plans.” Others made comments suggesting the potential for this modality to help teach lessons with impact outside the classroom, such as the student who remarked that they “learned to expect challenges” and another who said that their confidence “really did improve” through the process. These findings align with John Dewey's 'learn by doing' theory, which states "we learn only because after the act is performed we note results which we had not noted before" (Dewey, 1916), meaning that when students see and understand their performance, how they achieved those results is solidified in their learning.

Self-regulated Approach: The students took a much slower, more methodical, approach to completing the activity in an AR format, likely facilitated by the nature of the interface. In this activity, most of the students did not finish placing all pieces of the wall. Some got close, with one student placing all but the top plate and the plywood backing, while a few spent their time organizing and moving the pieces, but never actually installed any. Notably, the time needed for setup and registration process varied between students, which determined the amount of time available for active material placement. To objectively understand the rate at which students actively built, the average amount of time spent placing each piece during active building was calculated, resulting in an average of 3 min 26 second taken per piece placed. This average is notably higher than the 32 seconds per piece from Intervention 1 (2D Output). It is important to note that while both interventions similarly required the students to verify dimensions of existing pieces and to assign a construction order to these pieces, the mechanism for doing so is different between the two. Verbalizing and/or writing a series of numbers is different from physically having to move each one into place. Therefore, the comparison of time per piece is not intended as a measure of which task is superior or inferior, rather to provide a descriptive understanding of the difference between the two experiences.

In addition to the speed of the activity, it was noted that many students exhibited a pattern of referencing their resources. For example, many took the time to check the drawings multiple times throughout their process. Many also measured each piece before placing it, with some even taking the time to verify the measurements of pieces after installation. Even students who did not get close to finishing had the potential to study and utilize the 2D documentation, with some mentioning learning gains like a student who stated that the activity "helped me understand a lot about building plans that wasn't clear before. I think I learned more about reading drawings with this experiment [than] even the physical building process." They mentioned how physically moving the pieces into place while looking at the drawings helped them understand the drawings better, even though they only had time to place a few pieces.

In addition to leveraging physical resources, many students took the opportunity to ask questions to the facilitator, some of which related to the process of framing a wall, with students sometimes asking the facilitator if their work was correct thus far or asking for help reading dimensions on the drawings. While the researcher did not intervene to answer specific questions that would positively or negatively impact the students' processes during the activity, their interest in asking these types of questions suggest engagement with the task.

These behaviors point to the potential for learning based on both Thorndike's 'trial and error' theory of learning and Dewey's 'learn by doing' theory. Although considered opposing theorists on some aspects of educational reform (Gibboney, 2006), elements of both Thorndike and Dewey's learning theories persist in some forms today and motivate work in experiential learning. For either approach, the potential to impact student learning is predicated on students' abilities to identify success and errors by understanding output, which leads to a refinement of their behavioral inputs. In other words, it is important for students to have an opportunity to act for themselves, have successes or make mistakes, and recognize those successes or mistakes. The results from this study provided evidence that these critical checks are facilitated through the 2D input and AR output student experience.

3.6.3 Cross-Intervention Analysis and Discussion

The thematic analysis illustrated differences in students' abilities to visualize and detect mistakes as well as distinct approaches to each task. In addition to the thematic analysis, the post-activity survey answers to the cognitive load (based on NASA TLX questions and scaling detailed in the methods section) and performance-related questions give further insight into these differences, including mental demand, frustration, and perceived success. Figure 14 presents these results for the two interventions graphically, side-by-side.

For Intervention 1 (2D Output) students rated their mental demand at 2.8 on average (0-7 scale) and their frustration at an average of 1.7 (0-7 scale), which are both well below the midpoint of the scale. These results suggest that students perceived the task to be easy and not frustrating to complete, despite mixed actual success. For the AR activity, mental demand was rated at an average of 3.7—just above the midpoint—and frustration at an average of 3.2—just below the midpoint. In both measures, the ratings were higher for AR, suggesting that this activity requires more effort and engagement from students in terms of thinking and overcoming frustrating challenges. Some of the frustration could be due to using and learning a new technology, while some might be attributed to the challenges of the sequencing task itself, and this study does not claim to control for these differences, only noting that the overall AR experience presented higher frustration to students than the 2D worksheet counterpart. For both measures, the differences between the two interventions were significant

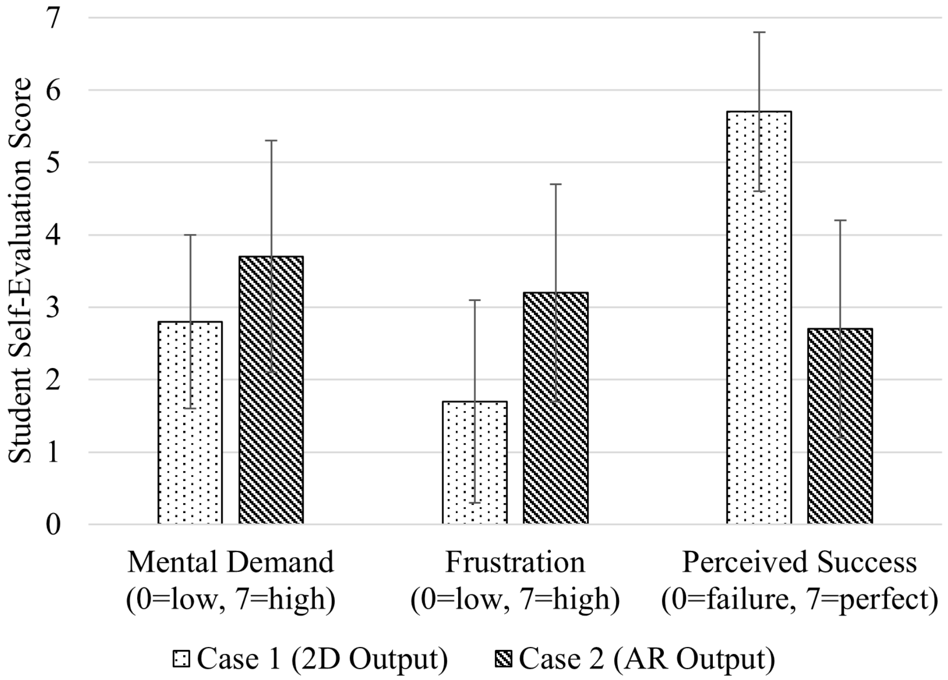


Figure 14. Post-Activity Survey Results of Student Self-Evaluations Regarding the Mental Demand, Frustration, and Perceived Success of the 2D Worksheet Activity (n=38) and the AR Experience (n=15), with Averages Shown by the Solid Bar Values and Standard Deviations Presented with the Error Bars.

($p<0.05$ for mental demand, $p<0.01$ for frustration) using an independent samples t-test. All variables met the assumption of normality needed to run this statistical analysis (skew < 1 for all variables involved).

Regarding students' perceived success on the activities, the average rating for the worksheet activity was 5.7 on a 0-7 scale. Interestingly, this score was very similar for students who finished the activity with an unresolved mistake (5.6) and those who finished the activity with no apparent mistakes (5.7), which offers further evidence to indicate that this method may not be ideal for students to engage in trial and error learning, since recognizing mistakes is critical to that process. On the other hand, students in the AR activity rated their success at an average of

2.7 on a 0-7 scale, indicating much lower satisfaction with their performance. It is hypothesized that both an awareness of mistakes and not finishing the activity both may have contributed to the low success rating. The difference in perceived success between the two interventions is statistically significant ($p<0.001$) using an independent samples t-test. Perceived success approximates confidence in a task, and confidence in graduating students is an asset, but perhaps just as important is knowing where knowledge falls short. Often, educators only look at success scaffolding, but failure scaffolding—intentionally exposing students to failure in the learning process—is an emerging research area that may be just as critical to truly internalizing lessons and using that knowledge in meaningful ways in the future Sinha and Kapur (2021). Using an AR output to help students conceptualize construction sequencing processes from 2D plans may support this process. These activities utilized minimal instructor involvement after initial instruction, a situation often used by design to promote independent learning (Gonzalez and Gilbert, 1980; Shah *et al.*, 2020). When working independently, students encounter both successes and errors and ideally learn from both. As foundational educational theorist Dewey stated, "by doing" an activity, the student "becomes familiar with its methods" and "acquires needed skill" (Dewey, 1916). The AR activity emerged as the learning environment that facilitated the performance awareness that allowed students to demonstrate high potential for learning by doing.

The survey results align with the approaches that were observed in the thematic analysis, with students approaching the 2D worksheet with speed and confidence, which aligns with the low mental demand, low frustration, and high perceived success of the survey. On the other hand, the higher mental demand and frustration and lower perceived success during the AR activity aligns with the more careful, deliberate, and time-consuming approach that was demonstrated in that activity.

3.7 Conclusions

From analysis of each of the two interventions explored, the emergent themes illustrated aspects of student performance that differed using each visualization mode as an output for documenting their work. The students who documented their construction sequences using the 2D worksheet completed the activity very quickly, but did not generally pay attention to dimensional details or make critical checks for errors. On the other hand, the students who documented their sequences using AR struggled much more while completing the activity, but demonstrated more propensity for critical checks, mistake recognition, and self-reflection during their process. Therefore, even though AR was slower and deemed to be more challenging by the students, the results suggest that AR has high potential to replicate some of the behaviors that make hands-on learning beneficial to students.

While the findings of this research are logical, based on the differences in the experiences provided to students, the approach taken by the authors to use AR as an output for student thought remains uncommon. Instead, most prior works in this domain focus on the use of AR as an input to support students' comprehension of a design concept. The approach used in this work illustrates ways in which documenting a construction sequence in an AR output can help students to recognize and fix their own mistakes in ways that may not be realistic to expect through 2D outputs. This may be an especially relevant skillset to develop through an AR, or otherwise virtual, mode of communication as long as comprehension of 2D documentation continues to be expected of students when they enter the construction industry, and also while the high cost of physical materials would prohibit most students from being able to physically construct a wall like the one incorporated in this research. As a result, the contribution of this work is in presenting findings that illustrate the opportunities, and potential challenges, related to using AR as an output to challenge students to produce valid construction sequences based on common 2D modes of design communication.

Chapter 4

EXPLORING AR AS A SIMULATION OF AUTHENTIC LEARNING EXPERIENCES

4.1 Publication Information

The text presented in this chapter is in the final stages of internal review and will be submitted for publication to the Journal of Architectural engineering under the title "Simulating Authentic Learning through Augmented Reality Hands-On Building Assessment and Construction".

4.2 Abstract

As educators in Architecture, Engineering, and Construction (AEC) domains seek to better prepare graduates for industry, one of the most effective ways to do this is by providing authentic, hands-on design and construction experiences. However, providing access to these experiences is costly, time consuming, and resource-intensive, which limits access to most students. To explore a cost-effective alternative to hands-on AEC learning, augmented reality is presented as a simulation of authentic learning in these domains. A full-scale design and construction experience is presented where students virtually perform design analysis, planning, and construction of renovations to an existing structure in an augmented reality environment. As students participated in the simulation, they reflected on their process and the realism of the experience. Student behaviors and perceptions were analyzed to determine where the experience

showed evidence of authentic learning characteristics and where the experience differed from traditional authentic learning. Ultimately, the experience showed strong evidence of promoting higher-level thinking and mixed results on which components of the experience felt realistic or unrealistic. These findings suggest that augmented reality has high potential to simulate authentic learning and lead to high-value evidence-based learning outcomes. Educators may find these results useful in considering augmented reality as a tool for simulating authentic learning in AEC or other fields where true authentic environments are not readily available.

4.3 Introduction

The Architecture, Engineering, and Construction (AEC) domains are currently struggling with a labor shortage (Kim *et al.*, 2020) while simultaneously grappling with a failing existing infrastructure (American Society of Civil Engineers, 2021). Historically, industry professionals developed their expertise over years of construction experience, but in order to fill the labor shortage, it is no longer possible to wait for new professionals to gain this experience. These circumstances necessitate better and faster preparation of students pursuing careers in these fields to address these societal needs. Thus, it becomes critical to understand the ways in which educators can effectively teach students the processes involved with construction. Authentic learning experiences provide ideal environments for developing understandings of actual construction processes because they situate learners in real-life contexts. In fact, having hands-on or project experience prior to graduation is one of the attributes most demanded by industry professionals (McCord *et al.*, 2021). An example of an authentic learning task is the Department of Energy's (DOE) Solar Decathlon, which tasks student teams with designing and building energy-efficient tiny homes. However, access to learning experiences like these is limited to very few universities and students. For example, in the most recent version of this biennial competition, teams of around 25 students from 6 U.S. Universities participated in the build challenge (US Department of Energy, 2020), a very small number compared to the over 15,000 graduates reported by ASEE in civil, construction, and architectural engineering disciplines in 2021 alone (American Society for Engineering Education, 2021). While internships can provide students with valuable experience and knowledge in a specialized area, there are few opportunities to take ownership of the entire design and construction process as a student and often student interns are not provided opportunities to make impactful decisions because of the high cost of failure (money, time, lives) in practice. Providing students with holistic design and construction experiences often requires prohibitive amounts of time, money, and other resources (US Department of Energy, 2009). Since authentic learning experiences like these can address many industry needs, but access within AEC domains is so limited, there is a need to explore alternative approaches to providing this type of learning for students.

Augmented reality (AR) may offer the opportunity to simulate a high-value authentic learning without many of the high costs and storage requirements for physical construction materials. Augmented reality displays virtual objects superimposed on a physical environment (Milgram and Kishino, 1994). Since AR uniquely allows the blending of virtual content with physical content, it enables researchers to purposefully incorporate physical and virtual elements, based on available resources. In this work, the authors provide undergraduate construction management students with an AR learning experience that challenges them to make design and construction decisions related to a simple play structure that requires renovations. The authors strategically incorporate physical elements into the activity where costs are low (i.e., drawings and measuring tapes), and virtual elements into the activity where costs would be prohibitive (i.e., the built structure and additional building materials). The value of this work is in providing an example of simulated AR authentic learning with analysis of student behaviors and perceptions when participating in the simulation. To determine the educational value of this proposed technology, it is important to understand where it can replicate established critical components of authentic learning components and where it may differ. This study addresses the following research questions:

1. What behaviors and perceptions emerge from student experiences in an AR simulation of hands-on learning that parallel factors from authentic learning theory?
2. What behaviors and perceptions emerge from student experiences in an AR simulation of hands-on learning that do not parallel factors from authentic learning theory?

4.4 Background

4.4.1 Augmented Reality for Hands-On AEC Education

Augmented Reality is gaining momentum in the AEC industries in both field and training contexts (Noghabaei *et al.*, 2020). Within AEC education specifically, researchers have begun to explore the use of AR in various learning contexts. Some have explored mobile AR to augment textbook curricula with supplementary demonstrations and visuals (Shirazi and Behzadan, 2015). Others have explored using AR visualizations to provide visual cues for developing spatial skills (Kim and Irizarry, 2021) or for aiding in the interpretation of 2D plans (Wen *et al.*, 2021). Researchers have also explored mobile AR with movable, interactive elements, such as teaching structural analysis where students interact with the tool by adjusting settings on a sample model and observing structural changes (Turkan *et al.*, 2017). The authors previously explored the utilization of head-mounted AR for teaching element sequencing using a full-scale wood-framing application (McCord *et al.*, 2022). While AR has been explored as a visual and interactive supplement to curriculum, it has not yet been explored as a simulation of authentic learning in design and construction processes. This work outlines the creation and testing of an AR experience where students design and construct renovations to an existing structure, a simulation of authentic learning in an AEC context.

4.4.2 Authentic Learning in AEC Contexts

Within an AEC context, authentic learning literature is limited, but in the research that has been published, the benefits of authentic learning are evident. For example, researchers observing the student learning outcomes during a Solar Decathlon event listed a wide range of student benefits. Students demonstrated personal initiative and ownership in the project, identified technical issues, gained appreciation for real deadlines, and showed persistence in doing whatever was required to complete the project with their team (Holt *et al.*, 2012). Another report outlined the benefits of a similar event in Europe, revealing that students gained a breadth of benefits through the experience, such as understanding construction processes, sustainability concepts, and home automation; communication skills; the ability to work on multidisciplinary teams; the ability to make decisions based on realistic conditions; and an understanding of professional and ethical responsibilities (Navarro *et al.*, 2014). The educational benefits of student-led design and construction experiences are clear. While authentic learning experiences are undeniably valuable, access to these experiences in a university context is extremely limited due to factors such as cost, time, and space constraints (US Department of Energy, 2009). This paper presents a design and construction hands-on experience in an AR environment, and to determine the educational value of this proposed technology, it is important to understand where it can replicate authentic learning components and where it may differ.

4.4.3 Authentic Learning Critical Components

To critically examine a simulation of authentic learning, an understanding of the components that are characteristic of authentic learning experiences is necessary. While research simulating authentic learning in AEC contexts is limited, extensive guidance has been published regarding what constitutes authentic learning in general. Fundamental literature regarding the critical components of authentic learning is provided in summatory form in Table 4. In this table, the elements reported to constitute an 'authentic learning experience' are listed, presented with citations from authentic learning literature.

Table 4. Components of authentic learning from learning theory literature.

Authentic Learning Component	Support from Authentic Learning Theory Literature
Situated in Real-World Context	Connects to real-world issues and contexts (Glossary of Educational Reform 2021; Rule 2006, Lombardi & Oblinger 2007), reflects how knowledge is used in real life (Herrington & Herrington 2005; Herrington & Oliver 2000; Lebow & Wager 1994),
Requires Higher Level Thinking	Develops critical thinking and problem solving (Glossary of Educational Reform 2021), Must balance large number of resources and discern relevance (Herrington & Herrington 2005; Lombardi & Oblinger 2007), Learning through inquiry and thinking skills (Herrington & Oliver 2000)
Ill-Defined Problem, Multiple Solutions	Mirrors complexity and ambiguity of real life (Glossary of Educational Reform 2021; Herrington & Herrington 2005), Learners are empowered to define path to solution (Rule 2006), Multiple interpretations and outcomes (Lombardi & Oblinger 2007; Lebow & Wager 1994)
Physicality	Learn by physically 'doing' (Glossary of Educational Reform 2021)
Multidisciplinary Thinking	Multiple skillsets for task completion (Glossary of Educational Reform 2021), Explore multiple perspectives (Herrington & Herrington 2005), Intentionally incorporates multiple perspectives, habits of mind, and ways of working (Lombardi & Oblinger 2007)
Culminates in the Creation of a Product	Culminate in a useful community contribution (Glossary of Educational Reform 2021), Creates polished product with intrinsic value (Lombardi & Oblinger 2007)
Reflection	Provides opportunities to articulate thought (Herrington & Herrington 2005; Herrington & Oliver; Lombardi & Oblinger 2007), Reflection as both a process and product (Herrington & Herrington 2005)
Collaboration	Collaborative knowledge construction (Herrington & Herrington 2005; Herrington & Oliver 2000; Lombardi & Oblinger 2007), Learning through discourse with others (Rule 2006; Lebow & Wager 1994)
Sustained Investigation	Enables sustained examination over time (Herrington & Herrington 2005; Lombardi & Oblinger 2007; Lebow & Wager 1994)
Assessment	Opportunities for formative and summative assessments (Herrington & Herrington 2005; Herrington & Oliver; Lombardi & Oblinger 2007)
Access to Experts	Expert modeling of processes, coaching, and scaffolding (Herrington & Herrington 2005; Herrington & Oliver 2000)

Authentic learning theory researchers have also considered the role of simulations in authentic learning (Herrington *et al.*, 2004). These researchers emphasize that simulations of authentic learning will, by nature, be a ‘view’ of reality (not reality itself) and that emphasis be placed on replicating the critical components of authentic learning (Table 4). This paper explores how AR could potentially simulate authentic learning scenarios in an AEC context, as simulations of authentic learning have not been explored extensively in this domain. The work presented here considers the emergent evidence within a design and construction authentic learning simulation that either parallels or does not parallel what would be expected in a physical authentic learning situation, guided through the lens of traditional authentic learning components (Table 4).

The scope of the AR simulation presented in this paper was developed as an individual experience to understand the common themes that occur in multiple user experiences without the confounding factor of interactions between simultaneous users. These users were observed in timed research sessions to allow for observation of a sample of individuals. This design enabled the researchers to observe a variety of students in a controlled environment to establish a baseline understanding of how students interact with this sort of experience. This exploratory research strategy was chosen due to lack of precedent in studying how students act in simulated AR design and build authentic learning environments. Due to this scope, some components of authentic learning were not observable within the experience. Authentic learning components listed in the table but not addressed in this paper include the following:

- Collaboration: not considered in an isolated testing environment designed to observe individual student behaviors.
- Sustained investigation: not within the scope of timed subject testing.
- Assessment: incorporated within this AR experience design, but authentic

assessment theory is outside of the scope of this paper and will be addressed in future work.

- Access to Experts: not included within the scope of this research testing environment, designed as independent activity to observe natural student behaviors.

Aside from these four excluded categories, all other authentic learning components were considered for the analysis and are presented with evidence derived from the observational protocol, included what was observed that students did or said during the independent build (Figure 16, step E).

4.5 Methods

4.5.1 Overview

To observe students' behaviors and perceptions when using AR to complete a simulated design and construction activity, subject testing was performed using an AR application that simulated a design and construction process involving the evaluation and renovation of an existing playhouse structure. This type of structure was selected to provide a design and build experience that could be displayed indoors at full scale. Since AR allows content to be presented in both physical and virtual formats, the resources used in this study were deliberately chosen to be presented to students in both formats. Virtual resources were selected to replace cost prohibitive elements that make this kind of learning traditionally prohibitive (i.e. actual construction materials) and to facilitate interaction with the virtual elements (i.e. virtual tools that enacted changes to virtual construction materials). Physical resources were chosen in situations where they were inexpensive and easily obtainable, and thus not the reason these authentic experiences are limited. Additionally, physical resources were included where possible when they represented the same types of resources students would have if tasked with physically working on a real play structure (i.e. safety handbook, item catalog, and blank paper for notes). This study explores how the use of this type of AR environment elicits behaviors and perceptions that align with tenets of truly authentic learning environments.

The AR application was designed in Unity game development engine and involved modeling an existing playhouse structure, virtual tools, and a set of over 100 orderable playground components including playground equipment (slides, climbers, games, auxiliary equipment, and ground surfacing), dimensional lumber, and prefabricated wood panels and assemblies. The playhouse, tools, and components were assigned functionalities to enable interactions. For example, non-structural components of the playhouse could be removed by using the drill to unscrew the fasteners and then moved using a "grab" gesture in AR. The various workflows enabled in the AR environment are illustrated in Figure 15.

4.5.2 Participant Experience

Participants were recruited from a fourth-year construction technology course for construction management and construction engineering students. Each student that signed up to participate completed an individual testing session that lasted one hour. The participant experience was comprised of the steps outlined in Figure 16 and explained subsequently.

First, the participants completed a pre-activity survey (Figure 16, step A), where

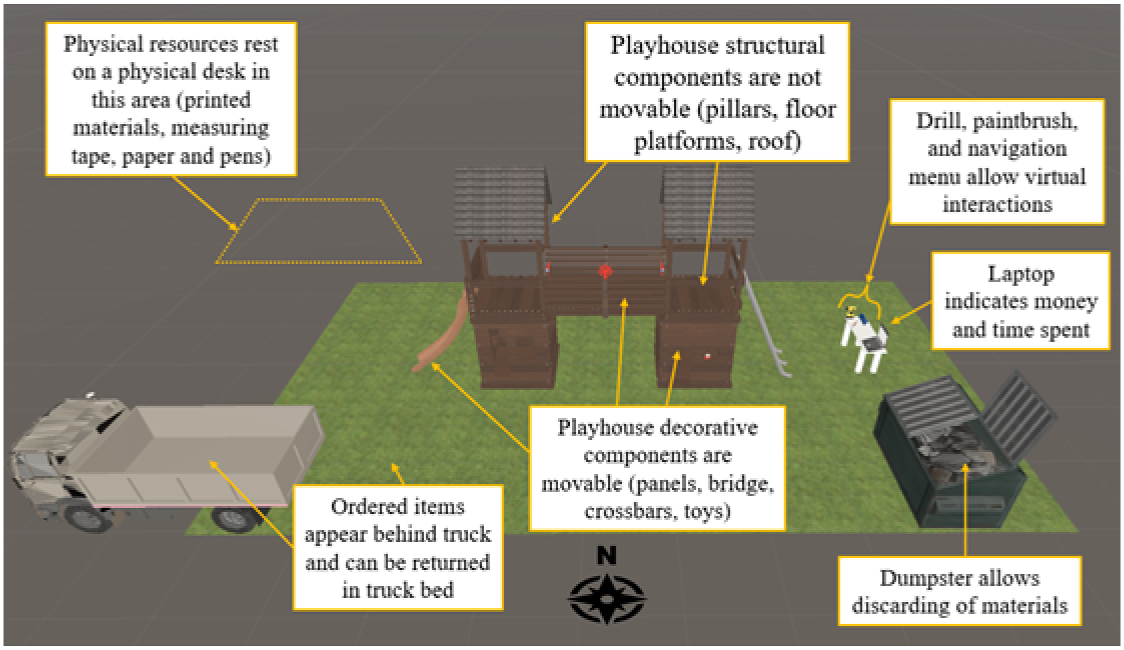


Figure 15. Representation of the Playhouse Environment Layout (Screenshot Taken Within Unity Game Development Engine).

they provided written informed consent[3], demographic information, and levels of familiarity with AR technology in general and also specifically with the device used in this study (Microsoft HoloLens 2). Following the pre-survey, participants were shown an introductory video (Figure 16, step B) with context about the activity they would be participating in. The video outlined the various objectives and stakeholders with an interest in the project, including a homeowner's association that supplied cost and time constraints, the city with sustainability concerns, the parents who had safety concerns, and children who wanted a fun play structure. Participants were instructed to consider each of these stakeholders and objectives in their build. At the completion of the video, participants were shown each of the physical resources (Figure 16, step C) they had at their disposal, including the following:

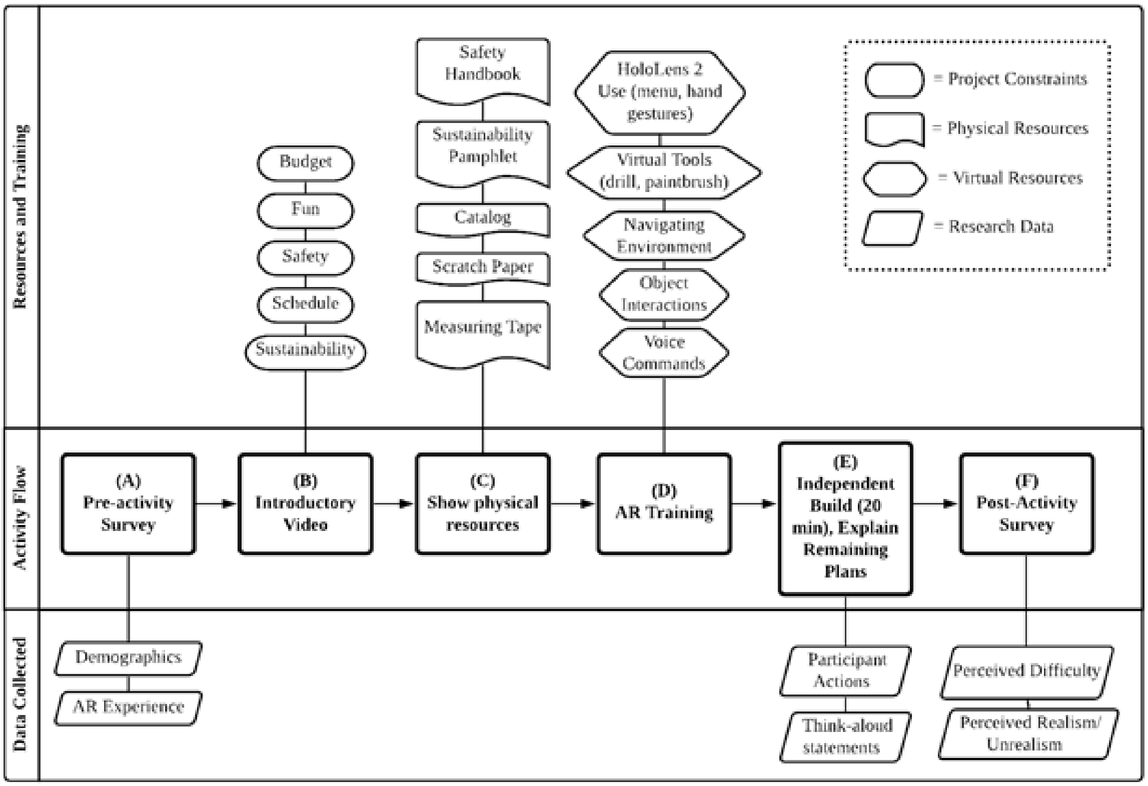


Figure 16. Flowchart of Steps Involved in the Student AR Experience.

- A tape measure - used by participants to take measurements of the structure during their independent work
- Blank paper, pens, and sticky notes - used by participants to keep notes, write down thoughts, create drawings, and aid in the independent work process
- Paint samples - used by participants as a physical reference in case they wanted to examine paint colors before purchasing a bucket of paint
- A safety handbook - used by participants to read about safety guidelines for play-structures
- A sustainability pamphlet - used by participants to assess the sustainability of materials listed in the item catalog

- An item catalog - used by participants to determine what items they could purchase to modify the play structure

These items were chosen to be provided physically to students since they were all inexpensive, easily obtainable, yet were all components that would have proven valuable if this activity were a true authentic design/build learning activity involving physical manipulation of a similar structure.

After familiarizing participants with the physical resources at their disposal, they were trained on how to use the head mounted AR Device, including a training on all voice commands and gestures needed to interact with the application (Figure 16, step D). Participants actively performed all associated functions and movements, with verbal guidance from the facilitator during the training process. Participants were told how navigate the device menus with associated hand gestures. Then, they were shown the virtual tools they had at their disposal, including a virtual drill and a virtual paintbrush. They were allowed to walk the environment to familiarize themselves with the virtual structure and the location of items like the virtual laptop, dumpster, and delivery truck. They were shown how to physically interact with virtual objects, including, picking up, fastening, and removing objects from the playhouse. They were trained on the voice commands involved with the process, which enabled them to order objects, trigger the drill, and navigate between the upper and lower levels of the playhouse. Refer to Figure 15 for the layout of the virtual space and the components involved with environment interaction.

After training the students and answering any questions, the facilitator would tell the participants that they had twenty uninterrupted minutes (Figure 16, step E) to make whatever changes they wanted to the play-structure. As the participants worked, they were encouraged to think out loud and narrate their decisions. If there was a clarification question related to AR workflow (e.g. 'what is the voice command for ordering?'), the researcher would answer. If there was a question that emerged related to critical thinking or relevant decision making, the researcher would not answer and would remind students that they needed to determine for themselves the best path forward. This process helped to ensure that the participants were challenged by the learning scenario, but not by their familiarity with AR.

The participants' view through the AR device was cast to a computer through Windows Device Portal to allow the researcher to monitor the AR simulation and see what the participant saw. A think-aloud protocol provided students with the opportunity to verbalize their thought process throughout the experience. Participants were observed in real time, and also video- and audio-recorded to enable confirmation and expand the depth of the findings. Following the 20-minute independent work session, participants were asked what else they would have done in the design and build scenario if they had not been constrained to a 20-minute time frame.

After the AR building session was completed, the participants took a post-activity survey (Figure 16, step F) that asked a number of questions relating to their experience. Specifically, the participants answered two open-ended written-response questions regarding the realism of the experience, including the following: (1) "Please describe what parts of the experience felt realistic" and (2) "Please describe what parts of the experience did not feel realistic". They also responded to six 5-point Likert scale questions regarding the difficulty of the different sub-tasks involved in the process including (1) manipulating virtual objects, (2) using voice commands, (3) measuring, (4) seeing virtual objects (visibility), (5) placing or installing virtual objects, and (6) making design decisions. These three post-activity questionnaire sections provided additional data to supplement and add clarity to the observational coding performed as students worked during the active build time.

4.5.3 Analysis

The researchers listened to the comments students made and noted their actions. The observational protocol included the researchers noting in a spreadsheet any comments and behaviors during the AR design/build activity that were perceived to parallel an authentic learning component or differ from an authentic learning component. Since the authentic learning activity that this experience was designed to simulate was a physical design and building scenario, behaviors or actions from the user were noted when the user performed an action that would be expected in a parallel physical context or was surprising or differed from what would be expected in a physical context. For example, students carrying playground components and fastening them on a playhouse would parallel the physical build experience, while students walking through virtual elements as if they do not exist would not be possible if the experience used real materials, so behaviors like these were also noted. In addition to what could be seen through simple observation, verbalizations from the think-aloud protocol provided much of the basis for the thematic analysis and were noted if they provided insight into the users' actions beyond what could be observed. For example, often students would say something like "I chose to order [this object] because it [rationale]", where the rationale would include statements like "reminded me of my childhood" or "seemed safer". The think-aloud statements were typically noted as they allowed the researchers to understand the thought processes students were using, which helped the researchers see when they were or were not demonstrating characteristics of authentic learning behavior.

A phenomenological approach guided overall analysis (Creswell and Poth, 2016), which seeks to find commonalities between various participants who have all experienced a particular phenomenon, in this case the AR simulation. Overall, the participant behaviors were analyzed using in-situ observations and video observations (Parameswaran *et al.*, 2020) to determine what behaviors and perceptions emerged that were pertinent to the research questions. The Braun Clark Six-Step thematic analysis approach was used in creating and interpreting codes generated through the observational protocol (Braun and Clarke, 2012), with the generation, review, and definition of the thematic categories guided by authentic learning theory but left open to allow additional thematic categories to emerge where appropriate. In this method of analysis, codes represent the "the smallest units of analysis that capture interesting features of the data" that relate back to the research question. These codes work together as part of larger themes, or "patterns of meaning" that relate back to a central idea (Braun and Clarke, 2012). In this case, the codes came from specific observed student behaviors or statements, the themes were guided by authentic learning components, and the central idea was authentic learning theory as it relates to a design and construction context. From the observational protocol, codes were identified in each of the participants' experiences until the point of saturation was reached, where eventually only existing codes emerged in participant observations and no new codes emerged after repeated investigation. Observed codes are presented through the lens of the existing theoretical outline of authentic learning theory (Table 4), with behavioral (student actions) and perceptual (student statements) evidence analyzed to determine where observations either contributed to or contradicted behaviors and perceptions expected in authentic learning environments, as explained previously.

While the thematic analysis constitutes the major substance of the findings presented in this paper, a supplementary analysis of the post-activity survey responses enhances the discussion of some of the authentic learning components. The 'realism' and 'unrealism' written-response subset of data was analyzed using descriptive and element coding on participant's statements according to the method outlined by (Miles *et al.*, 2014), used in similar studies within this domain (Hartless *et al.*, 2020). Additionally, the responses to the subtask difficulty questions are presented graphically in the results section when they pertain to the authentic learning theory component being discussed. The analysis of these additional data subsets is integrated in the discussion of the overall observational coding in the subsequent sections.

4.6 Results

4.6.1 Descriptive Statistics

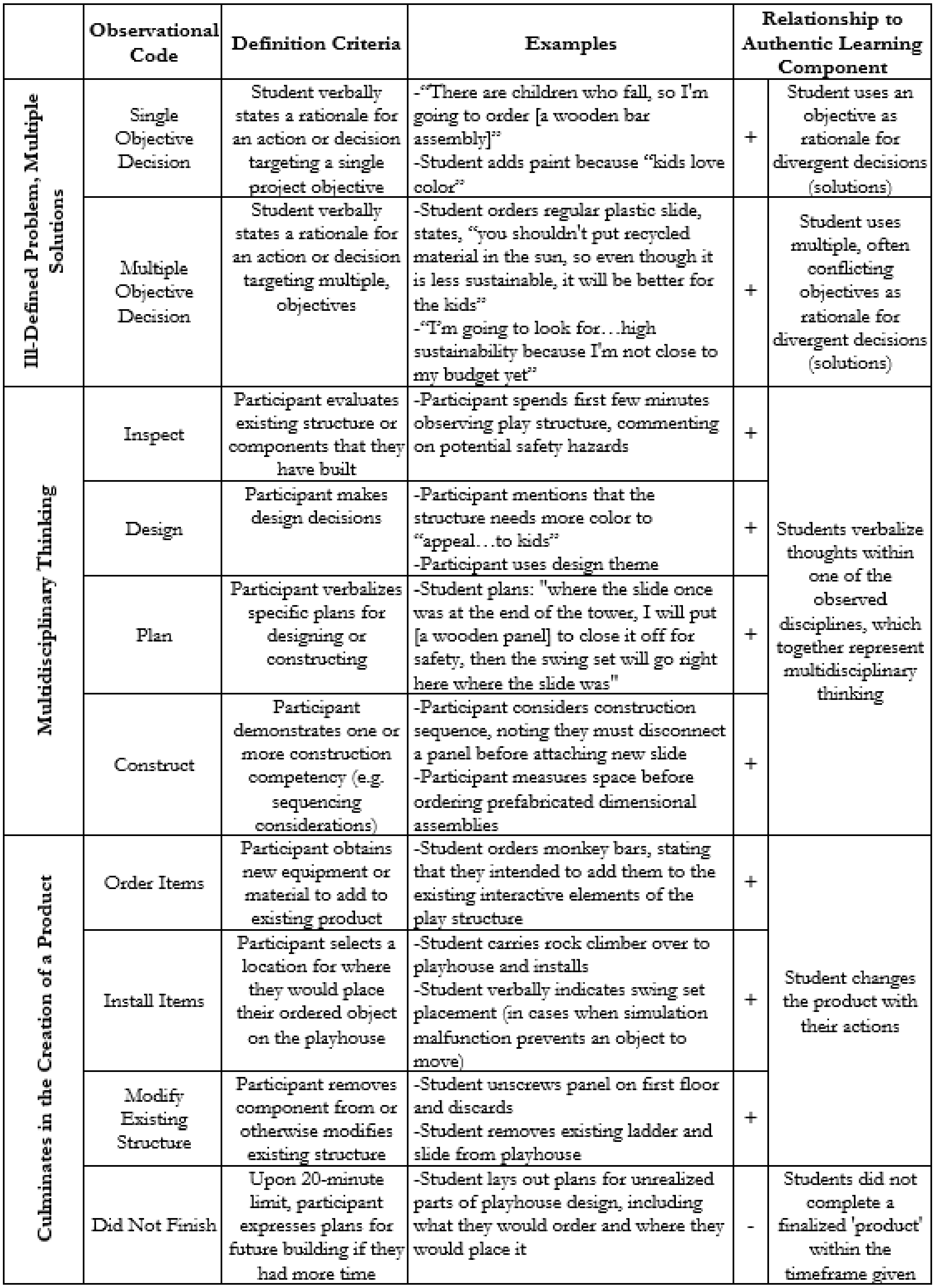
In total, 34 students participated in the design and construction experience. The participants included 6% Sophomores, 53% Juniors, and 41% Seniors. Of all participants, 74% were male and 26% were female. The self-reported race and ethnicity of participants are as follows: 5% American Indian or Alaska Native, 8% Asian, 5% Black or African American, 33% Hispanic or Latino, 44% White, 3% Prefer not to answer, 3% Other. On average, the participants had 1.6 years of experience in industry, including internships. Concerning prior AR experience, 94% had heard of AR, 38% had used AR, and 21% indicated that they had used a HoloLens before.

The results presented here consider emergent evidence of authentic learning that were displayed by students during the AR simulation, including both behavioral evidence and self-reported perceptions through spoken (think-aloud) and written (reflection) formats. The findings present emergent factors that paralleled or did not parallel authentic learning characteristics, organized by authentic learning component (Tables 5– 9). These themes follow the components of authentic learning outlined in the background section (Table 4), and are as follows: situated in a real-world context, requires higher-level thinking, ill-defined problems with multiple solutions, physicality, multidisciplinary thinking, creation of a product, and reflection.

4.6.2 Thematic Analysis

Through the thematic analysis process presented in the method section, 25 codes were identified and thematically organized within the authentic learning theory components (Tables 5– 9). A code was considered in this analysis if it emerged in two or more user experiences. Some of the emergent codes were intuitive and would be expected to emerge based on the experience design. Others were less intuitive and had conflicting evidence within the body of data. The authentic learning categories that only contained intuitive codes are listed in Table 5, which outlines the codes, definition criteria, examples, and the relationship to authentic learning for each observed code.

Table 5. List of Intuitive Emergent Codes, With + or - Indicating Whether These Emergent Codes Paralleled (+) or Countered (-) the Authentic Learning Protocol Under Which They Were Categorized.



	Observational Code	**Definition Criteria**	**Examples**	**Relationship to Authentic Learning Component**	
Ill-Defined Problem, Multiple Solutions	Single Objective Decision	Student verbally states a rationale for an action or decision targeting a single project objective	-"There are children who fall, so I'm going to order [a wooden bar assembly]" -Student adds paint because "kids love color"	+	Student uses an objective as rationale for divergent decisions (solutions)
	Multiple Objective Decision	Student verbally states a rationale for an action or decision targeting multiple, objectives	-Student orders regular plastic slide, states, "you shouldn't put recycled material in the sun, so even though it is less sustainable, it will be better for the kids" -"I'm going to look for…high sustainability because I'm not close to my budget yet"	+	Student uses multiple, often conflicting objectives as rationale for divergent decisions (solutions)
Multidisciplinary Thinking	Inspect	Participant evaluates existing structure or components that they have built	-Participant spends first few minutes observing play structure, commenting on potential safety hazards	+	Students verbalize thoughts within one of the observed disciplines, which together represent multidisciplinary thinking
	Design	Participant makes design decisions	-Participant mentions that the structure needs more color to "appeal…to kids" -Participant uses design theme	+	
	Plan	Participant verbalizes specific plans for designing or constructing	-Student plans: "where the slide once was at the end of the tower, I will put [a wooden panel] to close it off for safety, then the swing set will go right here where the slide was"	+	
	Construct	Participant demonstrates one or more construction competency (e.g. sequencing considerations)	-Participant considers construction sequence, noting they must disconnect a panel before attaching new slide -Participant measures space before ordering prefabricated dimensional assemblies	+	
Culminates in the Creation of a Product	Order Items	Participant obtains new equipment or material to add to existing product	-Student orders monkey bars, stating that they intended to add them to the existing interactive elements of the play structure	+	Student changes the product with their actions
	Install Items	Participant selects a location for where they would place their ordered object on the playhouse	-Student carries rock climber over to playhouse and installs -Student verbally indicates swing set placement (in cases when simulation malfunction prevents an object to move)	+	
	Modify Existing Structure	Participant removes component from or otherwise modifies existing structure	-Student unscrews panel on first floor and discards -Student removes existing ladder and slide from playhouse	+	
	Did Not Finish	Upon 20-minute limit, participant expresses plans for future building if they had more time	-Student lays out plans for unrealized parts of playhouse design, including what they would order and where they would place it	-	Students did not complete a finalized 'product' within the timeframe given

Observed content within these authentic learning categories (Table 5) generally presented strong evidence supporting AR as a simulation of authentic learning and are generally intuitive and would be expected due to the design of the AR experience. For example, the problem presented to the students required leveraging competencies from multiple disciplines, so it is natural that students would display behaviors and make comments that reference a variety of disciplines, seen in the 'Multidisciplinary Thinking' category within Table 5. The one intuitive finding that presented evidence contrary to authentic learning was the emergent code Did Not Finish within the authentic learning category 'Culminates in the Creation of a Product', where students were unable to present a fully constructed product at the end of their 20-minute build session. Given the allotted timeframe for building, this code is not surprising, and it is anticipated that it would not emerge if students were given more time to complete this learning activity.

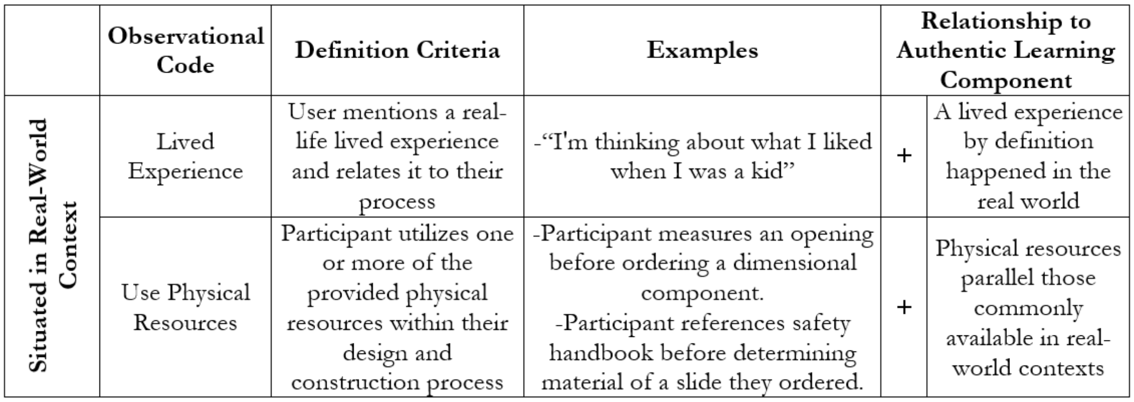
While several categories exhibited only intuitive findings, in some instances, conflicting or contradictory evidence emerged within a thematic category. Codes were considered conflicting or contradictory when they presented evidence that directly countered the authentic learning category where they were placed or if they presented evidence that both supported and countered the authentic learning category from learning theory literature, depending on the circumstance (see Table 4). For both the intuitive and contradictory codes, the relationship to their respective authentic learning component is defined in the emergent codes tables (Tables 5–9) and relates each code to what would be expected in a real-world authentic learning scenario. The contradictory or conflicting findings, also referred to as counterintuitive findings, and their implications are discussed in the subsequent section, including the following thematic categories and subtopics:

- Situated in a Real-World Context: Conflicting Evidence in Reported Perceptions of Realism
- Requires Higher Level Thinking: Conflicting Evidence for Critical Thinking
- Physicality: Conflicting Evidence for Authentic Environment Interactions & Assuming Virtual Shortcuts
- Reflection: Conflicting Evidence for Remediating Errors

Within the overarching thematic categories listed, a combination of intuitive and counterintuitive findings emerged. The intuitive findings are presented alongside the counterintuitive findings in tabular format, with counterintuitive findings highlighted within the tables and discussed after the presentation of each table. This presentation is intended to help readers better understand some of these nuanced findings for strategically targeting, or avoiding, similar learning experiences in the future.

4.6.2.1 Situated in Real-World Context: Conflicting Evidence in Reported Perceptions of Realism

Table 6. Emergent Codes Within the Category "Situated in a Real-World Context".



	Observational Code	Definition Criteria	Examples	Relationship to Authentic Learning Component	
Situated in Real-World Context	Lived Experience	User mentions a real-life lived experience and relates it to their process	-"I'm thinking about what I liked when I was a kid"	+	A lived experience by definition happened in the real world
	Use Physical Resources	Participant utilizes one or more of the provided physical resources within their design and construction process	-Participant measures an opening before ordering a dimensional component. -Participant references safety handbook before determining material of a slide they ordered.	+	Physical resources parallel those commonly available in real-world contexts

Being situated in a Real-World Context is one of the most consistently reported elements of an authentic learning experience by authentic learning theorists. Within the AR simulation, several factors were intentionally included to ground the experience in a real-world context. The existing playhouse design was developed with full-scale wood-framed components to create a realistic environment and the narrative included a project scenario where multiple stakeholders had conflicting interests, much like a typical real-life project. The virtual capabilities of the simulation were determined based on what would most closely parallel reality. For example, students could not 'summon' virtual objects from across the room, but rather had to walk over to them to move them. Similarly, to move an object, they had to physically intersect their hand with the virtual object and make a grabbing motion. The experience design was intended to parallel reality, and student observed behaviors seemed to support this intention. The two codes that emerged through the observational data (Table 6) were intuitive and provided evidence that AR can potentially simulate a real-world context. However, in addition to what was observed, the participants' perception of realism proved critical in understanding the extent to which a simulation parallels a real-world context. The two open-ended questions regarding realism in the post-activity questionnaire provided additional depth of understanding the realism of the experience and results are presented subsequently. Thematic coding in the method of Miles *et al.* (2014), revealed three thematic groupings regarding the various aspects of the student experience and which were perceived as realistic, unrealistic, or mixed: Virtual Environment, Overall Experience, and Virtual Object Interactions. The codes grouped under these themes were reported if they appeared in at least 10% of the responses in either the 'realistic' or 'unrealistic' responses (Figure 17). For analyses that include quantitative counts of open-ended or subjective data and involve multiple raters, interrater reliability, measured by Cohen's Kappa indicates the extent to which raters are consistent and ranges from -1 to 1, with 1 being perfect agreement. The interrater reliability of the two raters on this dataset indicated substantial agreement (Cohen's Kappa = 0.737) (Hallgren, 2012; Landis and Koch, 1977).

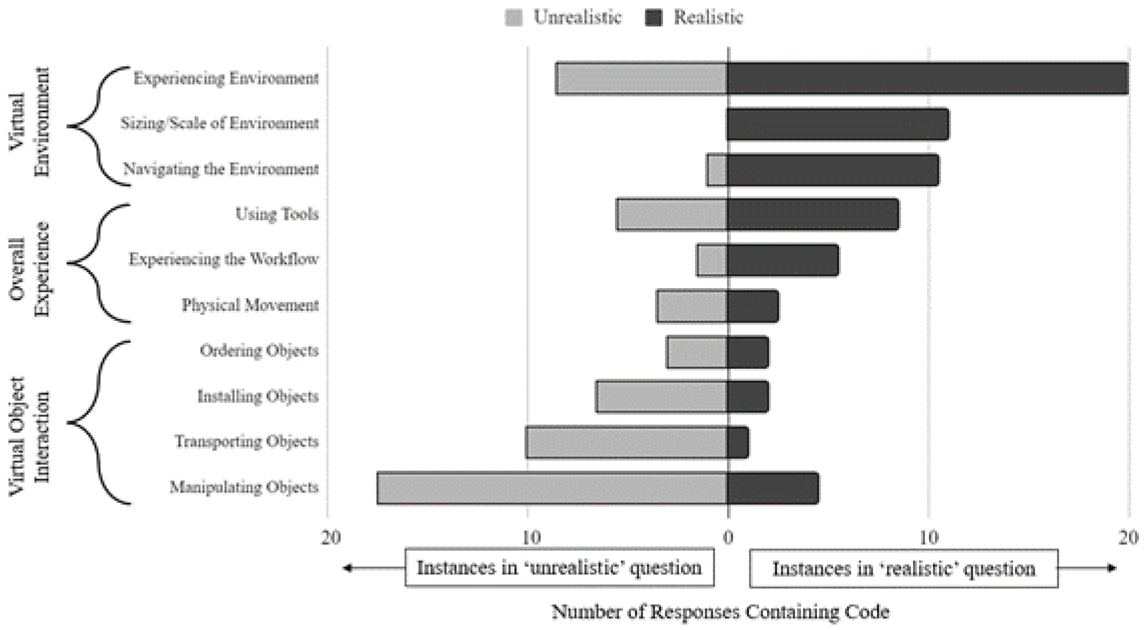


Figure 17. Thematic groupings of Emergent Codes in the Subset of Data Derived from the Post-Activity Questionnaire. Students Were Asked to Write What Parts of the Experience Felt Realistic and What Parts Felt Unrealistic (n=34).

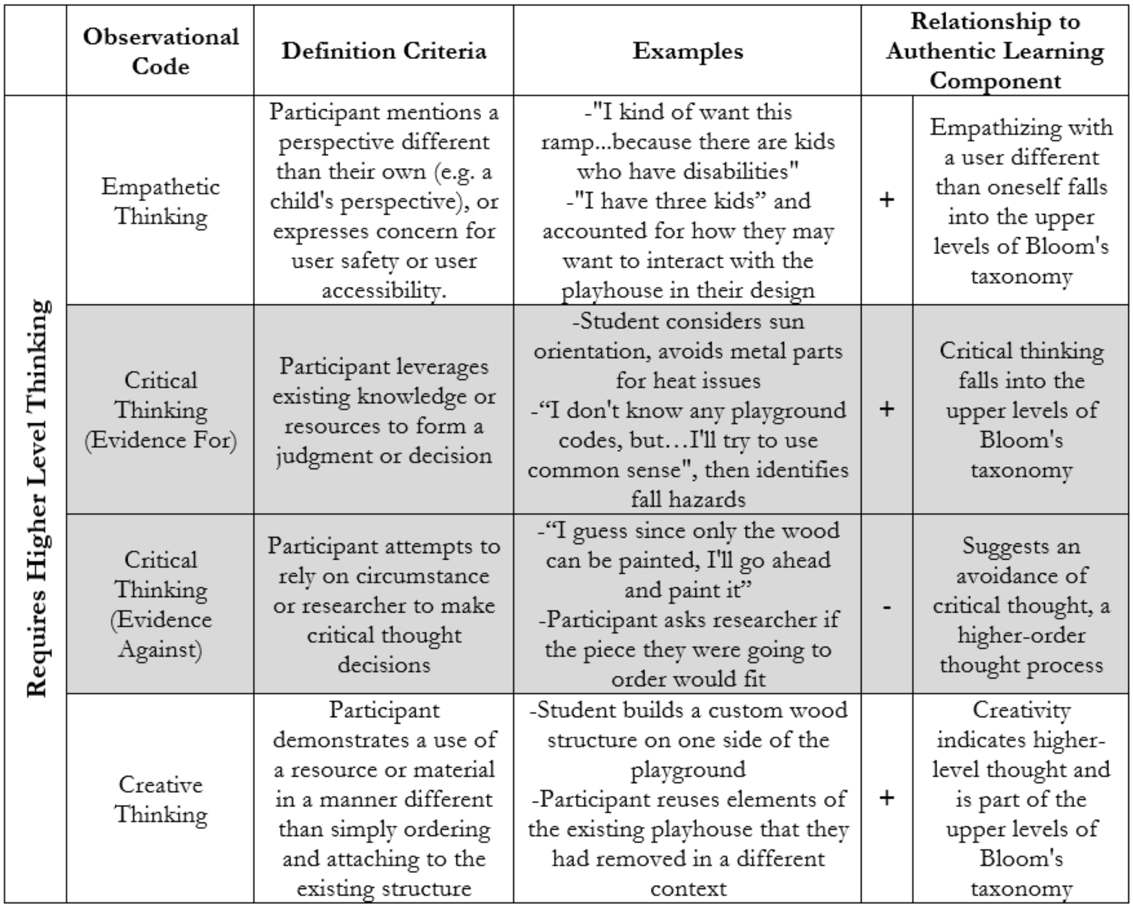
The most mentioned aspect of the experience was regarding the virtual environment itself, with the majority commenting that experiencing the environment felt realistic in how it looked and felt. They also commented on the realism of the sizing and scale of the environment and in their ability to navigate or walk around in the environment (Figure 17). A few participants mentioned these factors in their reflection on what was unrealistic but were outweighed by the comments within the 'realism' responses. Notably, virtual object interactions were by far the most commonly reported theme in the ‘unrealistic’ category, with many students commenting on how handling, transporting, and installing objects felt unrealistic. Many students reported unrealistic struggles with manipulating virtual objects, which for them detracted from the realism of the experience. It is possible that these unrealistic responses resulted from their lack of experience in interacting with AR, from glitches within the simulation, even could be related to the tactile difference between physically moving real building elements and moving weightless virtual ones in AR. Overall, the experience had several strong components that helped users feel grounded in a realistic situation, but also had some factors that pulled users away from feeling like they were in a realistic real-world environment. These results suggest that for physically navigating a static structure at full scale, the students overwhelmingly report it to be realistic. Conversely, for interacting with virtual objects through AR gestures, students overwhelmingly report it to be unrealistic, despite the simulation design elements intended to replicate realistic gestures like requiring proximity to an object to move it.

- **Practical Impact**: For future educators, if the goal is to have students explore a space in a realistic, yet cost-effective, manner, it is suggested that AR is a strong candidate for use. However, if educators want students to appreciate the realism of moving and handling actual construction materials, they should consider buying actual construction materials.

4.6.2.2 Requires Higher Level Thinking: Evidence For and Against Critical Thinking

Higher level thinking is commonly understood to incorporate the upper levels of Bloom’s taxonomy, which include Application, Analysis, Synthesis, Evaluation, rather than lower levels like knowledge recall and simple comprehension (Adams, 2015). Some have suggested that higher level thinking includes competencies like concept formation, concept connection, getting the big picture, visualization, problem solving, questioning, idea generation, analytical (critical) thinking, practical thinking/application, and synthesizing/creative thinking (for Literacy and Learning, 2021). The components of the virtual experience design intended to elicit higher-level thinking included requiring students to balance multiple resources (catalog, safety handbook, sustainability pamphlet, tools, prior knowledge) in executing their process and to think creatively to come up with a design that fit the project objectives. They were also asked to consider an end user different than themselves, in this case a child, requiring empathetic thought. Students would ideally think critically and practically in determining how to execute their design and balance their objectives. In most of these areas, behavioral evidence showed that students tapped into these higher-level processes during their design and build experience, as indicated in Table 7.

Table 7. Emergent Codes Within the Category "Requires Higher Level Thinking".



	Observational Code	Definition Criteria	Examples	Relationship to Authentic Learning Component	
Requires Higher Level Thinking	Empathetic Thinking	Participant mentions a perspective different than their own (e.g. a child's perspective), or expresses concern for user safety or user accessibility.	-"I kind of want this ramp...because there are kids who have disabilities" -"I have three kids" and accounted for how they may want to interact with the playhouse in their design	+	Empathizing with a user different than oneself falls into the upper levels of Bloom's taxonomy
	Critical Thinking (Evidence For)	Participant leverages existing knowledge or resources to form a judgment or decision	-Student considers sun orientation, avoids metal parts for heat issues -"I don't know any playground codes, but…I'll try to use common sense", then identifies fall hazards	+	Critical thinking falls into the upper levels of Bloom's taxonomy
	Critical Thinking (Evidence Against)	Participant attempts to rely on circumstance or researcher to make critical thought decisions	-"I guess since only the wood can be painted, I'll go ahead and paint it" -Participant asks researcher if the piece they were going to order would fit	-	Suggests an avoidance of critical thought, a higher-order thought process
	Creative Thinking	Participant demonstrates a use of a resource or material in a manner different than simply ordering and attaching to the existing structure	-Student builds a custom wood structure on one side of the playground -Participant reuses elements of the existing playhouse that they had removed in a different context	+	Creativity indicates higher-level thought and is part of the upper levels of Bloom's taxonomy

One code that had both positive and negative instances emerge was in critical thinking, defined here as "the ability to consider a range of information derived from many different sources, to process this information in a creative and logical manner, challenging it, analysing it and arriving at considered conclusions which can be defended and justified." (Moon, 2007). This definition makes clear that critical thinking is active, meaning a student makes an effort to 'consider', 'process', 'challenge', and 'analyze' to form a decision. There was certainly evidence from student think-aloud statements that indicated students were thinking critically about how to execute their process. For example, some students recognized the complexity of the task and how it would require both long-term plans and short-term decisions, such as the student who contemplated, “not sure if it’s better to address the whole thing at once or partial things” and was able to independently come up with an executable plan. Additionally, critical thinking was displayed when students were required to think beyond their prior knowledge or comfort zones, such as the student who noted “I don’t know any playground codes, I only know normal codes, but I guess I’ll try to use common sense". Students who exhibited critical thinking were able to consider constraints and circumstances and come up with implementable solutions. For example, one student dealt with the practical constraint of limited space, stating, “I’m moving the slide from the end to the second tower so I can put in a swing set where the slide once was”. Another student considered the practical implications of a memory they had, where ‘lots of kids’ would play on the bridge at a time. This student decided to add additional structural supports to the bridge area in order to preemptively address this potential issue. In this case, whether this additional support was necessary or not, the student leveraged existing knowledge to form a judgment or decision regarding their build. Overall, some emergent codes suggested potential for the AR simulation to challenge students in their ability to think critically, a key component of authentic learning.

However, despite evidence of critical thinking, this code also emerged in an opposing manifestation, when students displayed evidence of avoiding critical thought, instead relying passively on external circumstances or people to make decisions for them. For example, one student stated, “I guess since only the wood can be painted, I’ll go ahead and paint it”, indicating that their rationale for this decision was dictated simply by the design of the experience and not by a motivating overarching objective. In another instance, a student left a decision to chance, stating “I chose red because it was the first thing I saw". Others tried to rely on the researcher for making opinion-based decisions, like the student who asked if the piece they were going to order would fit, or the student who asked about whether they should order first then disassemble the existing playhouse elements, or vice versa. While these students showed a tendency to look to someone else for decisions, the researcher always responded the same way, indicating that there are multiple ways to execute the process and that they had to make the decision for themselves. This type of behavior—the tendency to look to another person for external validation or decision making—is not a phenomenon unique to the virtual environment and can be addressed through a simple protocol in how these statements or questions are addressed to encourage higher level thinking.

The emergent codes indicated that this simulation enabled critical thinking in many instances, but did not eliminate all non-critical thought. While creating a learning environment that exclusively requires critical thought is likely impossible, maximizing the amount of critical thought that is encouraged can create the best scenario for authentic learning, since higher-level thinking is a prominent component of authentic learning. For this simulation, the post-survey results regarding task difficulty provide insight into which parts of the simulation were most difficult, thus requiring mental energy from the students. The results from the Likert-scale questions regarding each subtask are shown in Figure 18.

In general, students found tasks involving physical manipulation of a virtual resource, including manipulating objects and placing objects, to be difficult, evidenced by the left skew of those two categories in Figure 18. Students reported generally neutral responses regarding measuring and seeing virtual objects. Most found voice commands, where vocal statements enact change on a virtual resource, to be easy. These five categories are task-based, where each represents an isolated action that

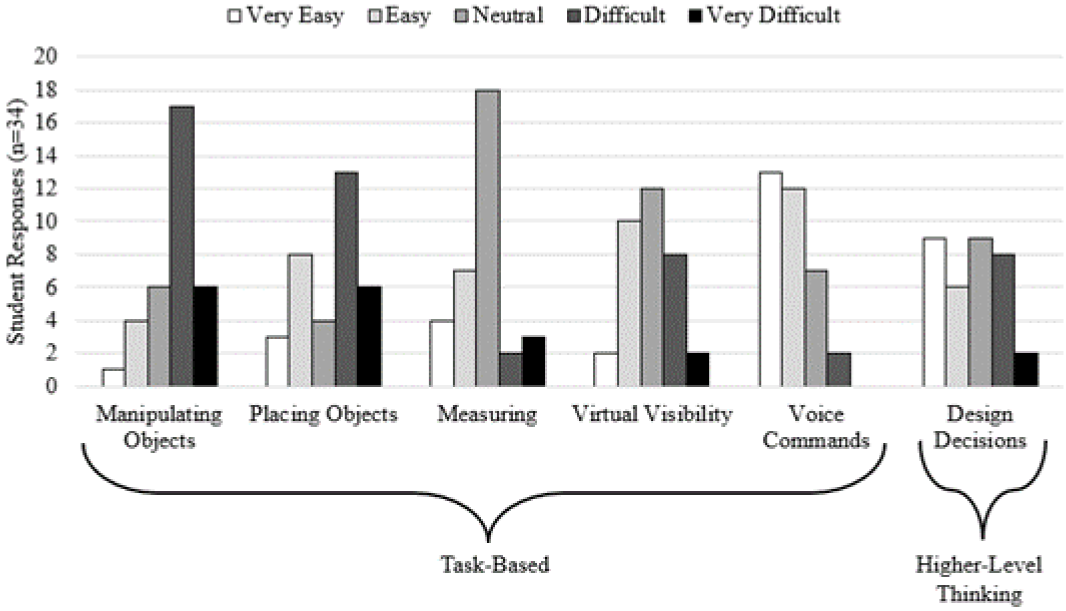


Figure 18. Student Responses to Likert-Scale Questions About Task Difficulty Provided in the Post-Activity Questionnaire.

may be required in performing more big-picture tasks. The last item, making design decisions, represents one of the key higher-level tasks that students undertook during the independent build. Results indicated a relatively even spread of students reporting this task across the spectrum of difficulty. There is a limit to how many places a person's attention can be devoted at a time, referred to as working memory (Cowan, 2010). Thus, the ideal situation in a simulated environment would be that an individual is able to focus on critical thinking tasks, such as making design decisions, and not on tasks associated with utilizing the technology, such as object interaction, voice commands, or object visibility. From these results, it is evident that manipulating virtual objects may have demanded a lot of user attention, which could potentially take away from more critical thought and higher-level thinking tasks, which are consistently reported as vital components of authentic learning. Other subtasks, however, like voice commands, seemed to be easier for students, thus demanding less of their mental attention, which could then be devoted to higher-level thinking. Some amount of difficulty is always expected in learning and, in fact, learning is often facilitated by difficulty, especially when that difficulty is strategically targeted to support the learning outcome (Bjork *et al.*, 2011). Thus, the goal in considering the difficulty of a learning experience is not to eliminate challenges but rather center the challenges around the aims of the learning experience.

- **Practical Impact**: For future implementations of similar interactive AR activities, educators should consider these mixed results in how the experience is designed. To combat the student tendency to look to external sources for decision making, educators can enact policies that encourage critical thinking, like turning the responsibility back to the student when they ask the instructor to make a design decision. Regarding the simulation design, educators can consider the elements of the simulation that they feel are most impactful for student learning (e.g. decision making, sequencing, planning) and make efforts to simplify the other parts (e.g. virtual object interactions) in order to maintain students' focus on critical thinking tasks rather than simulation logistics. In instances where manipulations could be supported through either gestures or voice commands, students consistently reported greater levels of ease using voice commands.

4.6.2.3 Physicality: Conflicting Evidence for Authentic Environment Interactions & Assuming Virtual Shortcuts

Table 8. Emergent Codes Within the Category "Physicality".

	Observational Code	**Definition Criteria**	**Examples**	**Relationship to Authentic Learning Component**	
Physicality	Environment Interactions (Evidence For)	Participant physically moves to avoid colliding with virtual elements despite their virtual nature	-Student ducks underneath the playhouse bridge to avoid 'collision' -Student crouches to enter the short openings to look inside the structure's lower tower -Student walks around exterior of playhouse to reach other side	+	Participant treats objects as physical and tangible
	Environment interactions (Evidence Against)	Participant does not physically move to avoid colliding with virtual elements and navigates through them	-Student walks through a panel they ordered -Student notes, "I can just walk through everything" as they explore second level of structure	-	Participant treats objects as virtual and intangible
	Forced Travel	Student was forced to navigate to another part of the environment to retrieve an item or complete a task	-Participant must physically walk to truck to retrieve ordered item or to dumpster to discard waste -“Dang it, I forgot to grab my drill before I moved down”	+	The necessity of movement parallels the necessity and inconvenience of travel in a real-world environment
	Assuming Virtual Shortcuts	Students make assumptions that shortcuts would be available based on being in a virtual environment	-Participant tries to move object from a distance -"I can't just summon the drill?"	-	Participant expects virtual simulation to be different from reality, expects conveniences not available in reality

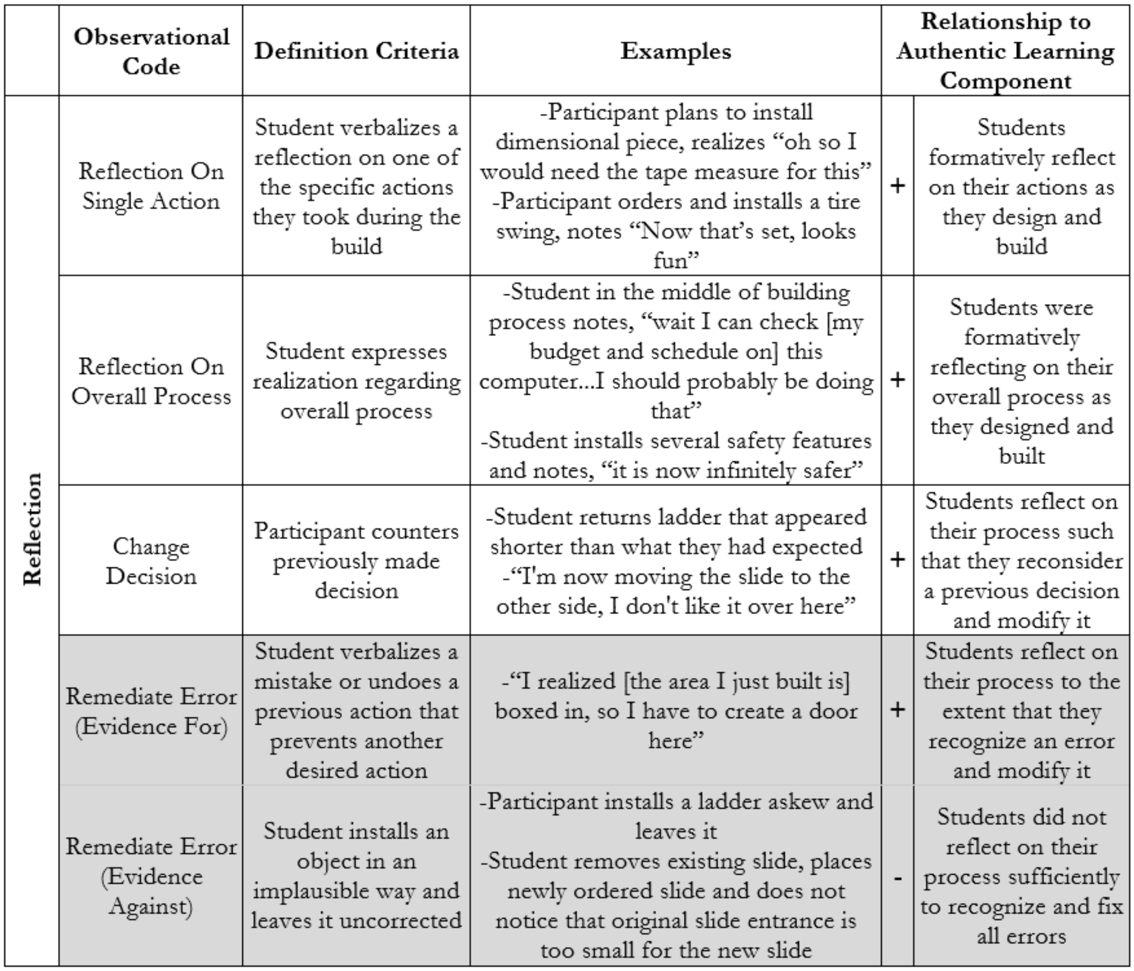
During the observations, the researchers noted some conflicts in how students physically interacted with and navigated the virtual environment (Table 8). In general, students displayed a behavioral tendency to avoid physically colliding with virtual elements as if they really existed, even though participants could theoretically walk through the holographic elements with no physical resistance. For example, students would frequently duck under the bridge or crouch to enter the short openings enabling them to look inside the structure's lower tower. Most students stepped around the virtual elements as if they were truly presenting a physical barrier to the students. This supports the findings presented in Figure 17, where many students indicated feeling that the environment itself felt realistic. While most of the students treated the virtual environment as a real structure and ducked under and stepped around virtual elements, a few did not, like the student who noted as they were exploring the second level of the structure "I can just walk through everything" or the student that walked through a panel they had ordered. While the emergence of this code was rare, it did emerge in multiple student experiences, indicating that perhaps not all students experience the virtual environment with the same level of immersion, or perhaps that some students like to intentionally explore the limits of what can or cannot be done in a 'simulated' environment. This conflicting evidence supports what was found in the emergent coding regarding 'realism' and 'unrealism', where many students felt that experiencing and navigating the environment was realistic, but a few did not (Figure 17), in part evidenced in part by the way they walked around or through objects.

In addition to the observations regarding physical navigation of the virtual environment, one interesting code that emerged was when students would make assumptions about what was possible based on being in a virtual environment, like assuming that they could summon or move objects from a distance. The experience was intentionally designed for students to have to physically walk up to an object to move it, like they would in a physical authentic learning environment. However, this may be different from other simulations that students may have experienced. The emergence of this code suggests that students retained to some extent the understanding that they were in a virtual simulation and made assumptions based on what they might expect in a game-like environment. In this case, the simulation was designed to keep inconveniences that may contribute to student learning, such as the necessity of walking back to where an object was left or fixing mistakes by undoing actions rather than simply snapping fingers or pressing undo. Despite the intention of adhering as closely as possible to a physical authentic learning experience, students commonly reported certain object manipulations as unrealistic and difficult, as explained in previous sections (Figure 17, Figure 18). While students did not feel that the overall experience required high physical effort, evidenced by the right skew of the physical demand responses in Figure 18, certain sub-tasks involved with moving and placing virtual objects seemed to consistently present challenges to the students. As mentioned previously, eliminating difficulty from an experience is not a realistic or desirable goal, but if a challenge does not contribute to the learning outcome, educators can choose to simplify the distracting difficulties in order to make space for the desirable difficulties (Bjork, 2011). While making virtual shortcuts available may at first glance seem like it would counter authentic learning by giving the experience less physical fidelity to reality, the difficulty and frustration of 'realistic' movements should be balanced with the overall learning objectives such that no single type of interaction significantly detracts from the desired learning outcome.

- **Practical Impact**: Students may vary in their perception of realism of physical interactions in AR, which may impact their behaviors in the environment. If the way a student navigates an environment is a critical component of the virtual experience, educators should be aware of the possibility of some students treating virtual objects as not physically present and can consider designing appropriate repercussions for colliding with virtual objects. Regarding virtual object manipulation, when designing an AR simulation, instructors should consider what elements they would like to simplify in the virtual world and what elements they would like to retain as close to realism as possible. Due to the artificial difficulty of some parts of the experience, such as manipulating and installing virtual objects, some parts of the simulation could include virtual features that assist the user to the extent that operating the simulation is not the primary challenge and the users can focus on the overarching objectives rather than non-value-added subtasks. For example, if moving an object from one point to another does not add value to a specific type of learning experience, educators could allow object movement by gestures that allow interaction from a distance or by voice command.

4.6.2.4 Reflection: Evidence For and Against Remediating Errors

Table 9. Emergent Codes Within the Category "Reflection".



	Observational Code	**Definition Criteria**	**Examples**	**Relationship to Authentic Learning Component**	
Reflection	Reflection On Single Action	Student verbalizes a reflection on one of the specific actions they took during the build	-Participant plans to install dimensional piece, realizes "oh so I would need the tape measure for this" -Participant orders and installs a tire swing, notes "Now that's set, looks fun"	+	Students formatively reflect on their actions as they design and build
	Reflection On Overall Process	Student expresses realization regarding overall process	-Student in the middle of building process notes, "wait I can check [my budget and schedule on] this computer...I should probably be doing that" -Student installs several safety features and notes, "it is now infinitely safer"	+	Students were formatively reflecting on their overall process as they designed and built
	Change Decision	Participant counters previously made decision	-Student returns ladder that appeared shorter than what they had expected -"I'm now moving the slide to the other side, I don't like it over here"	+	Students reflect on their process such that they reconsider a previous decision and modify it
	Remediate Error (Evidence For)	Student verbalizes a mistake or undoes a previous action that prevents another desired action	-"I realized [the area I just built is] boxed in, so I have to create a door here"	+	Students reflect on their process to the extent that they recognize an error and modify it
	Remediate Error (Evidence Against)	Student installs an object in an implausible way and leaves it uncorrected	-Participant installs a ladder askew and leaves it -Student removes existing slide, places newly ordered slide and does not notice that original slide entrance is too small for the new slide	-	Students did not reflect on their process sufficiently to recognize and fix all errors

Reflection is a critical component of authentic learning and allows students to think about what they are learning, both during and after the learning experience. While many of the emergent codes regarding reflection were intuitive and expected based on the experience design (Reflection on Single Action, Reflection on Overall Process, and Changing Decision), one emerged with both evidence for and against, warranting further discussion: Remediating Errors (Table 9). It has been suggested that AR construction environments enable self-remediation (McCord *et al.*, 2022) and the observations from this experience support the idea that AR visualization environments allow students to recognize their mistakes in many cases. For example, one student was constructing a portion of the playhouse and noted, “so I realized [the area I just built is] boxed in, so I have to create a door here”. Another student took down an existing unsafe slide and went to place a new slide they had ordered in its place but realized the original slide entrance was too small for the new slide. They removed the new slide, then removed the original opening, then placed the new slide in the area once again. In this process, the student noted an error and had to expend time and energy to fix the error. The emergence of this code shows that AR has the potential to encourage self-remediation as students design, build, make mistakes, and expend the energy to fix their mistakes, a process that encourages deep and lasting learning (Fischer *et al.*, 2006).

While many students saw and corrected errors, there were also instances when students left mistakes uncorrected on the playhouse in the limited time given them to build. Some even noticed errors verbally but physically did not correct them, such as the student who struggled to install a large tube slide, noted that it was still askew, but decided to move on as to not waste time. From previously presented results, it was evident that many students reported difficulty manipulating and placing objects within the virtual space. For some students, this meant leaving a piece not perfectly installed or placed even if they noted awareness of its incorrect placement. In a few cases, either simulation glitches or user error resulted in a piece not being able to be moved at all. In other cases, the students could move a piece of equipment, but would struggle to get it aligned or oriented correctly. In addition to placement errors, there were a few sequencing errors noted in students’ builds. For example, that same slide opening that was noticed and corrected by one student was left by another student, where the opening was left too small for the newly installed slide, resulting in a trip hazard and access issues. Overall, conflicting evidence emerged for students' ability to self-remediate within the AR simulation. Most likely, the object manipulation challenges that have been consistently reported played a large factor in students' abilities and motivations to achieve accuracy and fix mistakes. Finding and fixing mistakes represents a desirable difficulty (Bjork, 2011) in an authentic design and construction activity, so the experience design could be modified to allow students to focus more consistently on this challenge.

- **Practical Impact**: AR presents a valuable opportunity for students to reflect on their process and self-remediate and in many cases allows students to notice and fix their own errors independently. However, since this is not without exception, difficulty with virtual object interactions should be minimized to the extent possible to enable the actual correction of mistakes when they are noticed. As in previous sections, favoring voice commands over hand gestures for object manipulation where possible may reduce frustration and free mental energy for reflection. In addition to optimizing the virtual environment design, educators should plan a protocol that meets their objectives with error correction.

4.7 Limitations

Researchers in other fields have reported that simulations have the potential to simulate authentic learning in many regards, but still realistically note that any simulation of reality warrants discussion on the nature of 'authenticity' (Herrington *et al.*, 2004). By necessity, a simulation is a 'view' of reality and not 'reality', so suspension of disbelief is necessary to some extent in all simulations. Since this experience was a technology-based simulation, there were some elements that were left to abstractions. For example, if there was a glitch in the software and an object could not move, participants were told to verbalize where they intended to move the object, imagine that it was moved there, then continue with the activity. Additionally, participants were also allowed to make assumptions regarding what could not be observed. For example, the simulation took place indoors, but was intended to be an outdoor play space, so some assumptions were made regarding where direct sun would hit or where there might be shade trees.

To maximize student participation, the research sessions were intentionally kept to one hour, leaving 20 minutes of independent build time. This is a short amount of time to evaluate and construct renovations to a structure, even one as small in scope as a playhouse. This time limit also limits the ability of the researchers to draw conclusions about certain facets reported of authentic learning that require longer periods of time to observe. Due to the time limit and the individual testing design, not all authentic learning elements were included in the observation analysis (see Table 4 and Methods Section). These elements, such as collaboration and sustained investigation, could be included in an expanded simulation or future research and it is possible that these elements could add, detract, or somehow otherwise interact with the other findings and could each represent interesting topics for future research. While the first 20 minutes in an individual setting may not be fully indicative of what may emerge over an extended period of time and with additional elements, the fact that students are showing evidence of authentic learning behaviors even in this focused environment shows potential for AR to elicit these types of behaviors.

4.8 Conclusion

Overall, this paper presents an AR simulation of an authentic learning experience in a building design and construction context, analyzing how student user behaviors and perceptions either parallel or do not parallel authentic learning theory components. The concepts presented in this paper can guide educators in understanding the aspects of authentic learning that can be effectively replicated through simulated experiential learning, while also considering the challenges that may emerge in simulations of an AR format. It is known that authentic learning has undeniable benefits for students, especially in AEC domains. This paper presents evidence that AR has the potential to simulate crucial aspects of authentic learning, while noting some areas where conflicting results in AR's ability to simulate authentic learning can guide future implementation.

The experience was designed to mimic a physical authentic learning experience as closely as possible, and most of the emergent codes did indeed parallel what would be expected in a physical scenario. However, perhaps the more noteworthy findings are the counterintuitive results, where researchers observed conflicting results within a category, like the nuanced perceptions of realism within the simulation, where parts of the experience were generally seen as realistic (the environment itself), while other elements were generally perceived as unrealistic (physically manipulating virtual objects). Another area with conflicting results was in the higher-level thinking category, where students displayed a propensity both for and against engaging in critical thought during the scenario, perhaps distracted from higher-level thought at times by difficulties with some sub-tasks of the experience, like moving and placing virtual objects. For those considering future implementation of similar scenarios, it is suggested that those designing the environment consider not just what seems to be most ‘realistic’, but rather what experience development decisions will best facilitate the overarching objectives of the experience. In some cases, this may require counterintuitive decisions regarding ‘realistic’ interactions, choosing a perhaps less realistic way of interacting (like choosing voice commands over physical object manipulation) to eliminate potential distraction from higher-order tasks. Overall, the nuances within the student behavioral and perceptual evidence provide insight into the ways in which this AR simulation does and does not parallel authentic learning in an AEC context, which can provide guidance for future educators who want to strategically target specific learning outcomes in their own classroom.

Chapter 5

CONCLUSION

In this dissertation, three papers were presented, each with their own study design and unique results, but with all three related to and building off each other. Figure 19 presents the major findings from each of the paper, which are summarized and discussed subsequently.

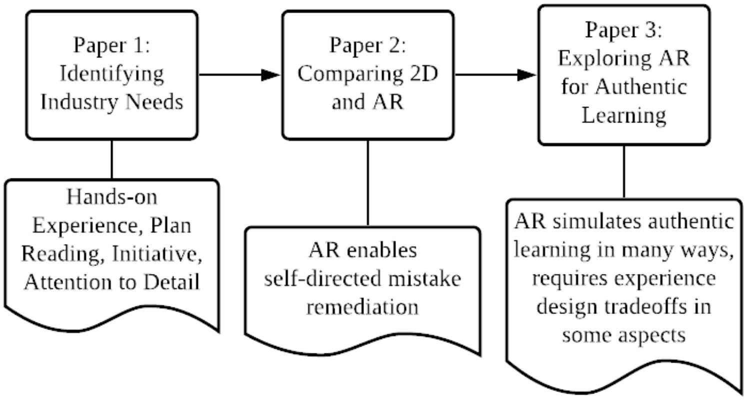


Figure 19. Flowchart of the Three Papers Presented in This Dissertation, With Key Findings Presented Below Each Paper Topic.

5.1 Discussion of Papers

In summary, Paper 1 explored the skills and competencies most desired by industry professionals for the students to develop in our construction programs. The method of analysis was unique in that it utilized a dataset comprised of 5 years of direct evaluations from current industry leaders to their interns who were construction students at the time. Their responses took the form of open-ended evaluations, where evaluators indicated which skills and competencies they would most like to see from their student employee. This method allowed these industry professionals to come up with any skills or competencies without limit, leading to a rich dataset of free responses. These responses revealed three thematic groups, including personal attributes, professional attributes, and technical skills. Within the personal attributes category, industry evaluators frequently mentioned wanting students to show initiative and pay more attention to detail. Above all, industry evaluators wanted to see more experience from students before graduating. In addition to the skills and attributes called for by industry, the paper also included a comparison with academic literature, exploring the frequency of mention for each of the industry attributes and skills in recent construction education literature. This comparison revealed some agreement, like in the call for hands-on experience. However, it also highlighted some of the differences between the knowledge, skills, and attributes called for by industry and those emphasized by academics. For example, many of the technical and practical skills frequently reported as important by industry received far less mention in academic literature, like legal contracts or scope considerations (see Figure 6). This disparity corresponds with a longstanding conflict in engineering education regarding the necessary balance of teaching fundamental knowledge versus technical or practical skills, with educators tending to emphasize the former and practitioners the latter. This debate within engineering education dates back to the 1900's with reports such as that by Charles Mann, which acknowledges the balance between "fundamental sciences" and "practical" knowledge, noting that there is a limit to the workload that students can handle so necessary trade offs have to be made (Mann, 1918). Another foundational report by William Wickenden acknowledges the complexity of engineering as a discipline, as it is tied to constantly evolving social premises regarding the role of the engineer. For example, replacing labor with machines and the growing need of management within engineering require curricular considerations within the lab and lecture courses available to students (Wickenden, 1930). The constant trade-offs between industry and academia ideally push each group to consider what is best for the preparation of students for industry. In light of these considerations, there is value in exploring educational interventions that can potentially target multiple skills and attributes simultaneously in order to maximize student learning without overburdening students with unmanageable workloads. The research in this dissertation explores a potentially high-impact method of targeting desirable skills and attributes, namely AR.

Paper 2 explored AR as an educational tool for allowing students to explore hands-on skill development, specifically in a task-based construction context, where the purpose was to converge on a correct execution of a process, in this case, correctly sequencing a wood-framed wall with a window. Since hands-on learning is known to develop desirable attributes (Holt *et al.*, 2012), simulating hands-on learning is worth exploring as a cost-effective alternative. The specific task presented here required students to utilize 2D drawings to come up with their sequence, either in a 2D format or by physically moving virtual objects in AR. Observations during subject testing in each of these situations revealed that mistake recognition and self-remediation were facilitated through this AR experience much more than in the 2D format, even though the 2D format was quicker and easier for students. Being able to visualize the process as they built enabled students to make critical checks throughout the process.

Paper 3 expanded the exploration of AR to a simulation of an authentic learning environment, with an ill-defined problem presented to students who could come up with multiple, disparate solutions. In this experience, students were asked to balance a number of tasks, including many of the technical skills called for in Paper 1, like scheduling, safety, and cost considerations. This authentic learning experience was designed to be situated in a real-world context, where students could potentially experience the well-known benefits of full-scale hands-on design and build experiences but without the prohibitive, recurring costs of real construction materials. Subject testing was performed, where students were observed designing and building in this environment. Their experiences and perceptions were documented and analyzed within the framework of authentic learning theory, where a number of critical components of authentic learning were considered in comparison with the student experience. From observing students in this environment, there was typically strong evidence that AR can simulate an environment that allows students to experience and demonstrate authentic learning components, but there were mixed results for some. These conflicting results not only provide an understanding of some of the potential limitations of AR for authentic learning, but also provide guidance for development of future AR-based simulations of authentic learning. One of the key takeaways from this study is the importance of considering the overarching objectives of a learning experience and what virtual environment design decisions may contribute most to facilitating the targeted authentic learning outcomes. For example, in this experience, students found many of the physical interactions with virtual objects, although designed to be realistic, to be difficult and frustrating, which potentially distracted them from critical thought and reflection processes. In this case, perhaps using alternative methods, like voice commands, could make the task-based processes less frustrating and free mental energy for higher-level learning tasks. When determining the most important components of a learning exercise, considering the results of Paper 1 and the skills most consistently reported of interest could be a beneficial springboard.

5.2 Overarching Contributions

The three papers presented previously related to each other in motivation, with aspects of one naturally leading to the next. In addition to connections in their motivation, there were also some common themes within the results and contributions of each. Connections between the overarching contributions of each paper are explained subsequently.

One common thread throughout these three research initiatives was the concept of self-regulation. First, one of the results from the internship reviews was that industry practitioners wanted more initiative and attention to detail from students. It is often difficult to target these personal attributes with traditional classroom exercises and learning. In the 2D vs AR comparison, the AR environment enabled students to visualize a process as they constructed, which facilitated self-remediation as students paid attention to details and fixed mistakes. Finally, in the simulation of authentic learning, students worked independently and took on an entire design and construction process, placing them in a simulated authentic learning environment and requiring them to make and follow through with decisions. Throughout this process, students were able to take the initiative to reflect on their experience, both on specific decisions and on the overarching process. While this experience enabled students to engage in self-remediation in many instances, there were also instances where students became distracted or frustrated with more small-scale aspects of the experience, like moving and placing virtual objects, which may have caused them to overlook minute details or opportunities for improvement. These findings suggest that educators should strategically design their AR experiences so that small, insignificant tasks are not difficult or distracting, which can draw away students' attention from more big-picture tasks like finding and fixing mistakes.

- Takeaway 1: Strategically designed AR experiences show high potential for enabling students to engage in self-remediation as they learn construction skills.

Perhaps the culminating contribution of this work is the exploration of the potential of AR to virtually simulate high-cost authentic learning experiences. Paper 1 found a strong call from industry for students to enter the workforce with more experience. Paper 2 explored AR as a learning resource that provides hands-on experience in a focused, task-based context where the goal was to converge on a correct execution of a construction process. This task seemed to challenge students in beneficial ways, like requiring them to take time and carefully consider their process. Since AR showed promising potential for educational experiences within a focused context, Paper 3 broadened the scope of the types of learning AR could facilitate. In addition to broadening the application of AR, Paper 3 also targeted key attributes and skills that were called for in Paper 1, in particular the call for hands-on experience. This paper looked at AR as a method of simulating an authentic learning scenario where students were tasked with completing the entire design and construction process for a small structure. This experience also required students to work independently, targeting the initiative that was so frequently requested by industry in Paper 1. The observational results of this experience were analyzed through the lens of authentic learning theory to determine which elements of authentic learning could be replicated in AR. Observations from subject testing indicated the AR simulation paralleled most of the authentic learning components considered, but that observations within several authentic learning components had conflicting evidence. Within these categories, some student behaviors and perceptions paralleled authentic learning and others differed from what would be expected in an authentic learning situation. These counterintuitive and nuanced findings were presented in detail, like conflicting student perceptions of realism and mixed abilities to engage in critical thought, along with specific recommendations for educators who are considering implementing similar AR activities to replace high-cost physical alternatives. The nuance of the findings in this paper provide tangible guidance for those considering implementing similar educational interventions.

- Takeaway 2: AR shows high potential for replicating high-impact components of hands-on and authentic learning scenarios, like self-remediation and , without the recurring cost of physical materials. However, some parts of the experience may require design trade-offs, where simplifying one part of the experience can be considered to enable students to focus on higher-impact aspects of the experience. Overall, the understanding of the parallels and detractors when using AR to simulate authentic learning presented in this work can provide direct guidance to future implementations of this technology in AEC educational contexts.

Overall, the findings of this dissertation can guide future educators when considering AR as a potential teaching tool. Current students have the potential to become the future leaders of the industry. If they are expected to grapple with the infrastructure crisis facing the country and fill the roles of the quickly retiring current workforce, they will need to leave their educational experience better trained than the previous generation. If students are expected to be better trained, then educators must innovate in the ways that their formal educational training is delivered. To meet this need for preparation and a clear call from current industry practitioners for more experience from graduating students, AR has promising potential as an educational tool that educators can utilize for simulating hands-on and authentic learning experiences, and this work contributes to the body of knowledge by presenting both the positive and the potentially conflicting aspects of AR in this context to guide future work.

5.3 Future Work

The AR playhouse application developed for the work presented in this dissertation represents a significant development effort by the research team. The application was developed over the course of several semesters. The author of this work led teams of undergraduate developers to assist in the technical creation of the application within the Unity Game Engine (using C# language). The time and personnel resources required to create this application were significant. If the intention of presenting this work is to allow future educators to replicate this process, it may be necessary to streamline the development processes and reduce the time and resources necessary to develop similar content. While developing the content for this application, the developers also created documentation for various parts of the process. Additionally, some of the code developed for this specific application can be generalized for any application that requires similar interactions. For example, the code developed that allows users to attach or remove objects from a main structure could apply to many construction, engineering, or other scenarios. The code developed for this work will be used to create an empty template that allows developers to import their own models and geometry and apply existing code to the environment instead of developing it from scratch. This template, in conjunction with the documentation, will provide a springboard to enable development of similar applications in a fraction of the time. It is anticipated that these tools will, with proper implementation, allow educators to create AR applications in a reasonable amount of time, removing many of the barriers that currently make creation and implementation of these activities prohibitive for most educators.

NOTES

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2. Approved through Arizona State University's Intitutional Review Board Requirements under STUDY00006302.

3. Approved through Arizona State University's Institutional Review Board Requirements under STUDY00006302.

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APPENDIX A

SET OF CONSTRUCTION DRAWINGS FOR WOOD-FRAMED WALL

This appendix includes a full set of drawings and activity provided to the students in the second study presented in this dissertation in PDF format, including (20) window elevation (21) top-of-sill floor plan (22) header floor plan and (23) windowsill floor plan.

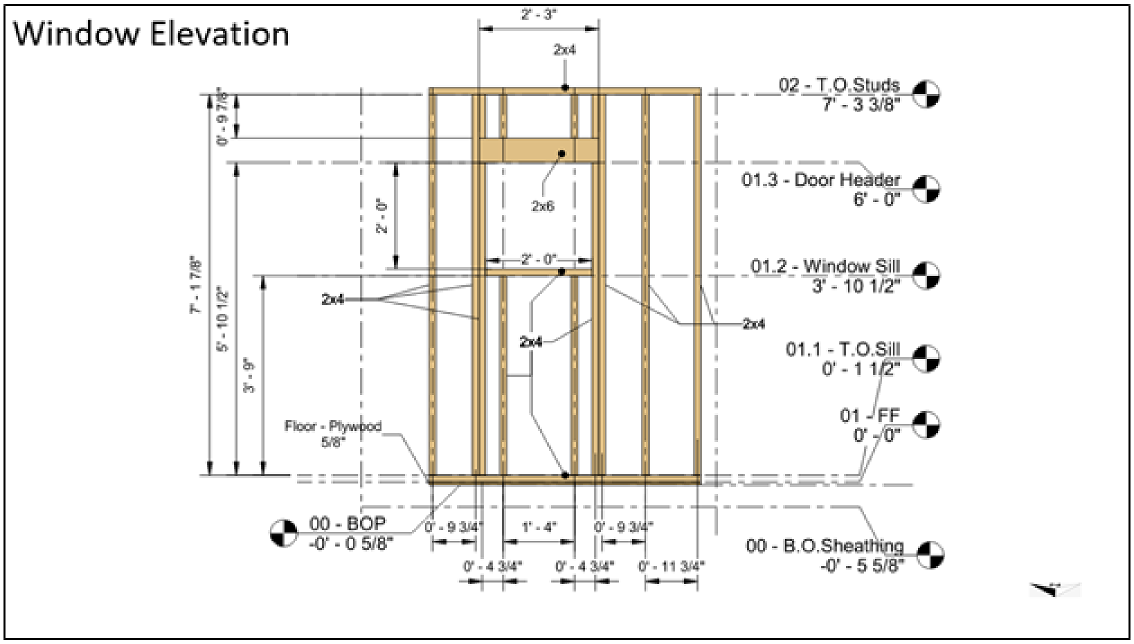

Figure 20. Window Elevation

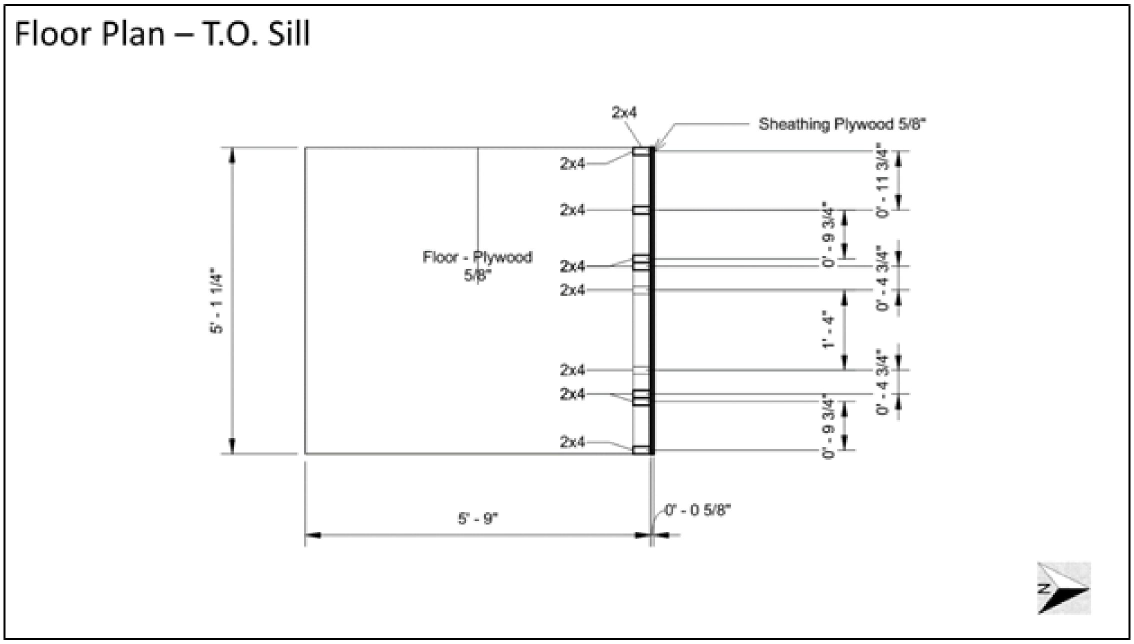

Figure 21. Top-Of-Sill Floor Plan

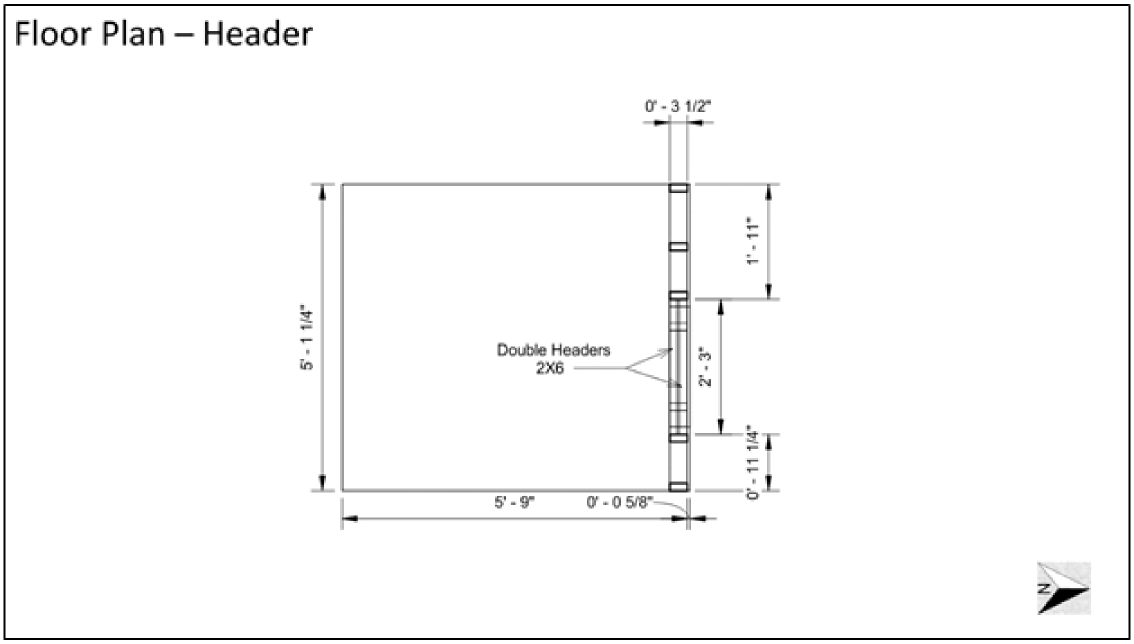

Figure 22. Header Floor Plan

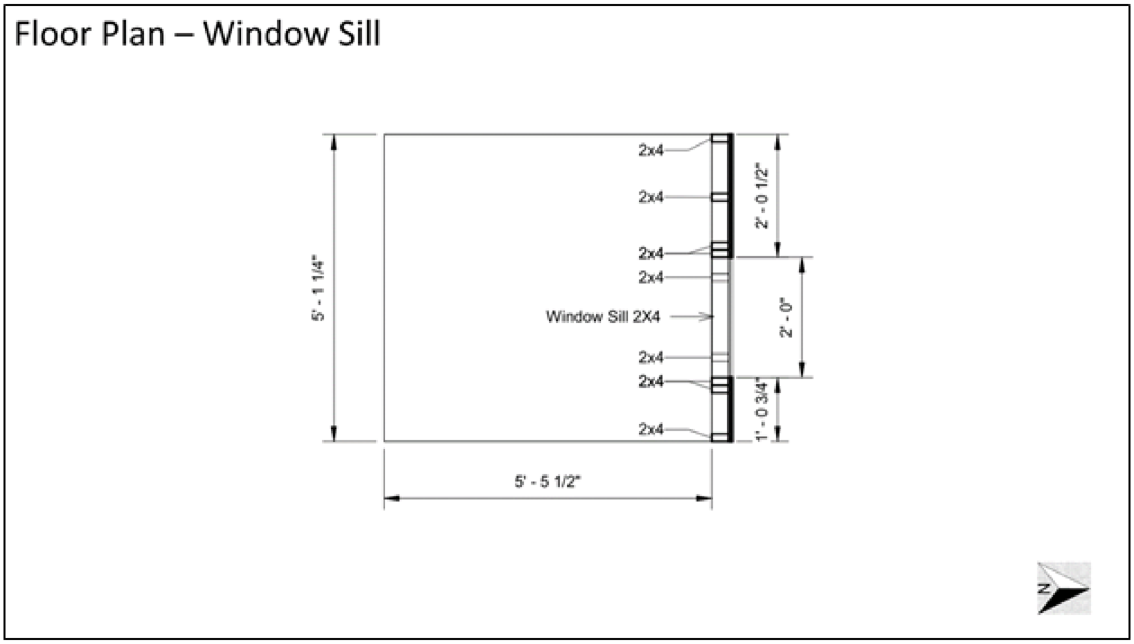

Figure 23. Windowsill Floor Plan