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Focusing on Improved Construction Quality through Augmented Reality Training

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Abstract
This research examines augmented reality (AR) technologies for improving construction quality control, focusing on material placement accuracy and workforce skill gaps. The industry struggles with labor shortages and outdated practices. AR enhances visualization, training, and inspection, aiding design interpretation and precision. This study assesses four AR devices—iPhone, iPad, HoloLens 2, and SiteVision—in a simulated construction task. The HoloLens showed the highest accuracy with the other devices exhibiting lower performance. While none of the devices met industry precision standards, the AR tool proved valuable for training and participants found them useful for learning. These findings highlight AR's potential in construction education and quality control, warranting further research.

Keywords: *Augmented Reality, Workforce Training, Quality, Construction Education*

1. Introduction and Background

The construction industry faces significant challenges in maintaining quality and productivity due to a shrinking skilled labor force and outdated inspection practices (Allen, 1985; Welfare, Sherratt, & Hallowell, 2021). Traditionally, industry professionals have relied on visual assessments of two-dimensional (2D) documents for three-dimensional (3D) construction tasks, a skill developed over years of experience. However, the retirement of seasoned professionals and the inexperience of newer practitioners contribute to inefficiencies, errors, and declining industry standards (Arditi & Gunaydin, 1997).

Addressing this skills gap requires innovative solutions, such as Augmented Reality (AR), which overlays digital information onto real-world environments, improving material placement and inspections (Sawhney et al., 2020). Unlike Virtual Reality (VR), AR enhances real-world tasks by providing contextual information, making it particularly valuable for construction. Research in many industries highlights AR's potential to enhance training, improve safety, and support quality control (Li et al., 2018; Harikrishnan et al., 2021).

However, AR's practical effectiveness in quality control for construction remains underexplored. For instance, the precise placement of underslab utilities is critical, as errors can lead to costly rework and project delays – there is a desire to improve this process. AR has been shown to facilitate inspectors in various industries and with numerous work tasks (Sawhney, 2020). Yet AR's ability to provide accurate overlays must be rigorously tested to determine its reliability and dependability (Hajirasouli et al., 2022; Adebowale & Agumba, 2022). Initially, this study aimed to evaluate different AR modalities in a simulated construction environment, but as it evolved, its impact as an educational tool was discovered and warranted testing. Therefore, by incorporating AR into construction education, this research aims to equip students with foundational skills that can enhance industry practices that focus on improving quality. As AR technology advances, its widespread adoption could modernize training, improve quality control, and boost overall industry productivity (Sawhney et al., 2020).

2. Methodology

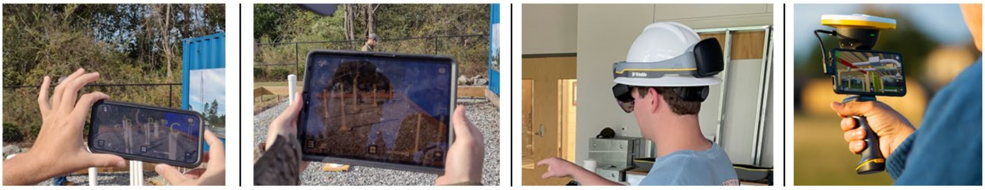
This study employs an action research methodology, integrating findings from previous interdisciplinary research that has evaluated the effectiveness of augmented reality (AR) tools in various contexts (Kahn et al., 2021; Scherl et al., 2021). The foundational premise is that superimposing virtual overlays onto real-world construction environments can enhance student preparedness for professional roles by bridging the gap between theoretical classroom concepts and practical construction quality inspections while instilling a sense of work experience to enhance the student's learning. While the primary objective was to evaluate the precision and accuracy of an AR-based quality inspection tool, the broader aim is to establish an innovative approach to training future quality inspectors. Additionally, the study will provide a nuanced context as to whether this AR tool can provide tangible benefits for industry professionals, particularly in enhancing quality control processes within real-world construction settings.

2.1. Participants

The participant cohort (N=32) comprised undergraduate students enrolled in a four-year construction management program at a university in the southeastern United States. Participation was voluntary, and the experiment was conducted during a regularly scheduled class session. These students were selected to represent an unskilled workforce in training, preparing for future roles as project managers or superintendents in commercial construction. Aged between 20 and 24 years, the participants had varying levels of hands-on construction experience, primarily gained through internships. These prior experiences provided a foundational understanding of construction practices and quality control procedures. The selection of this participant group was intended to enhance the credibility and reliability of the study by ensuring that the findings accurately reflected the learning process of emerging professionals in the construction industry.

2.2. The AR Learning Tools

To examine how different AR interactions influence learning outcomes, this study employed four AR devices, offering students a diverse AR experience. The selected devices included the Apple iPhone 13 Pro Max (iPhone), the Apple iPad Pro 12.9-inch 5th Generation (iPad), the Trimble XR10 HoloLens 2 (HoloLens), and the Trimble SiteVision GPS receiver with its HPS2-integrated handle (SiteVision) see Figure 1. The inclusion of the iPhone and iPad was based on their widespread familiarity and daily use among students, although no specific data were collected to assess the impact of this familiarity on learning outcomes. The HoloLens and SiteVision were incorporated for their advanced AR capabilities, allowing students to engage with innovative tools that hold potential for real-world construction applications. By integrating these devices, the study aimed to provide insights into the effectiveness of different AR technologies in construction quality control training and learning.



a. b. c. d.

Figure 1. AR Tools (a.) iPhone, (b.) iPad, (c.) HoloLens, and (d.) SiteVision

2.3. The Simulated Learning Environment

The AR experience was developed using Autodesk Revit, creating a *digital twin* virtual model of a simulated construction project site as the basis for a plumbing pipe layout experiment. The model replicated an actual construction project site, which consisted of wooden edge forms measuring 20 feet by 15 feet (6.1 m × 4.6 m), simulating a flat surface representative of the pre-stage for a concrete slab-on-grade (Figure 2a). This setup mirrored real-world construction conditions, where accurate plumbing pipe placement is critical to prevent costly rework and schedule disruptions after concrete placement.

a. b.

Figure 2. (a.) Simulation Construction Site and (b.) Proxy Plumbing Pipe

The simulation site was outdoors in a partially shaded area to replicate typical construction conditions, enhancing the study's external validity (Figure 2a). This setting aimed to improve student learning and retention by mimicking real-world scenarios. While AR functionality challenges in outdoor conditions were anticipated, no data were collected on their impact, assuming they would not significantly affect learning outcomes. After model development, the digital twin was integrated into the Trimble FieldLink MR platform, ensuring consistent AR experiences across all four devices and minimizing data variability.

2.4. Learning Activity Workflow

Before the study with student participants, a control point was established by aligning the digital twin model with the physical construction site. This alignment ensured accurate overlay of the virtual model onto the real-world environment, enabling students using AR devices to position proxy plumbing pipes correctly. Researchers later assessed placement accuracy by comparing student placements to predetermined control positions in the digital twin. The study aimed to evaluate the feasibility of AR devices for real-world construction quality inspections while also improving students' inspection skills through a competitive element.

Participants were randomly assigned to one of four AR device types and received brief training based on their familiarity. Each student used their assigned AR device to position plumbing penetration proxies within a simulated slab-on-grade area, adjusting placements to match virtual representations.

Researchers measured the accuracy of each student's placement using a robotic total station, comparing it with control data. Upon completing the task, participants filled out a perception survey evaluating their experience with the AR tool, its impact on learning, cognitive load, and effectiveness in construction education. The NASA Task Load Index (NASA-TLX) was also used to assess the cognitive demands of the AR tool, as excessive load can hinder learning effectiveness (Sweller, 2020).

3. Results and Discussion

Students positioned proxy pipes independently during the experiment. While accuracy and precision data were collected, this paper focuses on the learning experience. Results showed the highest accuracy and precision with the HoloLens, followed by the iPad and SiteVision, with the iPhone performing the worst. However, all measured errors exceeded industry tolerance standards, indicating that while AR enhances learning, it is not yet a viable replacement for industry tools in precise material placement. Further improvements are needed before AR can meet construction accuracy and precision requirements.

3.1. Student Perceptions Survey

At the conclusion of the experiment, students provided feedback on their learning experience with the AR tool. The assessment focused on four key parameters, measured using a 5-point Likert scale:

1. The AR tool **HELPED** my learning.
2. The AR tool **DISTRACTED** me from learning.
3. The AR tool was **EASY** to use.
4. I would **RECOMMEND** this AR tool to others.

Table 2 summarizes students' perceptions regarding their learning experience with the AR tool, offering insights into its perceived effectiveness, usability, and overall impact on the educational process.

Table 2. Student Perceptions of the AR Learning Tool (N=32)

CATEGORY	SD	D	Neither	A	SA
1.HELPED	-	-	6%	17%	78%
2.DISTRACTED	67%	17%	6%	-	11%
3.EASY	-	-	6%	22%	72%
4.RECOMMEND	-	-	3%	17%	81%

The survey results support the effectiveness of the AR tool as a valuable educational aid in construction management training. Overall, students reported that the tool enhanced their learning experience, with minimal reports of distraction. However, 11% of participants indicated that they experienced some level of distraction, which may be attributed to the novelty of AR technology in a traditional learning environment. Since no additional data were collected to investigate this discrepancy, future research should explore the potential impact of cognitive overload or technological unfamiliarity on learning outcomes.

Given that students in this demographic are generally proficient in using digital tools, it is unsurprising that they found the AR interface intuitive and easy to use. Moreover, their strong willingness to recommend the AR tool for future learning applications further reinforces its perceived value as an educational resource. These findings suggest that AR technology holds significant potential for enhancing construction management education by integrating innovative, interactive learning methodologies.

3.2. Task Load Index

The NASA-TLX is a widely used subjective workload assessment tool designed to measure cognitive and physical demands imposed by tasks. Its use in this study evaluates six dimensions: mental demand, physical demand, temporal demand, effort, performance, and frustration. As this is educational research, NASA-TLX is an effective instrument for assessing students' cognitive load and effort when interacting with technology in the classroom. By quantifying workload perceptions of the student's experience in this study, it can be determined whether a technology-enhanced learning tool facilitates or hinders student engagement. Applying NASA-TLX as a part of the exit survey enables the researchers to identify usability challenges, optimize instructional design, and enhance the effectiveness of digital learning environments. Table 2 enumerates the NASA-TLX data results for this study.

Table 2. NASA-TLX Survey Results

DIMENSION	MEAN	SD
MENTAL	-4.31	4.54
PHYSICAL	-5.78	3.70
TEMPORAL	-5.64	3.25
PERFORMANCE	7.17	2.83
EFFORT	-3.00	5.17
FRUSTRATION	-6.75	3.58

The mean MENTAL effort score (-4.31, SD = 4.54) suggests that students perceived the cognitive demands of the AR tool as relatively low. Similarly, PHYSICAL effort (-5.78, SD = 3.70) and TEMPORAL effort (-5.64, SD = 3.25) were also rated low, indicating minimal strain in terms of physical exertion and time constraints. The PERFORMANCE metric (7.17, SD =

2.83) reflects a strong perception of task success, suggesting that students felt confident in their ability to complete tasks effectively using the AR tool in this experiment. The overall EFFORT score (-3.00, SD = 5.17) aligns with the low mental, physical, and temporal effort ratings, reinforcing that students did not find the AR tool overly demanding. Lastly, the general FRUSTRATION score (-6.75, SD = 3.58) suggests a low level of frustration, indicating that the AR interface did not significantly impede the learning experience. These findings suggest that the AR tool was well received by students, imposing minimal workload while facilitating effective learning. This is a significant finding and one that positively aligns with Sweller's (2020) concerns when incorporating technology into the educational experience. The low frustration and effort levels, combined with the high-performance rating, highlight the AR tool's potential as a user-friendly and efficient educational resource for construction management training. However, further research may be needed to assess individual differences in cognitive load and long-term retention effects associated with AR-based learning.

4. Conclusion

The findings of this study underscore the significant potential of AR technology as a powerful and efficient educational tool for construction management training. Results from the NASA-TLX assessment reveal that students reported minimal cognitive, physical, and temporal demands, coupled with high perceived performance and low levels of frustration. These outcomes strongly indicate that AR can enrich learning experiences without introducing undue mental or physical burden. Moreover, student feedback demonstrated a high degree of acceptance and ease of use, reinforcing AR's practical viability as an instructional resource within academic settings.

However, the study's limited sample size (N=32) restricts the generalizability of these results. To substantiate these findings, future research should incorporate a more diverse participant base, encompassing a range of educational backgrounds, experience levels, and institutional contexts. Additionally, further investigation is warranted into the long-term retention benefits of AR-based learning and its effectiveness in enhancing real-world construction competencies. Examining factors such as cognitive overload and user familiarity with technology will also be critical in refining AR instructional design to maximize educational outcomes.

Broadening the application of AR across various construction disciplines and project scenarios could yield deeper insights into its adaptability and value in professional training environments. Comparative studies assessing AR-assisted learning versus traditional training methods would provide stronger empirical support for its role in addressing the skills gap within construction management education. As AR technology continues to advance, sustained research efforts will be vital to optimize its integration and ensure it aligns with the evolving needs of the construction industry.

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