

Full length article

Mixed reality environment for learning sensing technology applications in Construction: A usability study

Omobolanle R. Ogunseiju^a, Nihar Gonsalves^a, Abiola A. Akanmu^{a,*}, Diana Bairaktarova^b,
Doug A. Bowman^c, Farrokh Jazizadeh^d

^a Construction Engineering and Management, Myers Lawson School of Construction, Virginia Tech, Blacksburg, VA, United States

^b Engineering Education, Virginia Tech, Blacksburg, VA, United States

^c Computer Science and Center for Human-Computer Interaction, Virginia Tech, Blacksburg, VA, United States

^d Construction Engineering and Management, Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA, United States

ARTICLE INFO

Keywords:

Mixed Reality
Sensing Technologies
Eye Tracking
Laser Scanning
Construction Education
Usability study

ABSTRACT

Mixed reality is gradually becoming ubiquitous and significant in education owing to the inherent benefits of active participation and tacit knowledge development in a safe and engaging environment. However, limited studies have explored design features that facilitate its use as a pedagogical tool in construction education, particularly in equipping students with experiential skills that are otherwise challenging to obtain due to resource constraints and limited access to construction sites. By evaluating eye tracking, usability questions, and think-aloud protocol data and verbal feedback, this study investigated the usability of a mixed reality environment designed for equipping construction engineering students with competencies for deploying sensing technologies on construction projects. Results revealed features such as accuracy of represented construction activities, quality of animations, and easy access to information and resources as important for designing efficient mixed reality learning environments. While the usability data suggested that the user interface was usable, eye tracking provided profundity on encountered difficulties with the user interface. Through concise outline and sequential design of the user interface, this study revealed that knowledge scaffolding can improve task performance in a mixed reality learning environment. This study adds value to existing literature, in particular by providing insights into the affordances of mixed reality environments that address the technological gap between the construction industry and construction engineering education. The mixed reality learning environment contributes to the cognitive apprenticeship theory through the use of game objects to develop procedural knowledge for addressing construction industry challenges with sensing technologies.

1. Introduction

The rise in awareness of the potential of sensing technologies has spurred an increase in the adoption of the technologies in the construction industry [1]. Sensing technologies used in the construction industry extract useful information about construction resources to improve project productivity [2–4], quality [5], and workforce safety [3,6] and health [7]. These sensing technologies are broadly classified into vision and component-based sensing systems [8,9]. Component-based sensing technologies include radio frequency identification devices (RFID), global positioning systems (GPS), inertia measurement units (IMU) while vision-based sensing technologies include cameras,

laser scanners, and ground penetrating radars. Of these sensing technologies, laser scanners are one of the most widely used, with varying applications across the different phases of a project's lifecycle [9]. While laser scanners hold promise for mitigating the long-standing productivity, safety and health challenges of the construction industry [9–12], they also trigger the need for workforce with the competencies for implementing the laser scanners [9].

As explained by Blinn and Issa [13], laser scanning involves operational skills such as what a laser scanner is, how to operate a laser scanner, and how interactions with the scan settings influence scan time and quality. Blinn and Issa [13] further explained scan planning as another important skill in laser scanning, such as the significance of

* Corresponding author.

E-mail addresses: omobolanle@vt.edu (O.R. Ogunseiju), gonsnihar@vt.edu (N. Gonsalves), abiola@vt.edu (A.A. Akanmu), dibairak@vt.edu (D. Bairaktarova), dbowman@vt.edu (D.A. Bowman), jazizade@vt.edu (F. Jazizadeh).

<https://doi.org/10.1016/j.aei.2022.101637>

Received 30 June 2021; Received in revised form 19 April 2022; Accepted 15 May 2022

Available online 28 May 2022

1474-0346/Published by Elsevier Ltd.

selecting optimal scan locations and the effects of weather conditions on laser scanning. Acquiring these skills often requires some field experience for understanding the impacts of site limitations on scanning processes [13]. However, a recent survey [9] revealed that despite the high rate of adoption of laser scanners, the inclusion of laser scanning as a stand-alone course in construction institutions is limited. The cost of laser scanners and limited access to construction sites for experiential learning (due to due to safety, weather, and schedule constraints) are some of the barriers that imposing significant constraint to equipping students with the requisite skills. Even when access is granted, there may be limited opportunities to try out different scenarios that students could encounter in the future. These and similar challenges have prompted increasing interest in the exploration and adoption of virtual environments such as virtual reality and mixed reality [14–16]. According to Dung [17], Forbes predicts that there will be a spontaneous investment in virtual learning environments from \$107 to \$350 billion over a period of 10 years (2015–2025). With the possibility of virtual learning environments being more effective than traditional classroom lectures, it has been argued that virtual and mixed reality learning environments would be a solution to teaching experiential skills [18]. This is due to well recognized affordances of these reality environments such as heightened engagement [19,20], increased motivation [21–23], self-oriented [24] and self-paced learning [25,26]. Pan, Cheok, Yang, Zhu and Shi [27] explained that virtual learning environments enabled by virtual and mixed reality, encourages teamwork and project-based learning amongst students. While virtual reality offers complete immersion, mixed reality provides a virtual environment where learners are still cognizant of the real world. Mixed reality provides a safe environment for learning technologies and dangerous equipment [28,29]. For example, Kim, Go and Choi [30] proposed an mixed reality environment where drone users can safely learn drone navigations when surrounded with different obstacles. Such training may be unsafe in real life, posing hazards to the drone pilot and surrounding environment. Despite the benefits of mixed reality, the utilization in construction education is still nascent, particularly in equipping students with hands-on learning of sensing technologies.

With a growing adoption of laser scanners in the construction industry, mixed reality can provide a safe, engaging and motivating learning environment for students [19,31]. Construction engineering students can be equipped with skills that will prepare them to develop sustainable solutions to the industry's challenges. In a previous study [1], the authors described a mixed reality environment for equipping students with competencies for deploying sensing technologies such as laser scanners on construction projects. To understand what features of the learning environment could be improved to facilitate learning, it is essential to conduct a formative evaluation prior to the implementation of the pedagogical tool [32,33]. By conducting a formative evaluation such as usability study, the quality of an end-user's experience while interacting with the technology can be assessed [34,35]. Usability studies also reveal the success or failure of such technology to meet the intended design goals by evaluating its capability to enable users to achieve specified goals with effectiveness, productivity, and satisfaction in specified use cases [35]. Also, usability study can reveal the effectiveness of a user interface, since a well-designed interface can help the environment to be successful, while a poorly designed interface can frustrate users and discourage the adoption of the environment [36]. Therefore, to ensure that the developed mixed reality environment meets its intended goal of equipping students with skills for implementing sensing technologies (e.g., the laser scanner) on construction projects, it is important to assess its usability during the development phase.

In this paper, the usability evaluation of a mixed reality environment designed for learning sensing technologies, with an example of laser scanning, is presented. Nielsen [37] and Punchoojit and Hongwarittorn [38] explain satisfaction, learnability, efficiency, error, and memorability as the five dimensions of usability. While learnability is assessed

by the ease of completing tasks measured through task completion time and subjective evaluations, efficiency assesses how quick the tasks were completed and level of difficulty, memorability assesses if the system was remembered after sometime, and satisfaction measures the pleasantness of experience with the environment [39]. Since the mixed reality environment is intended as a pedagogical tool, the usability evaluation focuses on the learnability, efficiency, and satisfaction with the features of the learning environment. This study adopts a usability questionnaire and a think-aloud protocol and verbal feedback as subjective evaluations of the learning environment, and eye tracking as an objective measure of cognition to assess the usability of the learning environment as a pedagogical tool for construction engineering education. The paper first presents a literature review to demonstrate the need for the study and puts the work in proper context by describing the theoretical underpinning of the study. Next the paper describes the adopted methodology and presents a case study application of the mixed reality learning environment and results of the adopted methodology. The mixed reality learning environment contributes to the cognitive apprenticeship theory through the use of game objects to develop procedural knowledge for addressing construction industry challenges with sensing technologies. The study also contributes to the affordances or characteristics of mixed reality environments that can facilitate learning of laser scanning. Lastly, this study reveals the usability of mixed reality learning environment for providing hands-on experience in construction education.

2. Background

The learning environment evaluated in this research consists of sensing technologies currently deployed in the construction industry, which will be interacted with via mixed reality for equipping construction engineering students with the skills for implementing sensing technologies on construction projects. Therefore, this section provides a literature review of the applications of sensing technologies in the construction industry, the concept of mixed reality and applications for current and future workforce education, opportunities for usability evaluation with eye tracking data and the theoretical underpinning of the study.

2.1. Sensing technologies in the construction industry

There is a rapid growth in the adoption of sensing technologies in the construction industry. As revealed by Ogunseiju, Akanmu and Bairaktarova [9], 85% of surveyed construction companies have started adopting different sensing technologies such as laser scanners, drones, RFID, GPS, accelerometers, and gyroscopes. Based on their functionality, sensing technologies can be classified as image-based sensors such as laser scanners, drones, cameras, and ground-penetrating radar and component-based sensors such as GPS, RFID, accelerometers, and gyroscopes. Component-based sensing technologies provide identification and localization information about track resources on the jobsite. On the other hand, image-based sensing technologies procure data in the form of still images, point clouds, and videos, which are often utilized for modeling purposes [40].

Extant studies have explored the potentials of sensing technologies in the construction industry. Ergen, Akinci and Sacks [41] proposed the use of RFID to improve the lifecycle management of construction components for optimizing supply chain in the construction industry. Pradhananga and Teizer [42] reported the efficacy of GPS for automated equipment tracking for optimized layout decision-making and jobsite performance. Laser scanners have also been widely adopted in the construction industry. Ogunseiju, Akanmu and Bairaktarova [9] reported the adoption of laser scanners for procuring existing conditions, deck pre-pour scans, and obtaining grades and levels. Sanhudo, Ramos, Martins, Almeida, Barreira, Simões and Cardoso [43] presented a laser-scanning framework for acquiring buildings' geometric data. Shanbari,

Blinn and Issa [44] reported the potentials of laser scanning and building information modeling for improved accuracy in quantity management. Studies have also shown that sensing technologies can be jointly employed for combined benefits, such as the works of El-Omari and Moselhi [45] who explored a combination of laser scanners and RFID for automated progress reports on the jobsite.

This increasing adoption of sensing technologies, especially laser scanners, informs the need to prepare the future workforce with the skills to implement the technologies in the construction industry. However, limited access to construction sites to try out these technologies and the capital-intensive nature of sensing technologies are currently envisaged as some of the obstacles to equipping construction-engineering students with the needed skills.

2.2. Concept of mixed reality

Virtual environments are gradually becoming ubiquitous and significant in education owing to their ability to stimulate active participation [27,46,47] and tacit knowledge development [48–50]. The synergism of immersion and feeling of being present in the virtual world is often perceived as the cardinal and propelling features of virtual environments [51]. Virtual learning environments can be presented as virtual reality, augmented reality, and mixed reality. While virtual reality (VR) provides an immersive environment through its hardware and software components where students can interact and feel present in a digital world [52], augmented reality (AR) affords a learning environment where virtual objects are super imposed in the real world [53,54]. Mixed reality (MR) encompasses realities (e.g., VR and AR) that mix sensory stimuli from virtual and real components. While VR, provides a fully digital environment, and the feeling of being transported elsewhere without awareness of the real world, MR affords an environment where interaction with the real world is perceived, and both virtual and real-world are seamlessly blended [54]. Hence, MR provides better and robust learning as students do not feel completely alone, and teachers do not have to be represented as virtual avatars because students are still aware of the real world [55]. Teachers can see students' nonverbal cues, such as facial expressions, which are useful for gauging student's understanding [56–58]. Such student–teacher communication and interactions are important for improving learning outcomes such as critical reflections, recognizing unsuccessful outcomes, and drawing conclusions [59]. This is a benefit of MR learning environments over fully immersive virtual environments. Since MR allows awareness of the real world, obstacles can be avoided and students can learn in a safe virtual environment [60]. MR also provides a collaborative learning environment where students can learn together as a team [61]. Multiple students could see each other, interact with the same virtual world, and communicate easily with each other about elements of the virtual world through natural gestures.

Although this present study does not benefit from some of the advantages of MR such as interactions with real world information, and improved student–student and student–teacher interactions, the choice of MR fostered a seamless usability evaluation as participants could see the moderator and communicate easily during the study. Likewise, the moderator could easily observe participants' facial expressions and detect when they are experiencing interaction difficulties with the environment and when additional guidance was needed. Furthermore, the choice of MR would have these benefits in future real-world use of the learning environment when implemented as a pedagogical tool in construction education.

2.3. Mixed reality in construction education and workforce training

A number of studies have explored the potentials of MR as a learning environment for enhancing design comprehension, design review, and safety awareness in construction education and workforce training. In the construction industry, MR has been introduced for safety training of

construction workforce. For example, Segura, Moreno, Brunetti and Henn [62] presented a MR system for training construction workforce about safe machinery utilization and discussed usability issues during development of the system. Owing to the potentials of MR to facilitate training in a realistic environment without exposure to occupational safety hazards, Bosch , Abdel-Wahab and Carozza [63] proposed the development of an MR system for training construction trade workers. The authors reported the efficacy of the MR system for simulating a real jobsite where trade workers are exposed to different site conditions. Chalhoub and Ayer [64] leveraged the potential of MR for direct visualization of conduit systems from building information models. The authors reported better design communication with the MR system when compared to communicating with traditional 2D drawings.

In the area of construction education, MR has mostly been explored for teaching design communication. Wu, Tesei, Ayer, London, Luo and Gunji [50] proposed the design and assessment of a MR-based wooden frame lab for facilitating design comprehension and knowledge transfer. Azhar, Kim and Salman [65] assessed the impacts of MR and VR for teaching communication and safety education in construction programs. The authors reported the efficacy of MR and VR for improved learning experiences through engagement and active learning. Using VR and MR mockups, Wu, Hartless, Tesei, Gunji, Ayer and London [66] compared student novices' and professional experts' evaluation of the design of a tiny house. The authors reported similar behavior and performance between student novices and professional experts using the MR mockups. With the highlighted benefits of MR for enhancing education in the construction industry, it is significant and meaningful to explore its impact on equipping construction students with the required competencies for learning sensing technologies.

2.4. Eye tracking approach to usability studies

In human–computer interaction, usability can be defined as the ease of use, quality of use, satisfaction, and effectiveness of achieving the designed goal of an environment [67]. Usability measures can vary from the measure of efficiency such as task completion time, measures of satisfaction such as questionnaires, and measures of perception towards the environment [67], which is similarly adopted in relevant studies (Table 1). However, by procuring and analyzing eye movements in form of fixations, saccades, and gaze plots (scanpaths), eye tracking affords an objective evaluation of users' perception, and behavior within an environment [68]. According to Poole and Ball [69], eye tracking is often adopted in usability studies to track participants' eye movements (e.g., per time and sequence of movement from one location to another). Importantly, eye tracking reveals the cognitive process and perception during learning [70] and is often adopted in formative evaluation of learning environments. However, selected eye-tracking measures may

Table 1
Mixed Reality in construction education and workforce training.

References	Sector	Evaluation Tools
Wu, Tesei, Ayer, London, Luo and Gunji [50]	Design comprehension	Pre- and post-survey, audio, and video recordings
Wu, Hartless, Tesei, Gunji, Ayer and London [66]	Design review	Pre- and post-survey, think-aloud protocol audio, and video recordings
Chalhoub and Ayer [64]	Electrical design communication	Task duration, pre, and post-activity questionnaires
Azhar, Kim and Salman [65]	Construction communication and safety education	Task duration, questionnaires
Segura, Moreno, Brunetti and Henn [62]	Construction machinery training	Usability questions and perceptions
Bosch�, Abdel-Wahab and Carozza [63]	Construction workforce training	Learners' observation and reflection

vary across studies and is dependent on the context of use (Table 2).

Several studies in construction have explored the efficacy of eye-tracking data as a usability measure. For example, Zou and Ergon [71] employed eye-tracking data to assess the impacts of salient architectural features on human-building experience. Mohammadpour, Karan, Asadi and Rothrock [72] utilized eye-tracking to assess the extent of end-users' participation in the design of a construction project. Shi, Du and Zhu [73] assessed the importance of engineering information formats on cognitive development during the performance of pipeline maintenance tasks. In construction education, Wang, Huang, Liao and Piao [74] investigated the effectiveness of AR for learning steel installation in construction education. The authors employed eye-tracking metrics such as fixation counts, fixation duration, and average fixation duration to compare cognitive processes in AR, text graphs, and physical model-based learning environments. With only a few studies adopting eye-tracking for measuring usability in construction engineering education, this study employs eye-tracking data as an objective measure of cognitive processes in the learning environment. To ensure a holistic usability evaluation of the learning environment, this study further adopted subjective measures such as usability questionnaires and audio recordings of a think-aloud protocol and verbal feedback during the experimental task.

2.5. Theoretical motivation

The design and evaluation of the learning environment are supported by the theory of cognitive apprenticeship, which explains learning as a situative cognitive process. The theory posits that cognitive development happens when learners' previous knowledge is enhanced through the reification of cognitive activities [75]. Collins, Brown and Newman [76] explains that learning can be enhanced through modeling, scaffolding, coaching, fading, articulation, and reflection on their problem-solving skills. In particular, 'Scaffolding refers to the help which thereby enables learners to engage more successfully in activity at the expanding limits of their competence, and which they would not have been quite able to manage alone, i.e. within the 'zone of proximal development' [77]. Brown and Ferrara [78] explained the zone of proximal development as the difference between actual development based on the learner's problem-solving skills and potential development decided through problem-solving abilities when guided.

To ensure knowledge is scaffolded, as described in Section 3.1, the learning environment is divided into three scenes in this hierarchy: (1) explore jobsite scene; (2) sensor tutorial scene; and (3) sensor implementation scene. While learners explore construction activities, risks, and resources in the explore jobsite scene, the sensor tutorial scene provides a sequential guide on the use of each sensing technology in a less distractive learning environment (Fig. 2b). That is, in the sensor tutorial scene, only construction resources associated with the selected construction activities are displayed. In the sensor implementation scene, learners deploy the same sensing technologies on resources of activities in a busy construction site (Fig. 2c). Hence, learning in each

scene builds upon knowledge acquired in the previous scene. Learning was also scaffolded via the use of menu interfaces to guide the learning process in each scene. According to Lunsford [79], Vygotsky posits that students often possess the inherent ability to learn which can be fostered through assistance and learning strategies. Hence, each scene further entails affordances that assisted and enhanced the learning phases. In the sensor tutorial scene, it is hypothesized that learners are in a state of potential development and the stated scene features seek to facilitate proximal development of the required competencies. Compared to the sensor tutorial scene, learners are not instructed on the procedural steps to operating the sensing technologies. It is expected that in the sensor implementation scene, learners demonstrate actual development of the competencies for deploying the represented sensing technologies on construction activities.

3. Methodology

The development of an MR environment to enable the learning of sensing technologies was investigated. Usability assessment techniques are leveraged to evaluate the features of the MR environment that will improve the learning outcome. The methodology outlined in Fig. 1 was adopted for the usability study. This section describes the composition and evaluation of the learning environment.

3.1. Description of the learning environment

In a previous study [1,80], a learning environment was developed to equip construction engineering students with skills for implementing sensing technologies on construction projects. The learning environment comprises of virtual sensing technologies and applications of the sensing technologies that are typically implemented in the construction industry. The sensing technologies and applications were earlier established via a survey of construction industry practitioners and a focus group of selected industry practitioners who have experience implementing the technologies on construction projects as explained by the authors in a previous study [80]. The learning environment, shown in Fig. 2, was developed using Unity3D game engine and consists of three scenes in this hierarchy: (1) 'Explore jobsite' scene; (2) 'Sensor tutorial' scene; and (3) 'Sensor implementation' scene [1]. 'Scene' as used in this paper represents environments where learning occurs within the MR learning environment. In the 'Explore jobsite' scene, students are presented with a series of construction activities (Table 3), and they can selectively explore and familiarize themselves with tasks, operations, resources involved and workspaces (Fig. 2a).

During the experimental tasks, participants will be asked to identify the construction resources and risks within the selected activity. For example, on selecting 'truck load and haul' activity, students will be presented with an activity where a backhoe loads some gravel unto a truck (Fig. 2a). The construction resources such as workers, equipment, and materials to be identified are labelled (Fig. 2a), and the risks to be identified (e.g., safety hazards) are embedded in the activity.

Afterward, students can proceed to the 'Sensor tutorial' scene where concise information and procedural knowledge of the implementation of each sensor are presented to them. This scene features only one activity per sensor, and students are guided to implement selected sensors to address risks to project performance such as cost, quality, schedule, and safety risks (Fig. 2b). This scene encourages students to construct their own knowledge of the workings of each sensing technology. After learning how each sensor works, students can proceed to the 'Sensor implementation' scene, where they perform selective implementation of sensing technologies on construction activities (Fig. 2c).

3.2. Evaluation of the MR learning environment

This section describes the evaluation of the learning environment and presents the facilitating technology, experimental procedure, data

Table 2
Related eye-tracking studies in construction.

References	Context	Eye-tracking data
Wang, Huang, Liao and Piao [74]	Steel construction	Fixation counts, fixation duration, average fixation duration
Zou and Ergon [71]	Architecture	Heatmaps, completion time, Fixation counts, Time to first fixation
Mohammadpour, Karan, Asadi and Rothrock [72]	Construction project design	Fixation counts and fixation duration
Shi, Du and Zhu [73]	Engineering information formats for task performance	Review fixation ratio, stationary gaze entropy, pupil dilation

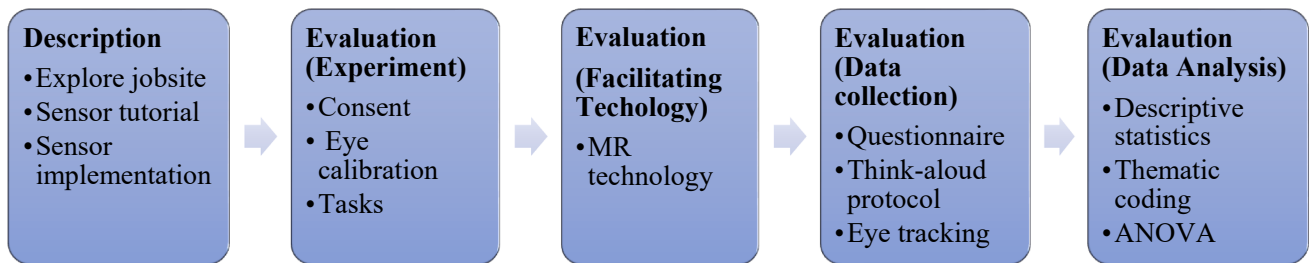


Fig. 1. Methodology.

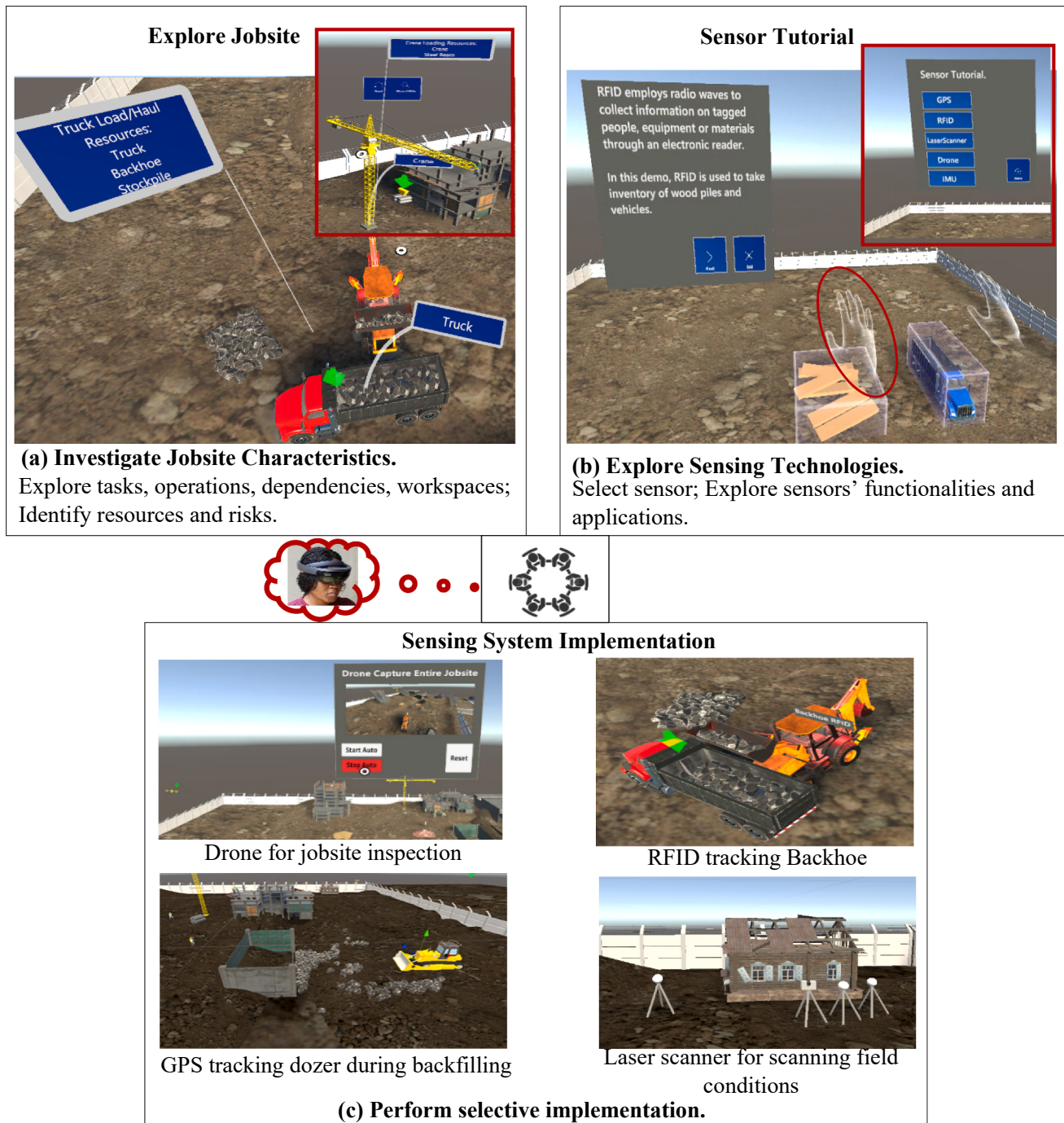


Fig. 2. MR environment for learning sensing systems [1].

Table 3
Represented construction activities, resources, and sensors [62,80].

Activities	Resources			Sensors
	Equipment	Material	Personnel	
Dozer backfilling	Dozer & roller	Stockpile		GPS
Crane loading	Crane	Steel Beam	Supervisor	GPS
Materials delivery	Truck	Rebars in truck		GPS & RFID
Material Handling (1)			Worker 1	GPS & RFID
Truck Load/Haul	Loader & Truck	stockpile		GPS & RFID
Material Inventory		Log, steel, & wood		RFID
Material Handling (2)			Worker 1,2, & 3	RFID & GPS
Cladding		Building 1		Laser scanner
Flooring		Matte slab		Laser scanner
Stockpile unloading		Stockpile 1&2		Laser scanner
Renovation		Old building		Laser scanner & Drone
Site inspection & safety inspection		Overall jobsite		Drone
Painting		Building 2	Painter	IMU, GPS & RFID
Labor work			Labor	IMU, GPS & RFID
Carpentry			Carpenter	IMU, GPS & RFID
Drywalling		Drywall	Drywallor 1&2	IMU, GPS & RFID
Masonry		Bricks & wall	Mason	IMU, GPS & RFID

collection, and data analysis. The usability study was conducted after approval was obtained from the Virginia Tech Institutional Review Board (IRB). The experiment was designed to procure demographics, objective data from eye-tracking, and subjective data from usability questionnaires and think-aloud protocol.

3.2.1. MR facilitating technology

The blending of the real and virtual worlds afforded by MR allows opportunities for immersive and interactive experiences. MR affords easy navigation and completion of tasks in a safe learning environment. Since the experimental tasks in this study entailed activities and interactions in three learning scenes, it was important that the participants can safely navigate the learning environment. Also, the ease of navigation could impact the usability of the learning environment, which further influenced the selection of MR for this study.

The study was conducted with Microsoft HoloLens 2, a MR head-mounted display (HMD). Participants were required to wear the HMD, through which they interacted with the learning environment. Microsoft HoloLens has been widely adopted in academia for providing MR experiences [81]. However, the restricted field of view (FOV) limits the projected visualizations in the application window. While popular MR devices like HoloLens 1 has a FOV of 34° [81], and Magic leap has a FOV of 50° [82], HoloLens 2 offers a FOV of 52°, a resolution of 47 pixels per degree, a display rate of 60 frames per seconds and an integrated eye tracker. The eye-tracking feature of the HoloLens 2 obtains data on the eye gaze directions, eye gaze origins, eye hit positions, eye data timestamp, and target location at approximately 30 frames per second.

3.2.2. Experimental procedure

Eighteen students (15 males and 3 females) from Virginia Tech were

recruited to participate in the usability study. The participants were required to have some background knowledge in construction engineering. Only students from building construction, construction engineering and management, and civil engineering were recruited for the study. The experimental procedure illustrated in Fig. 3 was followed. Owing to the COVID-19 risks, participants were required to sign two consent forms before participating in the study. The first consent form was particularly for safety practices to mitigate risks of transferring the COVID-19 virus across participants during the study, while the second consent form was specific to obtaining permission to participate in the usability study. The study was only introduced to the participant after obtaining the signed consent forms. The participants were required to complete the first section of the questionnaire (i.e., demographics) before beginning the experiment. Afterward, the workings of the HoloLens was briefly explained to the participants. Participants were advised to adjust the HMD to their comfort. Participants calibrated their eye gaze to ensure accurate eye-tracking data. The study began after a successful eye calibration was achieved. Participants were immersed in the learning environment where they completed specific tasks in the 'Explore jobsite', 'Sensor tutorial', and 'Sensor implementation' scenes. Think-aloud protocol and verbal feedback were adopted during the study. The scenes explored by the participants and their verbal responses were recorded via the HoloLens and a mobile recording device respectively. Participants completed the usability questionnaire after the study. This procedure was repeated in the same order for all participants.

3.2.3. Data collection

This study procured self-ratings on the usability of the learning environment through a usability questionnaire and responses from the think-aloud protocol and verbal feedback. Eye-tracking data during the experimental tasks were obtained through the embedded eye-tracker. The data collected from this study is further elucidated in this section.

3.2.3.1. Usability questionnaire. The questionnaire was divided into three sections to procure information on the design and usability of the learning environment. The first section was focused on obtaining data on the demographics of the participants such as their age, and level of experience with MR or VR and sensing technologies. The second section procured data on the precision of the virtual site reflecting real jobsite conditions, and issues experienced while using each of the sensors. The third section was designed to capture the perception of the participants of the usability of the virtual sensors and the user interface of the learning environment using a five-point Likert scale (1–5). 1 represents strongly disagree, and 5 represents strongly agree.

3.2.3.2. Think-aloud protocol and verbal feedback. Similarly, the study employed a think-aloud protocol to obtain immediate feedback on the usability of each scene in the learning environment and verbal feedback on responses to specific questions relating to each scene. While engaged in the 'Explore jobsite' scene, participants were asked to identify the construction resources and risks associated with the selected activity. In the 'Sensor tutorial' scene, participants were asked if the demos improved their learning of the sensor, suggestions for improving the demo to improve their learning experience, and issues with the interface e.g., menu, tagging resources, and moving the sensor components. Within the 'Sensor implementation' scene, participants were asked about issues they encountered with manipulating components of the sensing technologies and these responses were audio recorded. The think-aloud protocol procured other comments based on their experience in the learning environment.

3.2.3.3. Eye-tracking data and task completion time. This study harnessed the eye-tracking feature of HoloLens 2 for procuring eye movements during the experimental tasks. As explained in previous studies

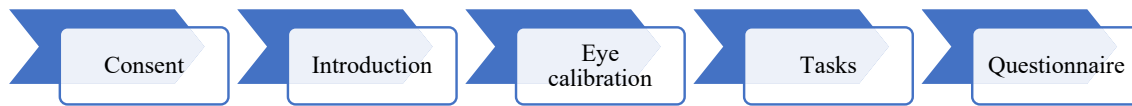


Fig. 3. Experimental procedure.

[83,84], fixation is the static eye movement with underlying information processing. Just and Carpenter [85] explains that there is an instantaneous relationship between eye fixations and cognitive process in the mind. In this study, the eye tracking metrics (shown in Table 4) e. g., fixation counts, fixation duration, and average fixation duration were extracted and analyzed for each area of interest within the sensor tutorial and sensor implementation scenes. According to Zou and Ergon [71], areas of Interest (AOI) can be explained as specific areas in the design that are of interest to the researcher. The AOI for the laser scanning process are the components of the laser scanner (e.g., tripod, scanner, and targets 1, 2, and 3) and the menu interface that enables interaction with the components (e.g., menus for the Laser scanner setup and scan settings).

3.2.4. Data analysis

Fig. 4 illustrates the types of analysis that were performed on the data obtained from the participants. Similar themes were extracted from responses to the open-ended questions. To extract responses from the think-aloud protocol, recorded videos of each participant's interaction with the learning environment was extracted and transcribed. For each question, similar themes were searched out within the transcript to further categorize and describe the data. Demographics and other usability questions were analyzed using descriptive statistics such as mean and standard deviation. To analyze, the eye-tracking data, desired eye-tracking metrics, such as gaze duration for each area of interest were sorted using Microsoft excel. This is feasible because the eye-tracking data includes the target names of each object in the learning environment. Fixation was detected from the gaze duration based on the minimum fixation duration [86,87]. According to Olsen [88], minimum fixation duration of 60 ms can be adopted to preserve fixations during reading, although typical minimum fixation duration can vary from 80 to 100 ms [89,90]. Hence, to account for fixation during text-reading of the menu interface and fixations on the sensor components, a minimum fixation duration of 75 ms was utilized. To compare the cognitive load across the AOIs within each scene, one-way ANOVA using Kruskal-Wallis test was conducted. This test was also selected because most of the dataset were not normally distributed, and Kruskal-Wallis does not assume a normal distribution of data. This statistical analysis was similarly adopted to compare cognitive activities between the scenes. For all the analyses, significant effects were reported at a 95% confidence level, and all pairwise comparison using Dunn method was conducted on significantly different mean ranks. All statistical analysis of the eye-tracking data was performed on SPSS.

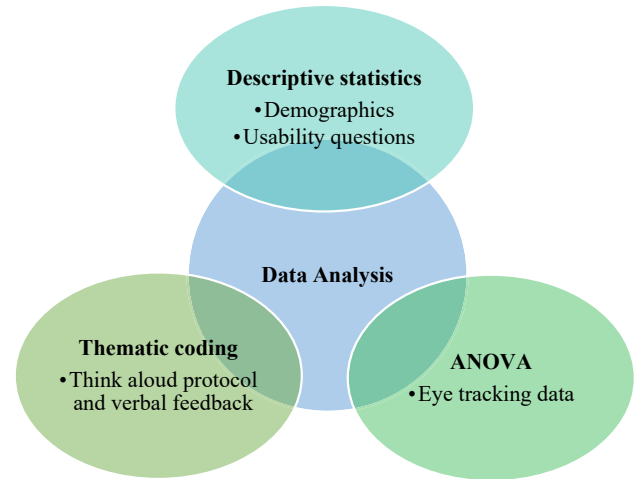


Fig. 4. Data Analysis.

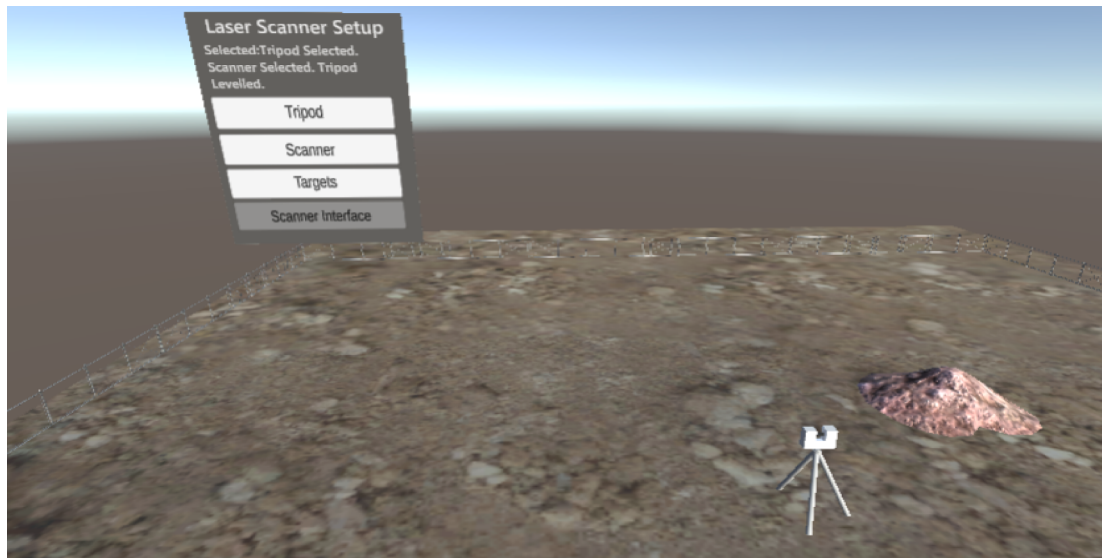
4. Case study – An example of laser scanning within the learning environment

This section describes a case study of the usability evaluation of laser scanning within the learning environment. Although the usability study was conducted on the five sensing technologies represented in the learning environment, only the evaluation of the laser scanner is presented as a case study. The choice of the laser scanner is driven by a study by Ogunseiju, Akanmu and Bairaktarova [1] which identified the laser scanner as the most adopted sensing technology in the construction industry with a wide range of applications across all phases of a project lifecycle. Besides, laser scanning involves multiple cognitive stages requiring technical expertise and decision-making skills. Shanbari, Blinn and Issa [44] who described the learning phases of laser scanning, explained that while operational principles of a laser scanner and scan settings are fundamental learning phases, decision-making is required for selecting scanner location, occlusion avoidance, positioning of laser scanners, and analyzing the impact of on ongoing construction activities for successful laser scanning. Blinn and Issa [13] further noted that poor planning and scanning techniques can result in unusable scans culminating in time wastage and costly rescanning. To acquire these skills, experiential learning of laser scanning is significant.

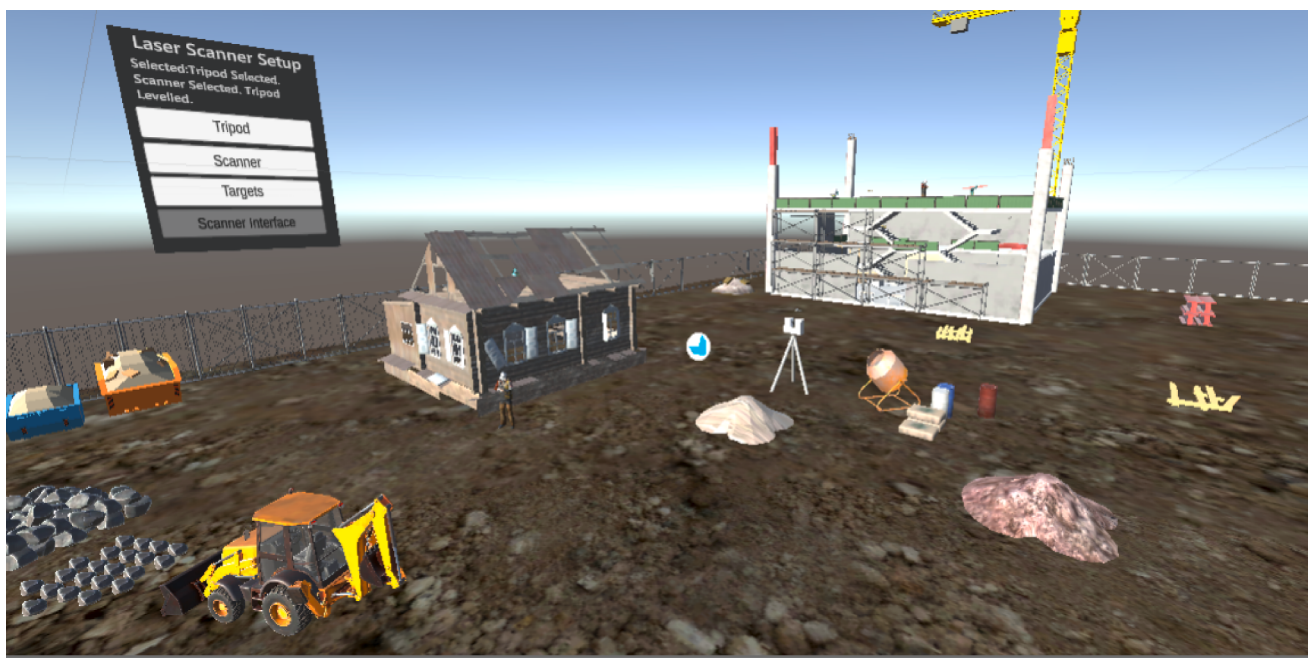
According to Blinn and Issa [13], laser scanning often requires some field experience for understanding the impacts of site limitations on the scanning processes. Therefore, to expose students to construction activities during scanning and improve their knowledge of the interaction between laser scanning processes and construction activities, participants were engaged in the three scenes of the learning environment: (1) Explore jobsite; (2) Sensor tutorial (Fig. 5a); and (3) Sensor implementation (Fig. 5b) scenes. In the 'Explore jobsite' scene, participants explored the potential benefits of laser scanner for scanning an existing stockpile and identified all the construction resources within the location of the activity. This acquainted them with the interaction between the resources involved in the activity. Afterward, participants proceeded to the 'Sensor tutorial' scene where the procedure for scanning a stockpile was demonstrated. Compared to the 'Sensor implementation' scene, the 'Sensor tutorial' scene is aimed at enhancing students' knowledge of the workings of a laser scanner in a less-crowded

Table 4
Eye-tracking features and task completion time.

Features	Description
Areas of interests (AOI)	Areas of Interest (AOI) are the components of the laser scanner (tripod, scanner, and targets 1, 2, and 3) and menu interface (laser scanner setup and scan settings).
Fixation counts	Fixation counts represent the number of times a participant fixates on an area of interest.
Fixation duration	Fixation duration is the cumulative time spent fixating on an area of interest.
Average fixation duration	Average fixation duration is the ratio of fixation duration to the number of fixations (fixation counts).
Task completion time	Total task duration for each participant during the experimental tasks.



(a) Sensor tutorial scene.



(b) Sensor implementation scene.

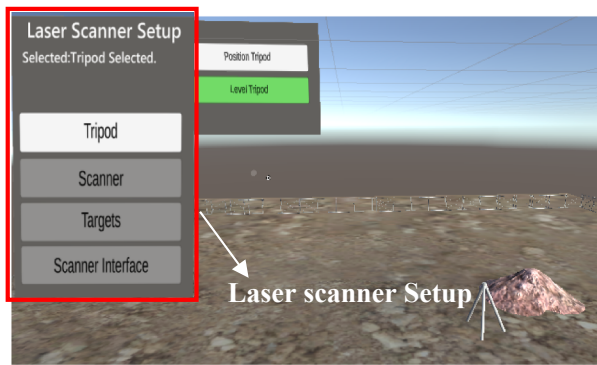
Fig. 5. Laser scanning location in sensor tutorial and sensor implementation scenes.

environment (with only necessary construction resources for learning the selected sensor) which is proposed to facilitate improved attention and cognition. Peculiar to the 'Sensor tutorial' scene is an interface providing the definition of a laser scanner and a procedural guide to capturing images of resources with a laser scanner.

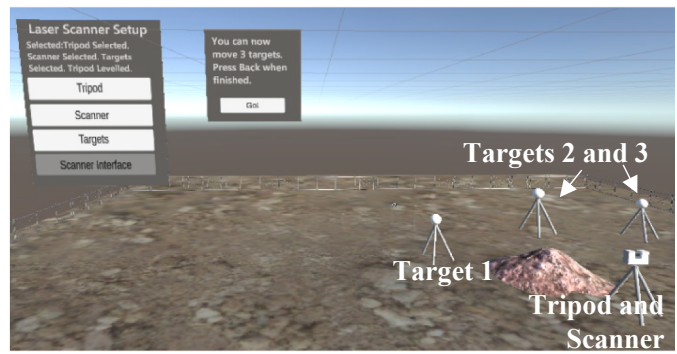
The laser scanner in the learning environment was modeled after two commercially available laser scanners - Faro Focus M70, and Trimble X8. Laser scanning in the learning environment was guided by a menu interface broadly divided into 'Laser scanner setup' and 'Scan settings'. On selecting the laser scanner from the list of sensors, the 'Laser scanner setup' menu interface is activated. This menu interface enables users to interact with the laser scanner components such as tripod, scanner, and targets 1, target 2 and target 3 (Fig. 6b). Targets are markers that support the registration or stitching of scans from different locations. Targets are positioned in such a way that a minimum of two common targets

is visible in each scan. The farther the targets are from the scanner, the lesser the probability of being recognized in the scans. When placing the targets, it is important that they are not occluded and are visible from the scanner [91]. Hence, the environment was modeled to enable the participants to select and move the laser scanner components to their desired locations.

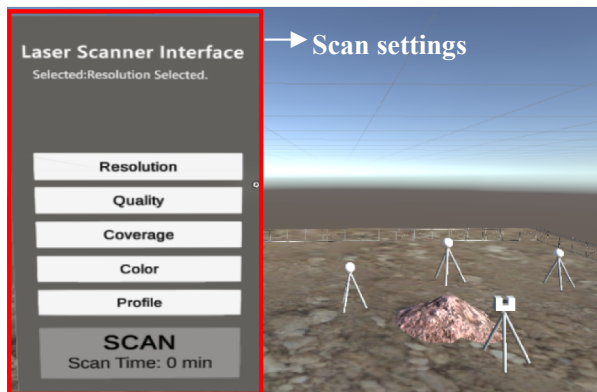
The menu interface was designed based on the sequential process involved in laser scanning to scaffold learners' knowledge. For example, it is important to determine the scanner location, place, and level the tripod stand before mounting the scanner on the tripod stand. Furthermore, the menu interface was designed to ensure engagement with one laser scanner component before the next can become interactable. For example, on selecting the tripod button, participants will be required to position the tripod in desired location for scanning the stockpile, and level the tripod before the scanner button can be activated (Fig. 6a).



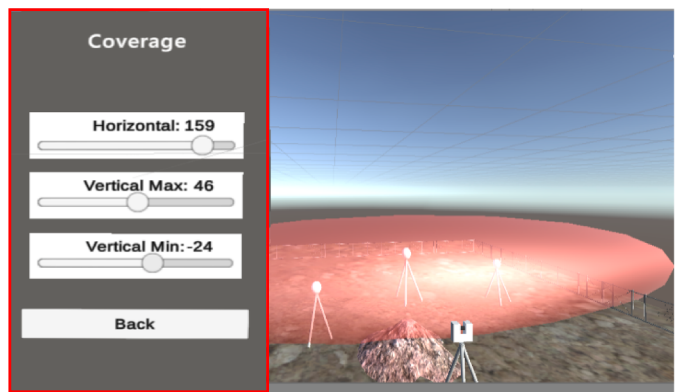
(a) Positioning tripod stand.



(b) Positioning of targets for scanning stockpile.



(c) Laser scan settings.



(d) Laser scan coverage visualization.

Fig. 6. Laser scanning in 'Sensor tutorial' scene.

Similarly, participants must interact with the scanner button before the targets button becomes activated. This feature guided the cognition process in the learning environment.

After interacting with the laser scanner components, the 'Scanner interface' button will be activated. This button opens up the 'Scan settings' menu interface (Fig. 6c). The scan settings comprise of the

configurations of the laser scan such as resolution, quality, coverage, color, and profile (Fig. 6c). This was designed after the scan settings of Faro Focus M70. Each configuration has a menu panel that provides different options of the selected scan setting. For example, on selecting 'Quality', distinct scan quality settings such as x2, x4, x6, and x8 will be displayed. Similarly, on selecting the 'Coverage' button, participants

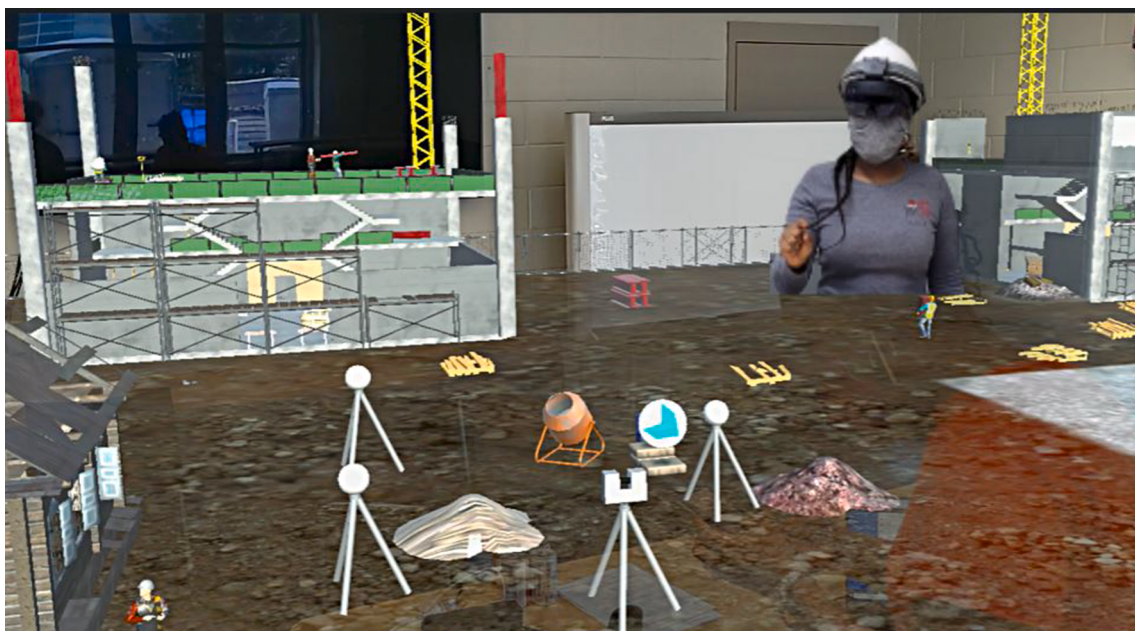


Fig. 7. A student interacting with the learning environment.

will be required to use the sliders for setting the vertical and horizontal coverage of the scan (Fig. 6d). To improve cognition, the scan coverage reflects as a 'red box' projected from the laser scanner (Fig. 6d). To reduce confusion, any selected scan setting will be displaced below the title of the menu interface as it is important to engage all scan settings before the 'Scan' button can be activated (Fig. 6c). Furthermore, the selected scan settings were designed to impact the scan time. This engages students' decision-making process in collecting scans on a time-constrained and busy construction site. On selection of the 'Scan' button, scanning of the stockpile will commence, and learners will be prompted to save the captured scan after the scanning ends. To simulate laser scanning on a busy and space-constrained jobsite, and reinforce the knowledge of laser scanning, participants performed similar laser scanning procedures in the sensor implementation scene (Fig. 5b). Fig. 7 shows a student performing a scanning activity with the learning environment.

4.1. Demographics

The study participants (N = 18) were fifteen males and three females with an average age and standard deviation of 28 years (± 7). This sample size is similar to other virtual environment usability studies [36,53,92]. While three of the participants have never tried VR or MR, twelve of them have tried VR or MR once or twice, and three of the participants use either reality environment regularly. Fifteen participants have 0–5 years of experience in the construction industry, two participants have 6–10 years, and one has 16–20 years of experience in the construction industry. Lastly, to assess the participants' level of experience with the sensing technologies, participants were asked if they had previously interacted with sensing technologies, and they were asked to state how long they have used each of the sensing technologies. Five participants reported having no experience with sensing technologies, and thirteen participants have interacted with sensing technologies. Of the participants who had interacted with sensing technologies, eight participants have prior experience with laser scanners, while ten participants have no experience with laser scanners. However, their years of experience with the laser scanner varied from one month to a year.

4.2. Usability questionnaire

The usability questionnaire was divided into open-ended responses regarding the precision of the virtual site reflecting real jobsite conditions, and self-ratings on the usability of the laser scanner and user interface. Similar to the usability questionnaire prototype provided in Yılmaz, Ergen and Artan [93], the usability questions were guided by the purpose of the learning environment and adapted from standard usability questionnaires: Post-study system usability questionnaire [94,95], system usability scale questionnaire [96], and Usefulness, Satisfaction, and Ease-of-use questionnaire [97].

Regarding the open-ended question, participants were asked 'why/why not is the layout of the construction site (and resources) reflective of a real construction site?' All the participants noted that the virtual site is reflective of a real jobsite, and further provided additional comments on the layout of the virtual site. Some participants commented on how the detailed activities and equipment were reflective of those on a real site, stating that: 'It shows the activities that are frequently done on common residential/ commercial projects'; 'It is reflective. The environment is very detailed, and there are many different components on the site'; 'Yes, It is very good, 90% represents an actual physical site'; 'It is reflective for the perspective of activities related to construction'. Two participants made similar comments on the animations and texture of the virtual jobsite: 'The layout was very realistic because of the textures, animations, and details'; 'There are animations of each activity which makes it realistic scenario of a real construction site'. Furthermore, the accuracy of the represented activities on the jobsite was examined. A participant stated that 'It is

reflective, most of the details have been shown correctly'. Also, a participant noted the ease of accessing information and resources in the learning environment, stating that 'Yes, it is reflective because I could access every... site details.' The ability of the site to enhance construction task exploration, identification of risks, resources, and dependencies between resources was also examined. A participant stated that 'The virtual site is reflective as I can see workers moving and working, equipment in action, and it can help understand if two activities can have problem with each other.'. In addition, there were suggestions for improving the construction site, a participant mentioned that 'I would like to be able to hear the environmental sounds, I will prefer to have more interactions with workers and objects on site'. Similarly, another participant pointed out the need for reflecting diversity of the construction workforce in the learning environment e.g., including women and minority workers.

Furthermore, self-ratings on the usability of the learning environment, user interface, and virtual laser scanner were procured through a usability questionnaire and reported in Table 5.

4.3. Think-aloud protocol and verbal feedback

During the experimental tasks, a think-aloud protocol was adopted, and participants were further asked to provide feedback regarding the effectiveness of the learning interface. Thematic coding was adopted to analyze the data was adopted using NVIVO (release 1.3 (535)). A total of 23 codes and 14 codes were extracted from the sensor tutorial (Table 6) and sensor implementation scenes (Table 7) respectively. To ensure consistency, the extracted codes were compared with the transcript. Also, to mitigate subjectivity, agreement with the codes was rated by two researchers, and the inter-rater agreement was good (Cohen's Kappa = 0.7). For each learning scene, similar themes were extracted from the codes to further describe the data.

4.3.1. 'Sensor tutorial' scene

While engaged in the 'Sensor tutorial' scene, participants were asked if the demo improved their learning of the sensor; issues encountered when interacting with the components and menu interface of the laser scanner; and salient features of the environment that contributed to the learning process. Participants were also asked for suggestions on improvements to the learning environment. The participants agreed that the sensor tutorial scene improved their knowledge of laser scanning. Some participants provided additional comments about the learning environment such as: 'for me, it is a good teaching material for helping us to learn how to operate a laser scanner'; 'It improved my understanding of the

Table 5

Usability responses. (Designed on a 5-point scale with 5 representing 'strongly agree'.).

Usability Questions	Mean	SD
<i>Learning environment</i>		
I can easily navigate the learning environment	3.8	0.9
The virtual site feels like a real construction site	3.4	0.9
<i>Virtual sensors</i>		
I would prefer to learn with virtual sensors than physical sensors	2.7	1.1
Learning with virtual sensors feels like learning with the real physical sensors	3.2	1.0
<i>User interface</i>		
I can locate information (e.g., sensors, activities, resources) I need easily and quickly	3.5	0.7
I understood the menus and other information presented on the interface	3.9	0.7
The information on the interface could improve my interaction with the sensors	4.1	0.8
The user interface obstructed my interaction with the environment	2.4	1.1
<i>Virtual scanner</i>		
It was easy to move the laser scanner and targets to my desired location	3.7	1.4
The buttons on the laser scanner's interface was understandable	4.3	0.8
The buttons on the laser scanner's interface was easy to control	4.2	1.0

Table 6
Codes, themes, and frequency for sensor tutorial scene.

	Codes/ description	Themes	Transcript's References
1	Basic operational steps included	Advantages	2
2	Easy to understand		1
3	Good teaching material		1
4	Improved understanding about the laser scanner		9
5	Reflects a real laser scanner		2
6	Scaffolded my learning of laser scanning	HoloLens device	3
7	Sequencing - procedural technique was helpful		4
8	Straightforward project		1
9	Well designed		3
10	Pain from device		1
11	Sunlight interference	Menu interface	2
12	Coverage - well visualized		6
13	Easy to control		3
14	Increase button size		1
15	More information needed		5
16	Move menu panels closer to scanner	Suggestions	1
17	Repetitive laser scanning will be helpful		1
18	Can't move tripod easily		2
19	Difficulty in understanding where to position laser scanner components		5
20	Easy to move laser scanner's components		11
21	Experience with MR needed	Challenges	3
22	Scan coverage hard to tell		1
23	A lot to do		1

Table 7
Codes, themes, and frequency for sensor implementation scene.

	Codes/ description	Themes	Transcript's References
1	No challenges	Benefits	4
2	Easy to move laser scanner components		4
3	Memorize process		2
4	Scaffolding helped		1
5	Sensor tutorial aid understanding		1
6	Useful for acquiring operational skills	Menu interface	1
7	Better understanding of coverage, than the ST scene		1
8	Chevron guides participants		1
9	Back option - not easily accessible		1
10	Difficulty moving laser scanner components		3
11	Chevron confuses participants	Suggestions	3
12	HoloLens is heavy		1
13	More information needed for profile		1
14	MR Experience needed for controlling laser scanner's components		2

pieces of laser scanning'; 'Yes, it improved my learning of laser scanner'; 'Actually, I could set it up anywhere and use the laser scanner'; 'Yeah yeah, yes it really helped me.'; 'Yes, it was great, it was awesome.'

When asked about issues encountered when interacting with the components and menu interface of the laser scanner, eleven participants stated that had no issue with moving the components to the desired location (Table 6). Additional comments such as 'no problem with moving it. It is probably the easiest part of moving it'; '... it is very easy'; 'It is very easy to move the targets'; 'it is actually very smooth; I can move them around'; 'no problem with moving it. It is probably the easiest part - moving it'; 'It was very easy to move the laser scanner components, once I was able to grab it'; 'it was easy, I could move it around where I want it to go'; 'I have moved the tripod- That is very nice and easy to lift', were provided from

different participants. However, two participants expressed issues encountered with interacting with the components, one stating difficulty in moving the tripod, while the other noted the need for familiarity with the HoloLens air tapping feature for easy manipulation of the components.

The participants were asked to state salient features of the laser scanner that contributed to the learning process. Some participants provided the following information regarding the overall design of the interface for laser scanning: 'I think it is a pretty straightforward project, and generally easy to understand. I think the general process is pretty well designed'; 'it is a good teaching material for helping us to learn how to operate a laser scanner; you have like the basic process or basic steps when you try to operate it. So, yeah I think it is a good teaching material'. During the task, comments such as 'Tripod is done, scanner has opened up'; revealed the effectiveness of the sequential design of the interface in scaffolding their learning. A participant explained that the interface provided the guidance needed to capture scans on the jobsite. The participant stated, 'tripod is required, place the tripod, leveling, place the scanner. Yes so, the sequencing is really helpful to understand how, and what I should be doing'. Others stated the visualization of scan coverage is important: 'I was able to see the coverage. When I was changing the coverage, I could see a box. That is one good thing because when we are doing it with a physical scanner, we cannot really see how much that means. But with this, I can see, do I need 180°? or do I need 360°?, that is a good thing. It is a cool animation'; 'Everything was well visualized, especially the coverage part'; 'While moving the coverage sliders', a participant stated — 'oh, I see what this does, it shows you where it is at, it shows you the coverage of the scan, telling you that it is really wide'. Lastly, engagement with the laser scanner components was also stated as an essential feature that enhanced learning of laser scanning. The participant stated 'moving the targets and the scanner is helpful for people who haven't done it before'.

When asked for suggestions on improving the learning environment, participants generally stated the need to provide additional information on the laser scan settings. Comments such as 'I felt I needed some more information with the coverage and some other categories'; 'If you are using this for someone who has never used the scanner before, placing the targets might be difficult to understand, but if you have used the scanner before, it is pretty straight forward'; 'I didn't understand some of the factors. Also, putting the target, I need to have more details, how to put the target, how does it work? And the coverage and profile need more description'; and 'giving a definition for each of the factors' were provided. Lastly, a participant suggested that the menu and the components should be placed together.

During the think-aloud protocol, participants highlighted the interference of lightning in the augmented display. A comment such as 'It was hard to see the popup- but I think it is just because of the sunlight, it was really bright' was provided. Comments were also provided on the representativeness of the leveling feature of the laser scanner tripod such as '...it's like the total station'. Although, a participant highlighted the reduced level of difficulty for leveling the tripod in the virtual site, stating 'The leveling part in real life takes so much time than what is represented here.'. In addition, the two participants who have no prior experience with the laser scanner highlighted the complexity of laser scanner activity. Comments such as 'A bit complicated, but pretty good'; '... there is a lot of things to do' were provided.

4.3.2. 'Sensor implementation' scene

In the 'Sensor implementation' scene, participants were asked to state issues with using the laser scanner and additional comments for improving the learning environment. While 23 codes were extracted from the 'Sensor tutorial' scene, fewer comments were provided during interaction with the sensor implementation scene, and a total of 14 codes were extracted (Table 7). This could suggest the participants' familiarity with the laser scanning activity. Participants pointed out the ease of moving the components of the laser scanner and placing the targets: 'It was easy for me to move the laser scanner components'; 'I will say placing the target was smooth'; 'Was it easy to move the tripod and laser

scanner accessories— Yes, it was easy, same as before. However, participant 9 experienced challenges with moving the laser scanner components, and participant 10 experienced issues moving the third tripod.

In this scene, a participant also stated the sequential process as a benefit explaining that ‘*This is good to know sequencing wise. First step this, second step that*’. Participants highlighted the significance of the sensor implementation scene for reinforcing their knowledge of laser scanning: ‘*It makes you memorize it. I got to do it the second time, so just to memorize the steps*’. Compared to the experience in the sensor tutorial scene, a participant who has no experience with laser scanner stated the process as easy and highlighted the benefits of the menu interface the participant explained ‘*... it was easy. Just follow the directions.*’ Another participant without experience explained that the learning environment taught the use of laser scanner, the participant stated ‘*...it definitely taught how to use the laser scanner.*’ Challenges such as recognition of the scanner’s camera view was called out within this scene.

4.4. Eye tracking data and task completion time

This study adopted fixation duration, fixation counts, average fixation duration, and task completion time to investigate the attentiveness of the participants within the learning environment. Table 8 presents a summary of the analysis of each outcome measure. The bolded p-values are significantly different at a 95% confidence level. LS means laser scanners.

4.4.1. Fixation count

In the ‘Sensor tutorial’ scene, the fixation count of the tripod and scanner was higher than the other laser scanner components ($p = 0.017$). Although not significant, the fixation count was higher for the tripod and scanner than other components within the ‘Sensor implementation’ scene. Comparing both scenes, the number of fixations on the other laser scanner components was consistently higher within the ‘Sensor implementation’ scene than the ‘Sensor tutorial’ scene (Fig. 8), and significant difference was observed for target 3 ($p = 0.003$).

For the menu interface, fixation count for the ‘Laser scanner setup’ and ‘Scan settings’ were compared during each scene. During the ‘Sensor tutorial’ scene, participants frequently fixated on the ‘Scan settings’ than the ‘Laser scanner setup’. However, when engaged in the implementation scene, the fixation count was comparable across the menu interface (Fig. 9). Comparing the fixation count across both ‘Sensor tutorial’ and ‘Sensor implementation’ scenes, the fixation count on the scan settings was significantly higher within the ‘Sensor tutorial’ scene (A) ($p = 0.012$) than the sensor implementation scene (B).

4.4.2. Fixation duration

For the laser scanner components, fixation duration was significantly higher for the tripod and scanner compared to other laser scanner components ($p < 0.001$) within the ‘Sensor tutorial’ and ‘Sensor implementation’ scenes ($p = 0.006$). Across both scenes, significantly different bars are labeled. Across both scenes, although not statistically

significant, participants had a longer fixation duration on the tripod and scanner within the ‘Sensor tutorial’ scene than the ‘Sensor implementation’ scene. However, fixation duration was higher for targets 1, 2, and significantly higher for target 3 ($p = 0.001$) within the ‘Sensor implementation’ scene (B) when compared to the ‘Sensor tutorial’ scene (A) (Fig. 10).

For the menu interface, participants had higher fixation duration on the ‘Scan settings’ than the ‘Laser scanner setup’ in the ‘Sensor tutorial’ scene and ‘Sensor implementation’ scenes (Fig. 11). Comparing the fixation duration for both scenes, higher fixation duration was observed on the menu interface in the ‘Sensor tutorial’ scene (Fig. 11), and participants spent more time fixating on the ‘Scan settings’ within both scenes. The fixation duration on the scan settings was significantly higher within the ‘Sensor tutorial’ scene (A) ($p = 0.034$) than the sensor implementation scene (B).

4.4.3. Average fixation duration (AFD)

The average fixation duration on the tripod and scanner was statistically higher than targets 2 and 3 during the sensor tutorial scene ($p < 0.001$) and significantly varied across the ‘Sensor implementation’ scene ($p = 0.003$), with participants having longer average fixation duration on the tripod and scanner than target 1 (Fig. 12). Comparing AFD for each laser scanner component within both scenes, AFD for tripod and scanner ($p = 0.003$) and two of the targets 2 ($p = 0.040$), and target 3 ($p = 0.026$) were significantly higher in the ‘Sensor implementation’ scene than in ‘Sensor tutorial’ the scene (Fig. 12). However, AFD for Target 1 was higher within the sensor tutorial scene than the ‘Sensor implementation’ scene.

Similar effects were observed for the menu interface. In the ‘Sensor tutorial’ scene, AFD was comparable across the menu interface (Fig. 13) and in the ‘Sensor implementation’ scene, higher AFD was observed on the ‘Scan settings’.

4.4.4. Task completion time

Task completion time during the sensor tutorial and sensor implementation scenes were extracted as the total duration of each participants’ eye-tracking data during the experimental tasks. Similar statistical analyses were conducted to compare the task completion time and presented in Table 9, where p is significant at a 95% level of confidence. Significant figures are emboldened.

The participants had a higher completion time during the ‘Sensor tutorial’ scene (Table 9). When engaged in the ‘Sensor implementation’ scene, the task completion time was significantly reduced ($p < 0.001$). Observing the trend in the completion time during both scenes across all participants, completion time was consistently reduced in the ‘Sensor implementation’ scene except for participant 12 and 16 (Fig. 14).

The total fixation duration on the laser scanner components and menu interface were further estimated as a percentage of task completion time. Overall, 3% of the task completion time was spent fixating on both the components and menu interface, when engaged in the ‘Sensor tutorial’ scene. The participants devoted more time devotion to the

Table 8
ANOVA results of eye-tracking data.

AOIs	Eye-tracking metrics	Learning scenes	Chi-square	Degree of freedom	P-Value
LS Components (Tripod, scanner, targets 1, 2, and 3)	Fixation count	Sensor tutorial	10.137	3	0.017
		Sensor implementation	7.802	3	0.050
	Fixation duration (ms)	Sensor tutorial	19.366	3	<0.001
		Sensor implementation	12.521	3	0.006
	Average Fixation duration	Sensor tutorial	18.704	3	<0.001
		Sensor implementation	13.881	3	0.003
Menu Interface (Laser scanner setup and Scan settings)	Fixation count	Sensor tutorial	3.205	1	0.073
		Sensor implementation	1.990	1	0.158
	Fixation duration (ms)	Sensor tutorial	2.403	1	0.121
		Sensor implementation	0.530	1	0.467
	Average Fixation duration (ms)	Sensor tutorial	0.009	1	0.924
		Sensor implementation	0.036	1	0.849

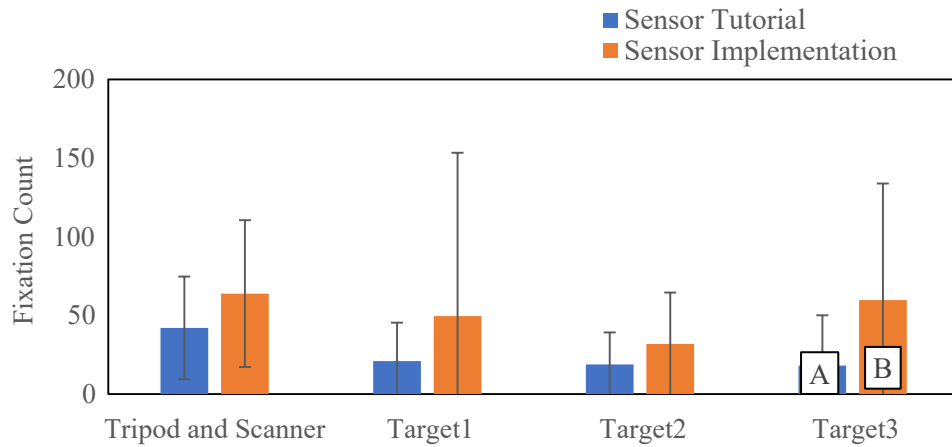


Fig. 8. Fixation count of laser scanner components. Letters A and B denotes significant difference between both bars, while unlabeled bars are not significantly different.

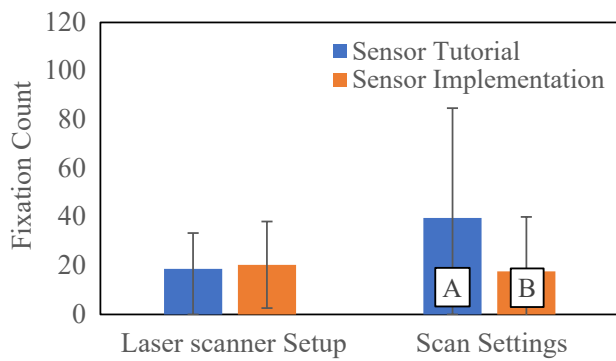


Fig. 9. Fixation count of laser scanner menu interface. Letters A and B denotes significant difference between both bars, while unlabeled bars are not significantly different.

sensor implementation scene. The participants fixated on the laser scanner components and menu interface for 7% and 4% of the task completion time, respectively.

5. Discussion

With a focus on laser scanning, this study presents the usability evaluation in terms of the learnability, efficiency, and satisfaction with a MR environment for learning how to implement sensing technologies on

construction sites. Eye-tracking data, self-rated usability questions, and responses during a think-aloud protocol were collected from 18 participants who performed laser scanning activities within the learning environment. While 83% of the participants have some experience with VR or MR, 44% have less than a year of experience with laser scanners.

5.1. Self-Perceptions of features of the learning environment

The usability questionnaire procured the self-perceptions of the learning environment features. The questions procured open-ended responses on the precision of the virtual site reflecting real jobsite

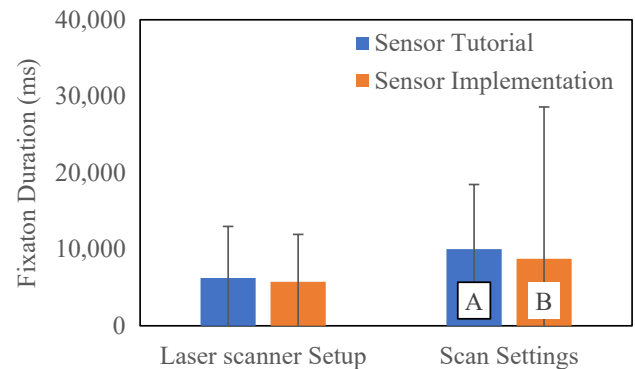


Fig. 11. Fixation duration of laser scanner menu interface.

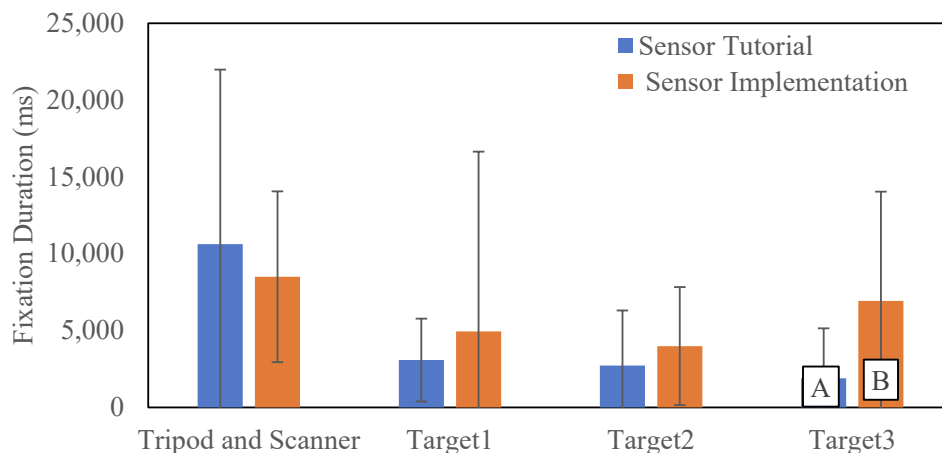


Fig. 10. Fixation duration of laser scanner components. Labelled bars are significantly different.

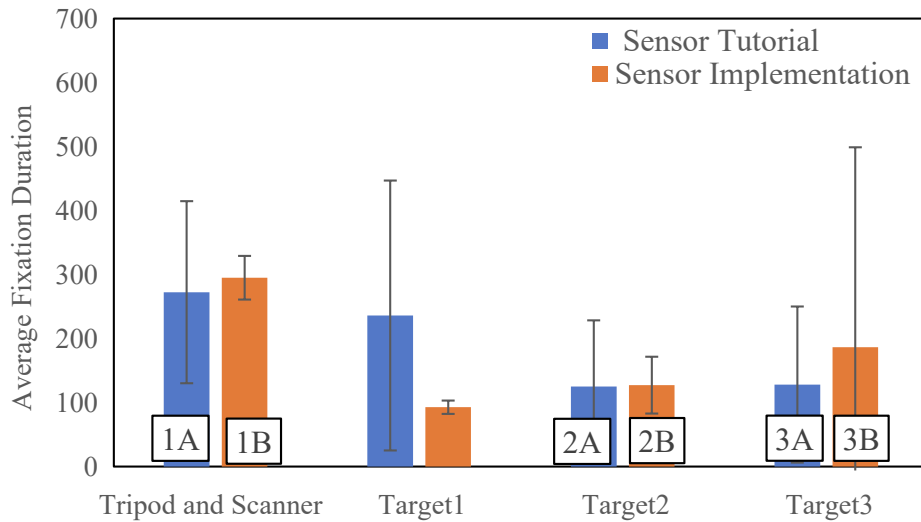


Fig. 12. Average fixation duration of laser scanner components. Labelled bars are significantly different.

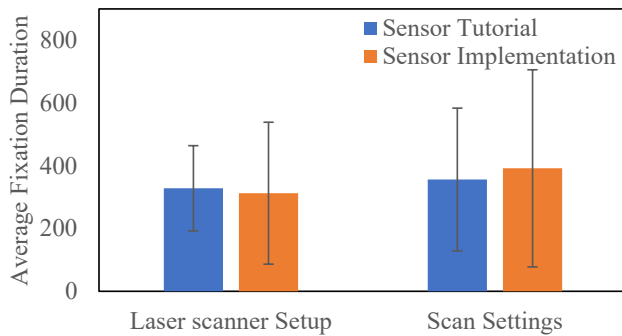


Fig. 13. Average fixation duration of laser scanner menu interface.

Table 9

Descriptive statistics of task completion time (secs).

Learning scenes	Mean	SD	Chi-Square	p-value
Sensor tutorial	652	300	12.333	< 0.001
Sensor implementation	383	183		

conditions, and self-ratings on the usability of the laser scanner and menu interface. Participants agreed that the virtual site reflects a real construction site due to the accuracy of the represented activities and equipment on the site, quality of the animations, representativeness of the activities as real construction activities, and the ease of accessing information and resources in the learning environment. The ability of the site to enhance exploration of construction tasks, identification of risks and dependencies between resources as important features of the virtual site was also highlighted. Suggestions were provided to improve the virtual site such as including equipment and construction sounds and enhancing the diversity of the construction workers.

Regarding the self-ratings, participants moderately agreed that the virtual site resembles a real jobsite. Self-ratings of the informativeness and effectiveness of the user interface were also provided. Participants agreed that the user interface was informative and improved their interaction with the laser scanner. They also moderately agreed to the understandability of the menu interface, which implies that the information presented was concise and clear. Similarly, participants agreed to ease of navigation in the learning environment, and could easily locate important information like activities, resources, and sensors. Participants also disagreed that the user interface obstructed interaction with the sensors. This suggests the effectiveness and satisfaction with the layout of the learning environment. With an average and SD of $4(\pm 1)$, overall, the participants moderately agreed to the ease of use of the laser

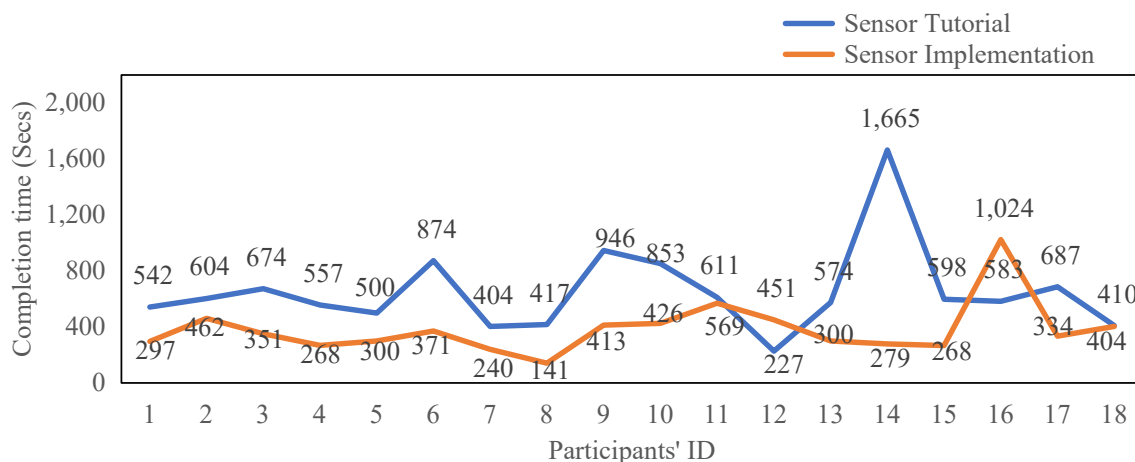


Fig. 14. Completion time for participants in both scenes.

scanner in the learning environment. Participants rated their perception of the virtual sensors in terms of ease of interacting with the laser scanner components as $4(\pm 1)$, ease of control of the menu interface as $4(\pm 1)$, and understandability of the menu interface as $4(\pm 1)$. Lastly, the participants agreed that learning with virtual sensors feels like learning with physical sensors and stated their preference for virtual sensors over physical sensors.

5.2. Immediate feedback on the efficiency of the learning interface

The think-aloud protocol and verbal feedback procured instant feedback on the efficiency of the learning interface during the cognitive activity in the 'Sensor tutorial' and 'Sensor implementation' scenes. During the 'Sensor tutorial' scene, it can be implied that the 'Sensor tutorial' scene improved the learning of laser scanning activity, and participants found the process engaging. 85% of the participants experienced no issue operating the laser scanner components and found them easy to move to desired locations without any difficulty. This validated an important characteristic of the learning environment, which is supported by the study by Wijesooriya, Heales and Rohde [98] who revealed that ease of use and control is significantly important for any virtual learning environment. However, other participants who experienced difficulty stated that the air tapping feature of the HoloLens interfered with easy movement of the laser scanner components, and lightening the real world can obstruct the visibility of the augmented display in the learning environment.

Important design features such as the concise outline of the laser scanning activities and sequential development of the activities for guiding the participants' learning process were crucial to the effectiveness of the learning environment. In addition, the ability to visualize abstract scan settings (which may not be possible in the real world), - such as coverage was noted as an intriguing feature that improved the learning of laser scanning. The ability to interact and move the laser scanner components in the MR environment was stated as valuable to the learning process. Hence, visualization is an important feature afforded by the learning environment. Suggestions were provided to increase the information in the 'scan settings' menu interface for better clarity. While the laser scanner setup is reflective of similar equipment such as the total station, the participants who have previous experience with the laser scanner noted that the real-life difficulty encountered with the setting of the laser scanner was not represented in the environment. However, participants who have no previous experience with laser scanners noted that the activity was complicated with a lot of processes to undergo.

In the 'Sensor implementation scene', fewer comments were provided. While participants equally interacted with the laser scanner components with ease, some participants experienced difficulty moving the targets to the desired location. This may be due to the scene change, and the presence of other construction resources. This scene also reinforced the students' learning of laser scanning, as the procedure had already been performed in the sensor tutorial scene.

5.3. Impacts of cognitive processing during the evaluation tasks

This study adopted objective measures from eye-tracking data such as fixation duration, fixation counts, average fixation duration, and task completion time to investigate real-time cognition processing in the learning environment. These eye tracking metrics were only assessed for the AOIs such as laser scanner components (tripod, scanner, and targets 1, 2, and 3) and the menu interface that enables interaction with the components (laser scanner setup and scan settings). The fixation count of the tripod and scanner was significantly higher than that of the other laser scanner components during the 'Sensor tutorial' and 'Sensor implementation' scenes. In the learning environment, it is expected that learners frequently fixate on the tripod and scanner for crucial laser scanning activities such as laser scanner setup and visualization of scan

settings. As such, the result of the fixation count supports this objective and points to the tripod and scanner as the most crucial laser scanner components. This is also supported by the study of Zou and Ergan [71] where the results showed increased attention to all areas of interest. However, comparing cognitive processing in 'Sensor tutorial' and 'Sensor implementation' scenes, the fixation count was higher across all the laser scanner components in the 'Sensor implementation' scene. Similarly, for the laser scanner menu interface, fixation count was higher on the scan settings within the 'Sensor tutorial' scene. Fixation count also reveals the attention and interest of participants to a particular area of interest [99]. This shows that participants were more interested in the scan settings than the laser scanner setup within this scene. Although participants frequently fixated on the 'laser scanner setup' than the 'Scan settings', comparable fixations were recorded on the menu interface in the 'Sensor implementation' scene. A balanced attention to the menu interface in this scene may imply a better understanding of the laser scanning activity. This can be supported by the think-aloud protocol and verbal feedback, where participants affirmed that the 'Sensor tutorial' reinforced their learning of laser scanning and eased the level of difficulty in the 'Sensor implementation' scene.

Similar results were observed for the fixation duration in both scenes. Fixation duration was higher on tripod and scanner during the 'Sensor tutorial' and 'Sensor implementation' scenes. The longer the fixation duration, the more crucial the element is for cognitive processing [100,101]. However, comparing other laser scanner components in both scenes, a high fixation duration was recorded for all targets in the 'Sensor implementation' scene which suggests higher cognitive processing during interaction with these targets. The complex nature of the 'Sensor implementation' scene may be an explanation, as participants may have to understand the nature of the surrounding activities before positioning the laser scanner components. It can be inferred that the decision-making process of where and how to position laser scanner components in the simulated construction site is a contributing factor to the cognitive process.

Fixation duration for the menu interface showed that participants devoted more time fixating on the 'scan settings' than the 'Laser scanner setup' when engaged in both scenes. This implies more cognitive load when interacting with the 'Scan settings' menu. Since longer fixation duration implies complexity, heightened cognitive processing, and difficult information extraction [102–104], it can also be inferred that the participants found information on the 'Scan settings' complex. Suggestions from the think-aloud protocol further affirm that more clarity is required for each scan settings to reduce the cognitive load. Comparing both scenes, fixation duration on the menu interface was higher in the 'Sensor tutorial' scene which also implies more cognitive processing while interacting with the menu interface in this scene.

The average fixation duration was comparable across the laser scanner setup for both scenes. For the scan settings, a higher average fixation duration was observed during the sensor implementation scene. Also, the average fixation duration for all laser scanner components except target 1 was higher across the 'Sensor implementation' scene than the 'Sensor tutorial' scene. A high average fixation duration indicates a high level of comprehension of the educational content [74]. With a higher average fixation duration across most of the AOIs during the sensor implementation scene, it can be inferred that participants demonstrated increased comprehension of the laser scanning activity when in the 'Sensor implementation' scene. This is consistent with comments from the think-aloud protocol and verbal feedback, as participants stated improved understanding from prior experience in the 'Sensor tutorial' scene. This is also consistent with Ozcelik, Karakus, Kursun and Cagiltay [100] where longer average fixation duration indicated better task performance and transfer scores.

Lastly, the task completion time in the 'Sensor implementation' scene was 70% lesser than the 'Sensor tutorial' scene. reduced completion time as usability measures may signify improved task efficiency and learnability culminating in increased productivity [38]. Also, when task

complexity is similar in both environments, a lesser task completion time indicates an increased level of attention [71]. Since attention is described as a key aspect of engagement [105], it can be inferred that participants were engaged during interaction with the learning environment. Consequently, the results indicated increased devotion to the laser scanning activity in the 'Sensor tutorial' scene.

6. Conclusion

With the professed benefits of virtual learning environments in this tech-savvy generation, it is imperative to embrace technologies such as MR as a pedagogical tool in construction education. A well-designed and efficient MR environment are however necessary for the effective delivery of educational contents. The goal of this study was to assess the usability of an MR environment for learning sensing technologies currently adopted in the construction industry. The usability study revealed the satisfaction, learnability, efficiency of the learning environment. The satisfaction with the representativeness and layout of the virtual site and evaluation of the learning environment for laser scanning were presented. The study adopted subjective measures in terms of self-rated perceptions through usability questionnaire and think-aloud protocol and verbal feedback. Objective measures in terms of eye-tracking data were procured to assess cognitive processing in the learning environment. Triangulating results from the outcome measures, more depth was provided on the usability evaluation.

As revealed in this study, features such as accuracy of the represented activities and equipment on the site, quality of the animations, representativeness of the activities as real construction activities, and the ease of accessing information and resources are important for designing efficient MR learning environments. Similarly, when designing an MR learning environment for construction students, the inclusion of construction and equipment audio may facilitate learning in the environment. Surprisingly, participants affirmed their preference for virtual sensors stating it was similar to learning with physical sensors; comments provided during the think-aloud protocol, verbal feedback and results from the task completion time highlight reduced level of difficulty, better visualization of scan coverage, and engagement with the laser scanner components as influencing factors. This suggests efficiency and satisfaction with the learning environment.

From the think-aloud protocol, verbal feedback and usability questionnaire, concise outline, and sequential design of the interface are important characteristics that influenced the learnability and satisfaction with the user interface. However, the eye-tracking data revealed some difficulty in comprehending information displayed in the 'Scan settings', which can be linked to the need for clarity suggested in the think-aloud protocol and verbal feedback. The ease of controlling the laser scanner components was consistent in the usability questionnaire, think-aloud protocol, and verbal feedback. However, in the 'Sensor implementation' scene, more difficulty was experienced moving the targets which was consistent with observed cognitive processing in the eye-tracking data. This implies that a congested learning environment increases the cognitive demand of the learners.

Overall, the reduced task completion time, improved comprehension, and comments from the think-aloud protocol and verbal feedback in the 'Sensor implementation' scene suggest that the learning environment is efficient for learning sensing technologies. It can be concluded that the design of the learning environment for scaffolding knowledge development was effective, as participants passed the zone of proximal development when engaged in the 'Sensor implementation' scene.

7. Limitations and future works

There are some limitations to the study, which should be discussed. The study revealed the effects of ambient lightening such as light reflections from the real world on the augmented display as a limitation to

the interactions in the learning environment. The HoloLens is an HMD with passthrough as an inherent feature [106], and the interference of ambient lightning (sunlight and indoor lightning) is often a limitation to the adoption of MR devices especially in bright environments [107,108]. Since this limitation is solely due to the MR technology, future work could explore the affordances of VR as a suitable learning environment for sensing technologies. Virtual scanners within the virtual environment could be integrated with tangible representations of the physical scanners to achieve embodied interactions and high-fidelity learning, which could potentially improve the learning experience within the environment. The main advantage of MR, which is interaction with real-world information, was not utilized in this study. Future work will explore compliments of virtual and physical representations of construction sites and sensing technologies. For example, the construction site could comprise of physical representations of partially completed buildings and simulated virtual construction equipment. Likewise, the laser scanner could comprise of the virtual scanner and a physical tripod. Using MR devices, the virtual objects can be mixed or complimented with the physical objects within a space. Furthermore, the physical environment could be augmented with tangible user interfaces that display digital information to make the physical and virtual representations interactive.

It is envisioned that the aforementioned MR and VR learning-based environments would enable students to work together collaboratively as a group to assess the need for sensing technologies and implement sensors for addressing construction risks. Based on user feedback from these studies, the learning environments would need to be improved prior to assessing their impact on student learning. During the assessment, a summative evaluation involving a comparative study of students' performance when taught with and without the learning environments, will be carried out.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This material is based upon work supported by the National Science Foundation (Award #: IUSE – 1916521). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF.

References

- [1] O. Ogunseju, A. Akanmu, D. Bairaktarova, Holographic Learning Environment for Bridging the Technical Skill Gap of the Future Smart Construction Engineering Students, in: Proceedings of the 20th International Conference on Construction Applications of Virtual Reality, CONVRTEesside University, UK, 2020, pp. 151–162.
- [2] I. Brilakis, M.-W. Park, G. Jog, Automated vision tracking of project related entities, *Adv. Eng. Inf.* 25 (4) (2011) 713–724, <https://doi.org/10.1016/j.aei.2011.01.003>.
- [3] M.-W. Park, C. Koch, I. Brilakis, Three-dimensional tracking of construction resources using an on-site camera system, *J. Comput. Civil Eng.* 26 (4) (2012) 541–549, [https://doi.org/10.1061/\(ASCE\)CP.1943-5487.0000168](https://doi.org/10.1061/(ASCE)CP.1943-5487.0000168).
- [4] Z. Pučko, N. Šuman, D. Rebolj, Automated continuous construction progress monitoring using multiple workplace real time 3D scans, *Adv. Eng. Inf.* 38 (2018) 27–40, <https://doi.org/10.1016/j.aei.2018.06.001>.
- [5] C. Wang, Y.K. Cho, Smart scanning and near real-time 3D surface modeling of dynamic construction equipment from a point cloud, *Autom. Constr.* 49 (2015) 239–249, <https://doi.org/10.1016/j.autcon.2014.06.003>.
- [6] M.R. Hallowell, D. Hardison, M. Desvignes, Information technology and safety: Integrating empirical safety risk data with building information modeling, sensing, and visualization technologies, *Construct. innovation* 16 (3) (2016) 323–347, <https://doi.org/10.1108/CI-09-2015-0047>.
- [7] T. Cheng, J. Teizer, G.C. Migliaccio, U.C. Gatti, Automated task-level activity analysis through fusion of real time location sensors and worker's thoracic posture data, *Autom. Constr.* 29 (2013) 24–39, <https://doi.org/10.1016/j.autcon.2012.08.003>.

- [8] B. Akinci, C. Anumba, Sensors in construction and infrastructure management, *J. Information Technol. Construct. (ITcon)* 13 (2008) 69–70.
- [9] O. Ogunseju, A. Akanmu, D. Bairaktarova, Sensing Technologies in Construction Engineering and Management Programs: A Comparison of Industry Expectations and Faculty Perceptions, 57th Annual Associated Schools of Construction International Conference, EPIC Ser. Built Environ. (2021) 505–513.
- [10] T. Hourigan, Importance of 3D Laser Scanning in, Healthcare Renovations (2014).
- [11] J. Miller, Skanska uses vela systems on new meadowlands stadium construction project to unite RFID and BIM for, *Mater. Tracking* (2008).
- [12] B. Matt, Turner Construction Uses Drones to Monitor Construction at Sacramento Kings New Arena. 2016, 2016.
- [13] N. Blinn, R.R. Issa, Parametric model for planning laser scanning jobs in the AECO industry, Proceedings ICCBE International Conference on, Computing Civ. Build. Eng. (2016) 1468–1475.
- [14] B. Balamuralithara, P.C. Woods, Virtual laboratories in engineering education: the simulation lab and remote lab, *Computer Applications Eng. Education* 17 (1) (2009) 108–118, <https://doi.org/10.1002/cae.20186>.
- [15] B. Kollöffel, T. de Jong, Conceptual understanding of electrical circuits in secondary vocational engineering education: combining traditional instruction with inquiry learning in a virtual lab, *J. Eng. Educ.* 102 (3) (2013) 375–393, <https://doi.org/10.1002/jee.20022>.
- [16] A.Z. Sampaio, P.G. Henriques, O.P. Martins, Virtual reality technology used in civil engineering education, *Open Virtual Reality J.* 2 (2010), <https://doi.org/10.2174/1875323X01002010018>.
- [17] D.T.H. Dung, The advantages and disadvantages of virtual learning, *IOSR J. Res. Method Education* 10 (2020) 45–48, <https://doi.org/10.9790/7388-1003054548>.
- [18] M. Koskela, P. Kiltti, I. Vilpola, J. Tervonen, Suitability of a Virtual Learning Environment for Higher Education, *Electronic J. e-Learning*, 3 (2005) 23–32, doi: <https://eric.ed.gov/?id=EJ1099351>.
- [19] R. Lindgren, M. Tscholl, S. Wang, E. Johnson, Enhancing learning and engagement through embodied interaction within a mixed reality simulation, *Comput. Educ.* 95 (2016) 174–187, <https://doi.org/10.1016/j.compedu.2016.01.001>.
- [20] Y. Turkan, R. Radkowski, A. Karabulut-Ilgü, A.H. Behzadan, A. Chen, Mobile augmented reality for teaching structural analysis, *Adv. Eng. Inf.* 34 (2017) 90–100, <https://doi.org/10.1016/j.aei.2017.09.005>.
- [21] A. Deshpande, I. Kim, The effects of augmented reality on improving spatial problem solving for object assembly, *Adv. Eng. Inf.* 38 (2018) 760–775, <https://doi.org/10.1016/j.aei.2018.10.004>.
- [22] R. Lovreglio, V. Gonzalez, Z. Feng, R. Amor, M. Spearpoint, J. Thomas, M. Trotter, R. Sacks, Prototyping virtual reality serious games for building earthquake preparedness: the Auckland City Hospital case study, *Adv. Eng. Inf.* 38 (2018) 670–682, <https://doi.org/10.1016/j.aei.2018.08.018>.
- [23] M. Mengoni, D. Raponi, S. Ceccacci, A method to identify VR-based set-up to foster elderly in design evaluation, *Int. J. Intell. Eng. Informatics* 4 (2016) 46–70, <https://doi.org/10.1504/IJIEI.2016.074501>.
- [24] S. Borsci, G. Lawson, S. Broome, Empirical evidence, evaluation criteria and challenges for the effectiveness of virtual and mixed reality tools for training operators of car service maintenance, *Comput. Ind.* 67 (2015) 17–26, <https://doi.org/10.1016/j.compind.2014.12.002>.
- [25] R. Eiris, M. Gheisari, B. Esmaeli, Desktop-based safety training using 360-degree panorama and static virtual reality techniques: A comparative experimental study, *Autom. Constr.* 109 (2020) 102969, <https://doi.org/10.1016/j.autcon.2019.102969>.
- [26] H. Tobar-Muñoz, S. Baldiris, R. Fabregat, Augmented reality game-based learning: Enriching students' experience during reading comprehension activities, *J. Educational Computing Res.* 55 (7) (2017) 901–936, <https://doi.org/10.1177/0735633116689789>.
- [27] Z. Pan, A.D. Cheok, H. Yang, J. Zhu, J. Shi, Virtual reality and mixed reality for virtual learning environments, *Computers Graphics* 30 (1) (2006) 20–28, <https://doi.org/10.1016/j.cag.2005.10.004>.
- [28] D. Müller, F.W. Bruns, H.-H. Erbe, B. Robben, Y.-H. Yoo, Mixed reality learning spaces for collaborative experimentation: a challenge for engineering education and training, *Int. J. Online Eng. (IJOE)* 3 (2007) 15–19, [10.1.1.520.2916&rep=rep1&type=pdf](https://doi.org/10.1.1.520.2916&rep=rep1&type=pdf).
- [29] S. Hasanadeh, N.F. Polys, J.M. de la Garza, Presence, mixed reality, and risk-taking behavior: a study in safety interventions, *IEEE Trans. Visual Comput. Graphics* 26 (5) (2020) 2115–2125, <https://doi.org/10.1109/TVCG.2020.2973055>.
- [30] D.-H. Kim, Y.-G. Go, S.-M. Choi, An aerial mixed-reality environment for first-person-view drone flying, *Appl. Sci.* 10 (2020) 5436, <https://doi.org/10.3390/app10165436>.
- [31] D. Lafargue, The Influence of Mixed Reality Learning Environments in Higher Education STEM Programs: A Study of Student Perceptions of Mixed Reality Self-Efficacy, Engagement, and Motivation Using Augmented and Virtual Reality, University of Louisiana at Lafayette, 2018.
- [32] H. Kaufmann, Virtual environments for mathematics and geometry education, *Themes Sci. Technol. Education* 2 (2011) 131–152.
- [33] N. Adamo-Villani, K. Wright, SMILE: an immersive learning game for deaf and hearing children, *ACM SIGGRAPH 2007 educators program* 2007, pp. 17–es.
- [34] A. Abran, A. Khelifi, W. Suryan, A. Seffah, Usability meanings and interpretations in ISO standards, *Software Qual. J.* 11 (2003) 325–338, <https://doi.org/10.1023/A:1025869312943>.
- [35] H. Cho, D. Powell, A. Pichon, L.M. Kuhns, R. Garofalo, R. Schnall, Eye-tracking retrospective think-aloud as a novel approach for a usability evaluation, *Int. J. Med. Inf.* 129 (2019) 366–373, <https://doi.org/10.1016/j.jmedinf.2019.07.010>.
- [36] L. Ramsier, Evaluating the Usability and User Experience of a Virtual Reality Painting Application (2019), <https://doi.org/10.17615/s9z1-m163>.
- [37] J. Nielsen, Usability engineering, Morgan Kaufmann, 1994.
- [38] L. Punchoojit, N. Hongwaritorn, Usability studies on mobile user interface design patterns: a systematic literature review, *Adv. Hum.-Computer Interaction* 2017 (2017) 1–22, <https://doi.org/10.1155/2017/6787504>.
- [39] N. Binnenmars, Usability studies evaluating Virtual Reality treatment in Mental Health Care: a literature review, University of Twente, 2020.
- [40] J.A. Pawłowicz, 3D modelling of historic buildings using data from a laser scanner measurements, *J. Int. Scientific Publications: Mater. Methods Technologies* 8 (2014) 340, [10.1.1.877.2148&rep=rep1&type=pdf](https://doi.org/10.1.1.877.2148&rep=rep1&type=pdf).
- [41] E. Ergen, B. Akinci, R. Sacks, Life-cycle data management of engineered-to-order components using radio frequency identification, *Adv. Eng. Inf.* 21 (4) (2007) 356–366, <https://doi.org/10.1016/j.aei.2006.09.004>.
- [42] N. Pradhananga, J. Teizer, Automatic spatio-temporal analysis of construction site equipment operations using GPS data, *Autom. Constr.* 29 (2013) 107–122, <https://doi.org/10.1016/j.autcon.2012.09.004>.
- [43] L. Sanhudo, N.M.M. Ramos, J.P. Martins, R.M.S.F. Almeida, E. Barreira, M. L. Simões, V. Cardoso, A framework for in-situ geometric data acquisition using laser scanning for BIM modelling, *J. Build. Eng.* 28 (2020) 101073, <https://doi.org/10.1016/j.jobbe.2019.101073>.
- [44] H.A. Shanbati, N.M. Blinn, R.R. Issa, Laser scanning technology and BIM in construction management education, *J. Information Technol. Construct. (ITcon)* 21 (2016) 204–217.
- [45] S. El-Omari, O. Moselhi, Integrating automated data acquisition technologies for progress reporting of construction projects, *Autom. Constr.* 20 (6) (2011) 699–705, <https://doi.org/10.1016/j.autcon.2010.12.001>.
- [46] S.-W. Hsieh, Y.-R. Jang, G.-J. Hwang, N.-S. Chen, Effects of teaching and learning styles on students' reflection levels for ubiquitous learning, *Comput. Educ.* 57 (1) (2011) 1194–1201, <https://doi.org/10.1016/j.compedu.2011.01.004>.
- [47] M. Awada, R. Zhu, B. Becerik-Gerber, G. Lucas, E. Southerns, An integrated emotional and physiological assessment for VR-based active shooter incident experiments, *Adv. Eng. Inf.* 47 (2021) 101227, <https://doi.org/10.1016/j.aei.2020.101227>.
- [48] E. Kurilovas, S. Kubilinskiene, V. Dagiene, Web 3.0–Based personalisation of learning objects in virtual learning environments, *Comput. Hum. Behav.* 30 (2014) 654–662, <https://doi.org/10.1016/j.chb.2013.07.039>.
- [49] C. Vogel, B. Großer, U. Baumöl, T.J. Bastiaens, Tacit Knowledge in Virtual University Learning Environments, *International Association for Development of the Information Society*, 2018.
- [50] W. Wu, A. Tessei, S. Ayer, J. London, Y. Luo, V. Gunji, Closing the skills gap: construction and engineering education using mixed reality—a case study, *IEEE Front. Education Conf. (FIE) IEEE* 2018 (2018) 1–5, <https://doi.org/10.1109/FIE.2018.8658992>.
- [51] D.-H. Shin, The role of affordance in the experience of virtual reality learning: Technological and affective affordances in virtual reality, *Telematics Inform.* 34 (8) (2017) 1826–1836, <https://doi.org/10.1016/j.tele.2017.05.013>.
- [52] J. Radianti, T.A. Majchrzak, J. Fromm, I. Wohlgenannt, A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda, *Comput. Educ.* 147 (2020) 103778.
- [53] X. Wang, P.S. Dunston, User perspectives on mixed reality tabletop visualization for face-to-face collaborative design review, *Autom. Constr.* 17 (4) (2008) 399–412, <https://doi.org/10.1016/j.autcon.2007.07.002>.
- [54] K. McMillan, K. Flood, R. Glaeser, Virtual reality, augmented reality, mixed reality, and the marine conservation movement, *Aquat. Conserv. Mar. Freshwater Ecosyst.* 27 (2017) 162–168, <https://doi.org/10.1002/aqc.2820>.
- [55] M. Haller, Mixed Reality@ Education, *Multimedia Applications in Education Conference, MAPEC Citeseer* (2004) 13.
- [56] E.M. Epp, K.F. Green, A.M. Rahman, G.C. Weaver, Analysis of student-instructor interaction patterns in real-time, scientific online discourse, *J. Sci. Educ. Technol.* 19 (1) (2010) 49–57, <https://doi.org/10.1007/s10956-009-9177-z>.
- [57] C.V. Clark-Gordon, N.D. Bowman, E.R. Watts, J. Banks, J.M. Knight, “As good as your word”: face-threat mitigation and the use of instructor nonverbal cues on students' perceptions of digital feedback, *Commun. Education* 67 (2) (2018) 206–225, <https://doi.org/10.1080/03634523.2018.1428759>.
- [58] M.L. Knapp, The role of nonverbal communication in the classroom, *Theory into practice* 10 (4) (1971) 243–249, <https://doi.org/10.1080/00405847109542337>.
- [59] S. Lal, A.D. Lucey, E.D. Lindsay, D.F. Treagust, M. Mocerino, M.G. Zadnik, A study of the relative importance of student interactions for the attainment of laboratory-learning outcomes, in: 30th Annual Conference for the Australasian Association for Engineering Education (AAEE 2019): Educators Becoming Agents of Change: Innovate, Integrate, Motivate, Engineers Australia Brisbane, Queensland, 2019, pp. 372–380.
- [60] M. Ostanin, A. Klimchik, Interactive robot programming using mixed reality, *IFAC-PapersOnLine* 51 (22) (2018) 50–55, <https://doi.org/10.1016/j.ifacol.2018.11.517>.
- [61] P. Giraudeau, A. Olry, J.S. Roo, S. Fleck, D. Bertolo, R. Vivian, M. Hachet, CARDS: a mixed-reality system for collaborative learning at school, in: *Proceedings of the 2019 ACM International Conference on Interactive Surfaces and Spaces*, 2019, pp. 55–64.
- [62] A. Segura, A. Moreno, G. Brunetti, T. Henn, Interaction and ergonomics issues in the development of a mixed reality construction machinery simulator for safety

- training, in: *International Conference on Ergonomics and Health Aspects of Work with Computers*, 2007, pp. 290–299.
- [63] F. Bosché, M. Abdel-Wahab, L. Carozza, Towards a mixed reality system for construction trade training, *J. Comput. Civil Eng.* 30 (2) (2016) 04015016, [https://doi.org/10.1061/\(ASCE\)JCP.1943-5487.0000479](https://doi.org/10.1061/(ASCE)JCP.1943-5487.0000479).
- [64] J. Chalhoub, S.K. Ayer, Using Mixed Reality for electrical construction design communication, *Autom. Constr.* 86 (2018) 1–10, <https://doi.org/10.1016/j.autcon.2017.10.028>.
- [65] S. Azhar, J. Kim, A. Salman, Implementing Virtual Reality and Mixed Reality Technologies in Construction Education: Students' Perceptions and Lessons Learned, in: *Proceedings of the 11th ICERI Conference*, 2018, pp. 12–14.
- [66] W. Wu, J. Hartless, A. Tesei, V. Gunji, S. Ayer, J. London, Design assessment in virtual and mixed reality environments: Comparison of novices and experts, *J. Construct. Eng. Manage.* 145 (9) (2019) 04019049, [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0001683](https://doi.org/10.1061/(ASCE)CO.1943-7862.0001683).
- [67] K. Hornbæk, Current practice in measuring usability: Challenges to usability studies and research, *Int. J. Hum Comput Stud.* 64 (2) (2006) 79–102, <https://doi.org/10.1016/j.ijhcs.2005.06.002>.
- [68] L. Cooke, Eye tracking: How it works and how it relates to usability, *Technical Commun.* 52 (2005) 456–463.
- [69] A. Poole, L.J. Ball, Eye tracking in human-computer interaction and usability research: Current status and future prospects, *Encyclopedia of Human Computer Interaction*, Idea Group, 2006.
- [70] R.E. Mayer, Unique contributions of eye-tracking research to the study of learning with graphics, *Learning Instruction* 20 (2) (2010) 167–171, <https://doi.org/10.1016/j.learninstruc.2009.02.012>.
- [71] Z. Zou, S. Ergun, Where do we look? An eye-tracking study of architectural features in building design, in: *Advances in Informatics and Computing in Civil and Construction Engineering*, Springer 2019, pp. 439–446.
- [72] A. Mohammadpour, E. Karan, S. Asadi, L. Rothrock, Measuring end-user satisfaction in the design of building projects using eye-tracking technology, *Computing Civ. Eng.* 20152015, pp. 564–571.
- [73] Y. Shi, J. Du, Q. Zhu, The impact of engineering information format on task performance: gaze scanning pattern analysis, *Adv. Eng. Inf.* 46 (2020) 101167, <https://doi.org/10.1016/j.aei.2020.101167>.
- [74] T.-K. Wang, J. Huang, P.-C. Liao, Y. Piao, Does augmented reality effectively foster visual learning process in construction? An eye-tracking study in steel installation, *Adv. Civ. Eng.* 2018 (2018) 1–12.
- [75] S. Hennessy, Situated cognition and cognitive apprenticeship: Implications for classroom learning, (1993), doi: 10.1080/03057269308560019.
- [76] A. Collins, J.S. Brown, S.E. Newman, *Cognitive apprenticeship: Teaching the crafts of reading, writing, and mathematics*, Routledge, 2018.
- [77] L.S. Vygotsky, *Mind in society: The development of higher psychological processes*, Harvard university press 1980.
- [78] A.L. Brown, R.A. Ferrara, Diagnosing zones of proximal development, *Culture, communication, and cognition, Vygotskian perspectives* (1985) 273–305.
- [79] K.J. Lunsford, Challenges to implementing differentiated instruction in middle school classrooms with mixed skill levels, (2017).
- [80] O. Ogunseiju, A. Akanmu, D. Bairaktarova, Mixed Reality Based Environment for Learning Sensing Technology Applications in Construction, *Information Technology in Construction (ITcon)*, 26 (2021) 863–885, doi:10.36680/j.itcon.2021.046.
- [81] R. Hammady, M. Ma, C. Strathearn, User experience design for mixed reality: a case study of HoloLens in museum, *Int. J. Technol. Marketing* 13 (2019) 354–375, <https://doi.org/10.1504/IJTMKT.2019.104600>.
- [82] M. Leap, *Field of View & Clipping Plane*, 2019.
- [83] K. Holmqvist, M. Nyström, R. Andersson, R. Dewhurst, H. Jarodzka, J. Van de Weijer, *Eye tracking: A comprehensive guide to methods and measures*, OUP Oxford 2011.
- [84] M. Noghabaei, K. Han, A. Albert, Feasibility study to identify brain activity and eye-tracking features for assessing hazard recognition using consumer-grade wearables in an immersive virtual environment, *J. Construct. Eng. Manage.* 147 (9) (2021) 04021104, [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0002130](https://doi.org/10.1061/(ASCE)CO.1943-7862.0002130).
- [85] M.A. Just, P.A. Carpenter, A theory of reading: From eye fixations to comprehension, *Psychol. Rev.* 87 (4) (1980) 329–354, <https://doi.org/10.1037/0033-295X.87.4.329>.
- [86] D.D. Salvucci, J.H. Goldberg, Identifying fixations and saccades in eye-tracking protocols, in: *Proceedings of the 2000 symposium on Eye tracking research & applications*, 2000, pp. 71–78.
- [87] S. Kapp, M. Barz, S. Mukhametov, D. Sonntag, J. Kuhn, ARETT: augmented reality eye tracking toolkit for head mounted displays, *Sensors* 21 (2021) 2234, <https://doi.org/10.3390/s21062234>.
- [88] A. Olsen, The Tobii I-VT fixation filter, *Tobii Technol.* 21 (2012).
- [89] O.V. Komogortsev, D.V. Gobert, S. Jayarathna, S.M. Gowda, Standardization of automated analyses of oculomotor fixation and saccadic behaviors, *IEEE Trans. Biomed. Eng.* 57 (11) (2010) 2635–2645, <https://doi.org/10.1109/TBME.2010.2057429>.
- [90] J. Salojärvi, K. Puolamäki, J. Simola, L. Kovanen, I. Kojo, S. Kaski, Inferring relevance from eye movements: Feature extraction, Workshop at NIPS 2005, in Whistler, BC, Canada, on December 10, 2005. 2005, pp. 45.
- [91] P. Wilkes, A. Lau, M. Disney, K. Calders, A. Burt, J.G. de Tanago, H. Bartholomeus, B. Brede, M. Herold, Data acquisition considerations for terrestrial laser scanning of forest plots, *Remote Sens. Environ.* 196 (2017) 140–153, <https://doi.org/10.1016/j.rse.2017.04.030>.
- [92] K. Hercegfi, A. Komlódi, M. Köles, S. Tóvölgyi, Eye-Tracking-based Wizard-of-Oz Usability Evaluation of an Emotional Display Agent Integrated to a Virtual Environment, *Acta Polytechnica Hungarica* 16 (2019) 145–162.
- [93] N. Yilmaz, E. Ergen, D. Artan, A Usability Test Protocol For Evaluating Mixed Reality Environments. *European Conference on Computing in Construction*, 2021.
- [94] W. T. PSSUQ (Post-Study System Usability Questionnaire), in: U. Trend (Ed.), 2021.
- [95] J.R. Lewis, Psychometric evaluation of the post-study system usability questionnaire: the PSSUQ, *Proc. Hum. Factors Soc. Annual Meeting* 36 (16) (1992) 1259–1260.
- [96] J.R. Lewis, J. Sauro, The factor structure of the system usability scale, in: *International Conference on Human Centered Design*, Springer, 2009, pp. 94–103.
- [97] M. Gao, P. Kortum, F. Oswald, Psychometric evaluation of the USE (Usefulness, Satisfaction, and Ease of use) Questionnaire for Reliability and Validity, *Proc. Hum. Factors Ergon. Soc. Annual Meeting* 62 (1) (2018) 1414–1418.
- [98] C. Wijesooriya, J. Heales, F. Rohde, Evaluation of virtual learning environment characteristics in learning performance, in: *Proceedings of the 10th International Conference on E-Education, E-Business, E-Management and E-Learning*, 2019, pp. 259–263.
- [99] A.A. Bojko, Informative or misleading? Heatmaps deconstructed, *International conference on human-computer interaction*, Springer, 2009, pp. 30–39.
- [100] E. Ozcelik, T. Karakus, E. Kursun, K. Cagiltay, An eye-tracking study of how color coding affects multimedia learning, *Comput. Educ.* 53 (2) (2009) 445–453, <https://doi.org/10.1016/j.compedu.2009.03.002>.
- [101] A.W. Joseph, R. Muruges, Potential eye tracking metrics and indicators to measure cognitive load in human-computer interaction research, *J. Sci. Res.* 64 (01) (2020) 168–175, <https://doi.org/10.37398/JSR.2020.640137>.
- [102] M. Pachman, A. Arguel, L. Lockyer, G. Kennedy, J. Lodge, Eye tracking and early detection of confusion in digital learning environments: proof of concept, *Australasian J. Educational Technol.* 32 (2016), <https://doi.org/10.14742/ajet.3060>.
- [103] B. Pan, H.A. Hembrooke, G.K. Gay, L.A. Granka, M.K. Feusner, J.K. Newman, The determinants of web page viewing behavior: an eye-tracking study, in: *Proceedings of the 2004 symposium on Eye tracking research & applications*, 2004, pp. 147–154.
- [104] R. Bernhaupt, P. Palanque, M. Winckler, D. Navarre, Usability study of multi-modal interfaces using eye-tracking, *IFIP Conf. Hum.-Computer Int.*, Springer (2007) 412–424, https://doi.org/10.1007/978-3-540-74800-7_37.
- [105] M.G. Violante, E. Vezzetti, P. Piazzolla, How to design a virtual reality experience that impacts the consumer engagement: the case of the virtual supermarket, *Int. J. Interactive Des. Manuf. (IJIDeM)* 13 (1) (2019) 243–262, <https://doi.org/10.1007/s12008-018-00528-5>.
- [106] R. Vassallo, A. Rankin, E.C. Chen, T.M. Peters, Hologram stability evaluation for Microsoft HoloLens, *Medical Imaging: Image perception, observer performance, and technology assessment*, *Int. Soc. Optics Photonics* 2017 (2017) 1013614.
- [107] A. Erickson, K. Kim, G. Bruder, G.F. Welch, Exploring the limitations of environment lighting on optical see-through head-mounted displays, *Symposium on Spatial User Interaction* (2020) 1–8, <https://doi.org/10.1145/3385959.3418445>.
- [108] R.T. Azuma, The challenge of making augmented reality work outdoors, *Mixed reality: Merging real and virtual worlds*, 1 (1999) 379–390, <https://ronaldazuma.com/papers/ismr99.pdf>.