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Desktop-based safety training using 360-degree panorama and static virtual reality techniques: A comparative experimental study

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ABSTRACT

Virtual reality (VR)-based approaches have been used to facilitate safety knowledge transfer and increase hazard awareness by providing safe and controlled experiences of unsafe scenarios in construction safety training applications. However, the long development times and high computational costs associated with existing VR methods have posed significant challenges to using such VR-based safety training platforms. Unlike VR settings that deliver computer-generated reproductions of the environment, 360-degree panorama can create true-to-reality simulations of construction jobsites. This research developed and compared two hazard-identification training platforms based on VR and 360-degree panorama. Construction students and professionals participated in an experiment to determine their perception of realism and evaluate their hazard-identification skills. It was found that students perceived the 360-degree panorama conditions as more realistic than the VR conditions, but professionals perceived no difference between them. Moreover, differences were found in the average hazard identification index (HII) scores for all participants, with higher scores for the VR conditions than for the 360-degree panorama conditions. Finally, it was found that there was an inverse correlation between the presence scores and the average HII scores for the participants in the study.

1. Introduction

Because safety training has a direct impact on the prevention of construction accidents, different techniques have been adopted by construction firms to improve the hazard-identification skills of their employees. Traditionally, lecture-based training incorporating passive instruction techniques (e.g., text, images, videos) has been used to teach hazard recognition to workers and professionals. The current literature has found that these passive methods for teaching hazard recognition have shortcomings in terms of knowledge retention, motivation, engagement [1,2], and attentional distribution [3], which translates to a reduction in the number of hazards identified by trainees. Additionally, it has been found that the effectiveness of safety training increases when trainees are exposed to hazardous events [4], which is often impossible in the real world. To overcome the existing limitations of traditional training techniques, research has found that instructional approaches should focus on high levels of hands-on, context-based, and activity-oriented interactions [5]. Computer-based techniques such as virtual reality (VR) and augmented reality (AR) have been widely used to deliver these types of interactive learning experiences that engage and motivate trainees.

In the context of VR computer-based techniques, learners can be placed in situations that are impossible, dangerous, or expensive to simulate in real-world training scenarios, effectively eliminating the risk for potential harm during training. While the location-independency afforded by VR computer graphics allows content creators to produce representations of the real environment, the quality of rendering and the complexity of the scenes are frequently constrained [6]. Comprehensive reproductions of complex real-world conditions can be time consuming, computationally intensive, and yield virtual environments that have limited resemblance to actual real-world locations [7]. Moreover, AR computer-based techniques leverage the real world to enable experiential learning through interactions with digital augmentations and jobsite surroundings. However, the physical location-dependent requirements for implementing AR safety training approaches in construction jobsites present serious challenges. Safety concerns due to proximity to hazards [8] and reliance on spatio-temporal contextual information for a fixed geolocation [9] potentially reduce the opportunities for active exploration and experimentation during educational interventions.

An emerging alternative to these techniques within the spectrum of mixed reality (MR) [10] is 360-degree panorama, a reality-capturing

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technique that creates an omnidirectional view of the surroundings for the viewer, providing a "*sense of presence, of being there*" [11]. This location-independent technique can be used to visualize true-to-reality captures of construction jobsites in a way that is analogous to VR approaches. These two techniques are similar as they enable safety training in a location-independent environment, introduce serious game mechanisms for interaction, and present trainees with purposefully created learning content. As a result, these training simulations deliver multiple scenarios for exploration, task-directed goals in a gamified manner, and immediate feedback to the trainee to reinforce learning.

While the application of computer-based techniques in construction safety training is gaining traction, limited knowledge is available regarding the effectiveness of modeled VR compared to that of 360-degree panorama training environments for improving hazard-identification skills. In particular, instructors are interested in knowing the impact of realism in digital construction sites for the development of hazard-identification skills in construction trainees. This research project aims to address this knowledge gap by comparing the performance of two different approaches, i.e., 360-degree panorama and virtual reality, as mediums to transfer safety knowledge to students and professionals.

2. Virtual reality and 360-degree panorama for construction safety training

2.1. Virtual reality in construction safety training

Academics have investigated different techniques and applications for VR to produce active learning experiences that engage and motivate learners. In the safety domain, VR systems have been classified depending on the level of immersion provided to trainees. The continuum of immersion for VR experiences ranges from desktop-based applications that utilize common PC peripheral devices (e.g., monitor, mouse, keyboard) to highly immersive environments that employ specialized head-mounted displays [8,12]. In the training and education domain, these immersion techniques are accompanied by serious game mechanisms to attain safety knowledge within virtual settings. For example, desktop-based VR games have been employed to enable university students to navigate a virtual construction environment and identify hazards within a time limit [13]. In another study, virtual representations of workers and equipment provided a simulation of an active jobsite in a similar VR desktop-based training for safety monitoring and visualization [14]. Likewise, immersive virtual systems have been used to allow users to assess working at dangerous heights on construction scaffolds [15].

Although VR is an exceptional method for visualizing and interacting with highly engaging computer-generated environments, major issues still exist. VR environments are expensive and time consuming to develop [16,17]. Modeling realistic settings requires substantial investments in terms of VR content development (e.g., 3D site, user interactions, model animations, pedagogical goals) [17]. After such efforts, the VR environment may apply to only one specific project or certain learning objectives, or it may be useful only to particular members of the construction industry [18]. Subsequently, VR is limited by its low agility, as work environments quickly evolve spatiotemporally. As these VR recreations provide a medium for replicating jobsite conditions, the resulting digital settings that are generated are not fully analogous to real-world working conditions. Moreover, it has been found that VR environments might diminish construction-related task proficiency in the real world when trainees practice these job-related tasks in unrealistic virtual environments [19].

2.2. 360-degree panorama in construction safety training

360-degree panorama has been used to provide a means of visualization in the context of hazard recognition in the construction domain. For example, [9] created a 360-degree panorama-based platform for safety training using augmented information from real environments. This system allowed users to actively navigate construction sites by visualizing realistic data-rich augmented environments. The platform was evaluated for fall hazard identification, and it was found that study participants identified an average of 52% of the presented hazards in such an environment. A subsequent study [20] found that users identified an average of 30% of hazards across different types of Focus Four hazards using the provided platform. This research demonstrated that the platform was simple to use and to learn by performing a usability study. Moreover, a pilot study [21] qualitatively explored hazard identification using 360-degree panorama and VR techniques. The authors found that construction management students had a higher rate of hazard identification in the VR condition but that they described it as too clean and organized in comparison to the more accurate representation of the 360-degree panorama condition. Likewise, [22,23] developed a learning system for enhancing safety education using 360-degree panorama scenes. The created system allowed students to perform digital site visits with the objective of recognizing hazards within digital 360-degree spaces. The system enabled the assessment of safety knowledge learned from the exploration using gamified testing mechanisms. This investigation found no significant differences between safety hazard identification of students who visited the construction site and students who used the 360-degree panorama system.

While 360-degree panorama scenes provide a realistic representation of jobsites, enabling a sense of presence to the participants, several limitations have been found concerning image quality, the static vantage point, and stitching error artifacts. The 360-degree cameras that are currently commercially available do not offer image quality comparable to that of traditional photography [24]. In 360-degree images, relatively low resolutions are experienced by the users as a result of the limited observable field of view, which requires the amplification of sections of the overall equirectangular projection. Moreover, 360-degree panorama technology uses photographic techniques that capture static vantage points from the obtained images. These static vantage points allow only visual rotation within the captured 360-degree field of view, eliminating the possibility of spatial movement. Finally, current stitching algorithms attempt to reduce image processing issues that introduce error artifacts (e.g., blurriness, discontinuities, illumination). However, stitching error artifacts still appear in 360-degree images depending on factors such as object proximity to the focal point of the camera, movement of objects on the stitching lines during capture, and light exposure differences between camera lenses.

3. Research challenges, questions, and hypotheses

Currently, two major challenges have been identified in virtual instructional methods that hinder the mastering of safety hazard identification skills. First, digital construction sites intend to provide a presentational vehicle for real-life situations, accurately simulating safety challenges that reproduce adopted safety training practices [25]. However, there are difficulties in defining the degree to which a digital platform represents a real-life situation and adequately depicts real-world operations and locations. Second, trainees respond differently to simulated environments (e.g., 360-degree panorama, VR), leading to uncertainty regarding proper learning outcomes for a given digital delivery method. Such learning outcomes seek to improve the capability of trainees to identify safety challenges within the complex context of a construction project. Because of these two challenges, this research aims to (1) investigate the realism of digital safety training environments and (2) evaluate the hazard-recognition capabilities of trainees within different digital safety training environments. These objectives led to the formulation of the following research questions and hypotheses for this study:

- Realism of digital safety training environments:
  - *Research Question (1)*: How realistic are 360-degree panorama and virtual reality environments in representing the safety challenges of a real construction site to develop hazard-identification skills?
  - *Research Hypothesis (1)*
    - H_0: 360-degree panorama and virtual reality conditions are equal in terms of presence.
    - H_1: 360-degree panorama and virtual reality conditions are not equal in terms of presence.

- Hazard recognition within digital safety training environments:
  - *Research Question (2)*: What are the effects of 360-degree panorama and virtual reality on the development of hazard-identification skills?
  - *Research Hypothesis (2)*
    - H_0: 360-degree panorama and virtual reality conditions are equal in terms of the development of hazard-identification skills.
    - H_1: 360-degree panorama and virtual reality conditions are not equal in terms of the development of hazard-identification skills.

4. Project overview

This research project builds on the outcomes of previous studies [20–22] to provide an in-depth quantitative evaluation of presence and hazard-identification skills in 360-degree panorama and modeled virtual reality environments. With the objective of assessing the research hypotheses formulated in this study, this project followed the steps illustrated in Fig. 1. Initially, safety training and assessment platforms were developed for 360-degree panorama and virtual reality desktop-based environments. Within these platforms, modules were established to perform the hazard-recognition tasks required for evaluation of the trainees. Subsequently, an experiment was used to compare the target populations under each study condition leveraging the created modules. Based on this experiment, an evaluation with user participation was performed utilizing the platforms as the experimental conditions. Finally, the study findings were reported, and the discoveries were discussed to provide insights for future research. To accomplish this, the data collected from the experimental assessment were analyzed using nonparametric statistical models, reporting results for the trainees' sense of presence and hazard identification index (HII) [26]. These results were examined in detail to better understand the use of 360-degree panorama and virtual reality as safety training methods. Ultimately, the research limitations were described, the conclusions of the study were defined, and the future direction of this research was stated.

5. Safety training and assessment platform development

Two platforms were developed to evaluate the research hypotheses formulated in this study: one based on 360-degree panorama technology and one based on current building information modeling technologies. These two platforms aim to provide an active learning and assessment method for hazard-recognition skills. Both platforms expand on previous studies' outcomes for the development of digital environments for safety training [20–22]. Consequently, the platforms leverage digital settings with similar layers of augmented information and graphical user interfaces that provide interactions conducive to developing hazard-identification skills for specific simulated environments. This section presents a detailed description of the technical development of each platform, the challenges observed during the usage of each type of technology, and how the training and assessment happen within each platform.

5.1. 360-degree panorama platform

The development process of the 360-degree panorama-based platform was performed in four steps, as illustrated in Fig. 2: (1) capture, (2) visualization, (3) augmentation, and (4) interaction. In the initial capture step, scenes were collected from real-world jobsites. To achieve this, the capturing process requires the creation of an equirectangular projection with multiple fish-eye lens cameras (e.g., Samsung Gear 360®, Insta360 One®, NCTech Fusion®). Computer software is used to stitch the scenes captured by each lens into a single equirectangular projection picture. The visualization step entailed the translation of the 2D equirectangular projection into a 3D projection using a game engine such as Unity3D®. This visualization technique leverages the equirectangular image to map the data into a rendering of a sphere, cylinder, or cube, allowing platform users to explore the scenes in a 3D digital setting.

The augmentation step introduced overlaid data, objects, animations, or sounds within the 360-degree panorama in the digital

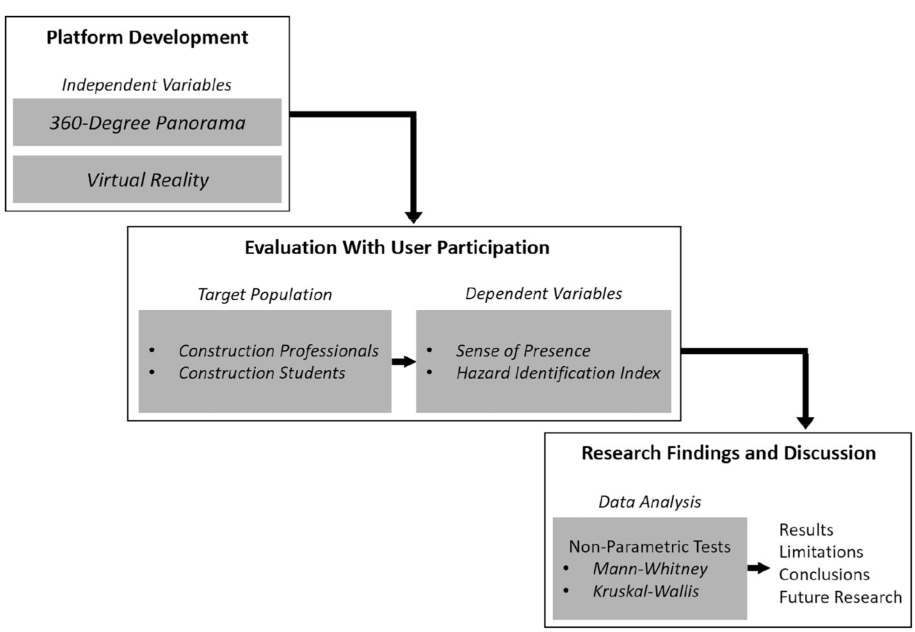

Fig. 1. Overview of the research methodology.

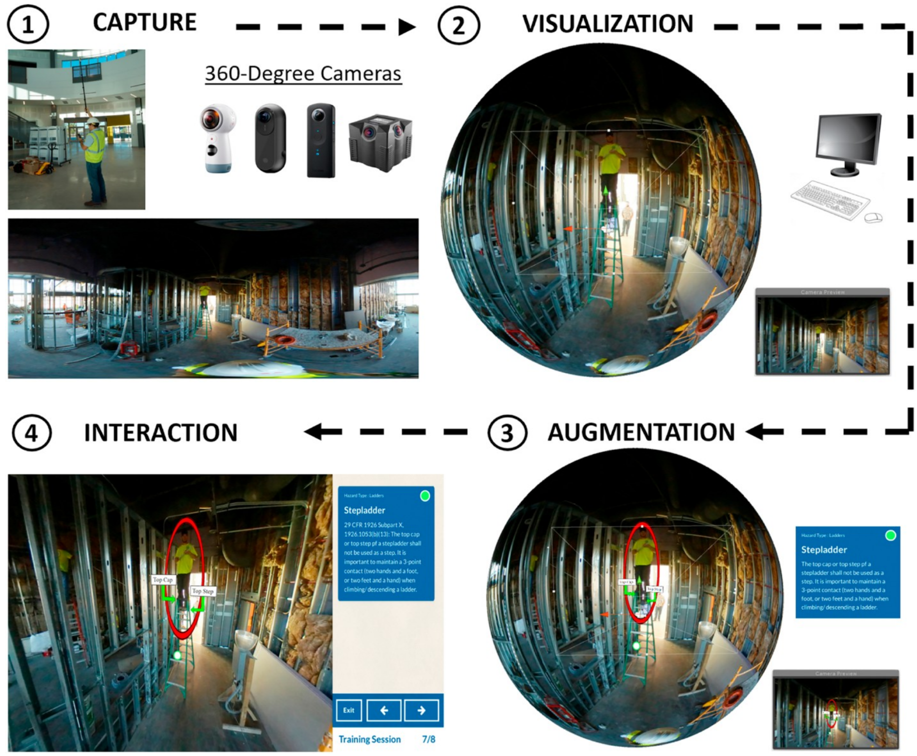

Fig. 2. 360-degree panorama platform development process.

environment. These augmentations or annotations allowed the display of additional information using graphical or auditive resources. This research used these augmentations as a method to describe safety material, leveraging the information captured in the 360-degree scenes. The augmentations employ pictographic and written content from OSHA's training manuals to enhance users' understanding of real-world jobsite safety conditions. The specific safety content for these augmentations is described in Section 5.5.

Finally, in the interaction step, a graphical user interface is presented to allow users to interact with the platform. These interactions depend on the activities that the users perform within the platform. For training interactions, a graphical representation of the hazardous conditions is displayed within the 360-degree panorama scenes using a hotspot, i.e., marker that directs the attention of the user to a hazardous situation and links to augmentations (e.g., data, objects, animations, sounds). Moreover, learning cards with written descriptive information of the hazard accompany a graphical representation of the hazard and descriptive information in a hotspot. The learning card information indicates the hazard category and hazard type and provides a summary that elaborates on the exact nature of the hazard displayed in the 360-degree panorama scene. For assessment interactions, an evaluation card is used to display a hazard checkbox list of the possible answers in the 360-degree panorama scene. The user registers their responses by selecting each checkbox, and feedback is provided after completing the hazard-recognition tasks.

The 360-degree panorama platform has the potential to be exported into any device (e.g., PCs, laptops, handheld devices, head-mounted displays) to allow users to interact with the information. In this study, PCs were targeted as the primary device for analysis, as they are easily accessible and do not require any special setup. A mouse-and-keyboard setting was utilized to allow trainees to navigate the virtual environments using drag-and-drop gestures within the interface contained in the scenes and point-and-click gestures in the designed graphical user interfaces.

5.2. Virtual reality platform

The development process of the virtual reality-based platform was performed following a similar method as that of the 360-degree panorama platform. This platform employed a similar four-step process, as shown in Fig. 3: (1) generation, (2) visualization, (3) augmentation, and (4) interaction. In the generation step, construction jobsites were modeled, and 360-degree virtual scenes were rendered. Four different software tools were employed to perform the modeling tasks: Autodesk Revit®, Trimble SketchUp®, Autodesk Infraworks 360®, and Lumion 9®. To generate federated virtual reality scenarios, buildings made of different construction materials (e.g., wood, steel, concrete) were obtained from Autodesk's BIMobject® and SketchUp®'s 3D Warehouse model libraries. These two model libraries were employed to shorten development time, as generating different types of commercial building models is a highly time-consuming task. The models were configured into a single cohesive scene that aimed to replicate, to the greatest extent possible, the real-world jobsite settings captured in the 360-degree panorama technique. Then, the building models were imported and placed into Infraworks 360®, which provided a city landscape for the background. Additional contextual details, such as heavy equipment, powerlines, and sand piles, were placed into the scenarios using both Infraworks 360® and SketchUp® 3D Warehouse models. Finally, the prepared scenarios, including the buildings, city landscape, and 3D construction equipment, were exported into Lumion 9® for further scene enhancement. Within Lumion 9®, modeled human workers were added, and the material properties of objects were adjusted to improve the realism of the scenarios. Via Lumion 9® software, 2D equirectangular projections of virtual reality were rendered, generating a series of 360-degree virtual scenes similar to those obtained from the 360-degree panorama capture process.

In the visualization step, the translation of the 2D equirectangular projection into a 3D projection using the Unity3D® game engine was achieved. This visualization method was parallel to the one used in the 360-degree panorama platform, utilizing an equirectangular scene to map the data into a rendering of a sphere, cylinder, or cube. This

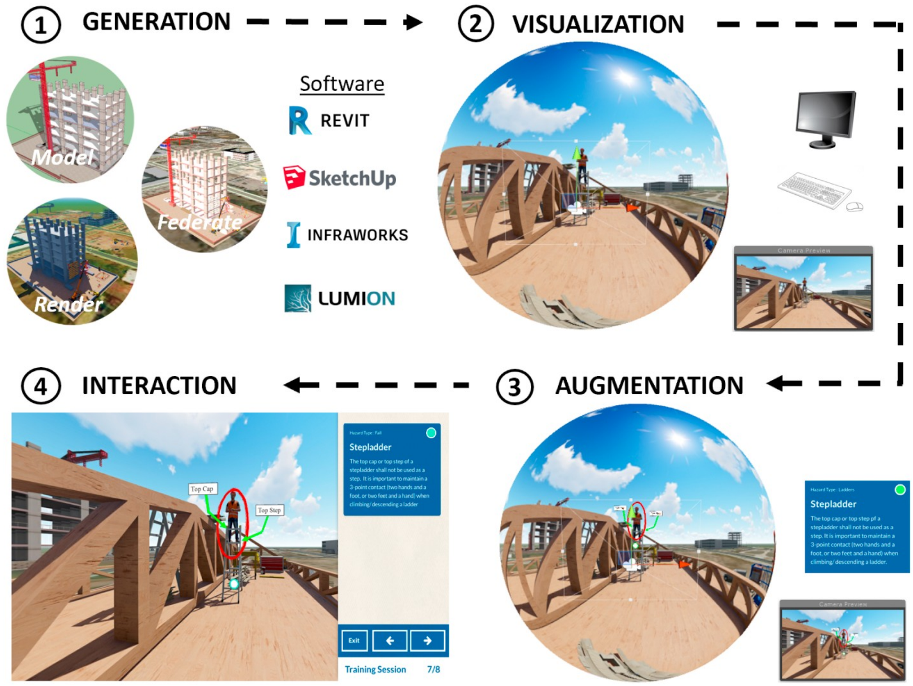

Fig. 3. Virtual reality platform development process.

allowed platform users to explore the scenes in the exact same fashion as the previously described for the 360-degree panorama platform, enabling detailed observation of interest areas but in a virtual reality setting. The augmentation step followed the same method to overlay data, objects, animations, or sounds within the virtual reality environment. The use of augmentations to describe safety material from OSHA's training manuals was analogous to the 360-degree panorama platform but adapted to the scenarios created in the virtual reality environments.

Finally, in the interaction step, the same graphical user interface was presented as in the previous platform, and it was used to allow users to interact with the platform. For training interactions, hotspots were used to mark hazardous situations and to activate the augmentations in conjunction with the written descriptions on the learning cards. For the assessment interactions, the same evaluation cards were used to display a checkbox list of the possible answers for a particular virtual reality scenario. Since the scope of the hazards remained the same, the actual content of these checkboxes did not change from one platform to another. Similar to the 360-degree panorama platform, the virtual reality platform had the potential to be exported by any devices (e.g., PCs, laptops, handheld devices, head-mounted displays) to allow users to interact with the information. Again, PCs were targeted as the primary device of analysis, as these are easily accessible and do not require any special setup. A mouse-and-keyboard setting was utilized to enable trainees to explore using drag-and-drop gestures.

5.3. Challenges in the technical development of the platforms

During the development process, challenges and limitations to produce real-life construction situations were observed for each technique. This section reports the main issues found in each approach.

5.3.1. 360-degree Panorama

Three major challenges were found during the data collection, implementation, and development of the 360-degree panorama platform. First, construction jobsites are very complex and dynamic, with ever-changing personnel, equipment, and materials. Due to the spatio-temporal nature of the data collection process in this research, the capture of active or potential safety hazards presented challenges as the contextual conditions of the visited projects varied constantly. Access to the sites, proximity to the workers, and movement of equipment or materials were some other variables necessary to consider during data collection with the 360-degree cameras. Second, the image quality of current consumer-grade 360-degree cameras is not comparable to that of DSLR or mirrorless cameras. To obtain high-quality 360-degree images, professional-grade setups must be utilized (e.g., NCTech Fusion®, Insta360 Pro®, Kandao Obsidian®). However, professional cameras sacrifice mobility and capture speed to obtain higher quality images. In the context of the construction jobsite, capture speeds directly impact the data collection process, as rapid image capture is necessary to observe the constantly changing safety conditions. Currently, rapid capture is available only on compact consumer-grade 360-degree cameras (e.g., Ricoh Theta V®, Insta360 One®, GoPro Fusion®). In this study, 360-degree panorama images were captured with the rapid-capture cameras Samsung Gear360® (2017) and Insta360 One®, which had photographic resolutions of 5000×2000 pixels and 6000×3000 pixels, respectively, in their equirectangular projection form. Third, 360-degree panorama techniques are inherently static, producing a single vantage point per captured scene. Static vantage points constrain user exploration within 360-degree panorama scenes to visual rotation exclusively. Furthermore, these restrictions introduce composition issues, as objects that are too close to the focal point can obstruct the field of view of the users and distract them from other important information in the scene or directly produce visualization errors.

5.3.2. Virtual reality

Three major challenges were found during the data collection, implementation, and development of the virtual reality platform First, virtual reality environments require a significant time investment to produce real-world scenarios using 3D models. The creation and composition of these scenarios to resemble hazardous situations in existing construction sites require dedicated professionals who understand the safety settings in the real world and who possess the skills to translate this knowledge into the digital medium. This introduces additional challenges, as the environment is created based on the modeler's perception of reality, resulting in an arbitrary representation that might not be entirely accurate. Second, scene complexity is constrained by the level of detail in each scene. Although modern rendering techniques produce very precise visualizations of 3D models, the level of detail required to reproduce real-world conditions has not yet been achieved. This impact on realism has been found to be detrimental for training applications, as the user might feel disconnected, distracted, or uncomfortable in the environment or situation, worsening the overall learning outcomes [27]. Third, the available rendering software allowed only a few options for the photographic resolution configurations for equirectangular projection that did not fully match the image resolution of the 360-degree panorama captures. The 360-degree renderings of the VR scenarios were produced with Lumion 9® in the closest available equirectangular photographic resolution of 4000×2000 pixels. Although these resolutions varied across formats, no differences were found by visual inspection of the images after spherical coordinate projection in Unity3D®. This was due to the image compression introduced by the Unity3D® game engine, which resizes all photographs to approximately 4000×2000 pixels.

5.4. Training and assessment modules in the developed platforms

As previously described, two platforms were developed using 360-degree panorama and VR environments. Each of these platforms contained two separate modules: training and assessment. The training module aimed to transfer necessary knowledge about different hazards in the construction industry, while the assessment module measured trainees' post-training hazard-identification skills. Having two separate modules enabled researchers to compare the effectiveness of 360-degree panorama and VR environments for the development of hazard-identification skills.

5.4.1. Training module

The training module concentrates on using the augmented data, objects, animations, or sounds within the 360-degree panorama or VR environments to enable the user to observe and understand safety-related information. Different from other existing platforms, the proposed training module specifically aims to spatially connect augmentations within the 360-degree scenarios to facilitate the learning of safety concepts. In this module, user interactions are driven by hotspots and learning cards, enabling multiple graphical signifiers (e.g., arrows, ellipses, lines) to direct the attention of the trainee within the digital site toward the active or potential safety hazard. Each platform provides exploration capabilities for the user to observe safety content on their own, promoting learning engagement. As illustrated in Fig. 4, both platforms operate under similar 360-degree training scenarios to display safety information. The trainees' interactions with each platform are identical, providing consistent training across the digital settings.

5.4.2. Assessment module

The assessment module focuses on leveraging digital sites to evaluate trainee safety knowledge, assimilated from the training module, similar to an evaluation at a real-world jobsite. In this module, trainees are presented with non-augmented scenarios to identify safety hazards. This proposed assessment module aims to promote exploration, as no graphical signifiers are provided to the trainees. In contrast to other existing assessment approaches, hazard-recognition tasks depend directly on participant safety knowledge, as the identification tasks are open-ended. Shown in Fig. 5, the hazard identification interactions were achieved by employing a checkbox interface that displayed all the possible hazards presented in the training module, grouped using the Focus Four categories. Once the trainees finish the hazard-recognition training in all the 360-degree scenes, feedback is provided to indicate the correct and incorrect selections on the assessments.

5.5. Hazard recognition content: OSHA's focus four

The Occupational Safety and Health Administration (OSHA) has identified the four leading causes of fatalities in the construction industry as fall, struck-by, caught-in-or-between, and electrical hazards; these hazards are called the Focus Four. Several training programs, such as OSHA's Susan Harwood Grant (SHG), have used this classification in their training materials. To maintain consistency with this industry practice, the research team developed training content for the learning modules based on the Focus Four hazard classification.

This study uses the library of 360-degree panorama scenes collected from a preliminary usability study, conducted exclusively for a 360-degree panorama platform [20]. The library is composed of over 600 scenes from eight different construction jobsites. A panel of eight construction safety professionals was formed to evaluate scenes and determine the specific hazards present in each scene. To be included in this panel, a safety expert needed to be a certified safety professional (CSP) with more than ten years of experience. After reviewing the scenes, the panel selected sixteen 360-degree panorama scenes that illustrated several common Focus Four hazards. These sixteen scenes were assigned equally to the training (8 scenes) and assessment (8 scenes) modules. Based on the set of scenes selected by the safety experts, the scenarios for the VR platform were developed. Table 1 illustrates the types of hazards present in the platforms organized by the Focus Four categorization scheme. For example, in the fall hazard category, the hazard type "ladders" is a topic addressed in the platform's training and assessment modules. The augmentations and content used for this example can be observed in Figs. 4 and 5, where scenarios that contain this hazard type are presented to the trainees for learning and evaluation of their hazard-identification skills.

6. Evaluation with user participation

The evaluation of the realism perceived by the study participants and of their skills to recognize hazards were assessed by using a research design and methodology established for this investigation. In the following sections, the experimental details, study measures, and data analysis techniques are presented in detail.

6.1. Experiment design

To effectively compare 360-degree panorama and VR environments during the training and assessment modules, each population was exposed to each condition shown in Fig. 6. A between-subject experimental design was selected for this research to reduce the learning effects produced by condition exposure during the intervention. This experimental design resulted in each participant—both professionals and students—being exclusively subjected to one of the platform's training and assessment modules. For each participant, two main metrics were measured through data collection: the sense of presence and the hazard identification index. These two measurements offered a method for evaluating the research hypotheses of this study.

6.2. Experiment methodology

The evaluation of perceived realism and hazard recognition was performed through an experimental process under IRB-201701616. Data were collected in situ from practicing professionals and active students. Professionals from different companies across the state of Florida were visited at their regional or local offices, where they were exposed to the experimental conditions and completed the survey instruments. Efforts were made to isolate the professionals from noise, distractions, and interruptions during the experiment; often, an empty office was reserved for performing the experiment, and time slots were assigned to each participant. Students were recruited at the University of Florida and were exposed to the experimental conditions in a

Fig. 4. Training module – 360-degree panorama and virtual reality environments.

controlled laboratory environment. Master's and Ph.D. students were targeted with the objective to ensure that the participants had real-world work experience, similar to construction professionals. By recruiting this particular selection of students, the researchers also aimed to reduce potential novelty factors in terms of safety information and technology usage. For the students, the experiment was performed in a quiet, air-conditioned room, where the participants had no distractions or interruption during exposure to the conditions in the simulations.

Three instruments were used to collect the data: a pre-test demographic survey, a hazard-recognition assessment, and a post-test presence survey. The data collection process took 45 min on average. In the pre-test demographics survey, information (i.e., age, sex, educational level, background, and previous experience/knowledge in construction) was collected from the platform users. Additionally, other data were collected regarding the participant experience with virtual/augmented reality and 360-degree panorama. Four-point Likert scale responses (i.e., none, some, fair, competent) were used for self-assessment of the participant's understanding of the topics.

During the hazard-recognition test, platform users assessed their knowledge of the different hazards present in the 360-degree panorama and virtual reality modules. Participants completed the training and assessment modules as described in Section 6.4 using laptop PCs with a display resolution of 2 K (2048 × 1080 pixels) or higher. The platform used on each of the computers was scaled across all the systems to the same resolution (1600 × 900 pixels) in full screen view for consistency purposes, and the Unity3D® executable launch interface was employed. The hardware sets were identical for data collection across all conditions and target participants. Moreover, all trainees viewed a brief introductory tutorial within the platform that indicated how the interactions utilized mouse-based gestures.

For the training module of each platform, eight scenarios displayed visual signifiers to help the participants identify and understand the active or potential safety hazards. The subjects were provided a total of 15 min to explore the eight scenarios freely, allowing them to revisit scenes within the established time limit. For each scenario, the number of hazards varied from 1 to 4 depending on the specific spatiotemporal context. The objective of exposing the participants to this training module was to allow active learning directed toward the Focus Four hazards presented in the scenarios. Once the 15 min were completed, participants were asked to exit the training module. Afterward, the assessment module, which contained eight consecutive scenarios without any type of augmentation or hotspot, was presented to the participants. For each scenario, a 2-minute exposure was provided for the participants to explore and identify the hazards. This exposure was controlled by an automatic timer built into the platforms that would continue to the next assessment scenario once completed. For this assessment module, the objective was to identify all the hazards within the scope of the hazards described previously in the training module. Data were collected within this module by automated processes embedded in the platforms to obtain the HII scores for each participant.

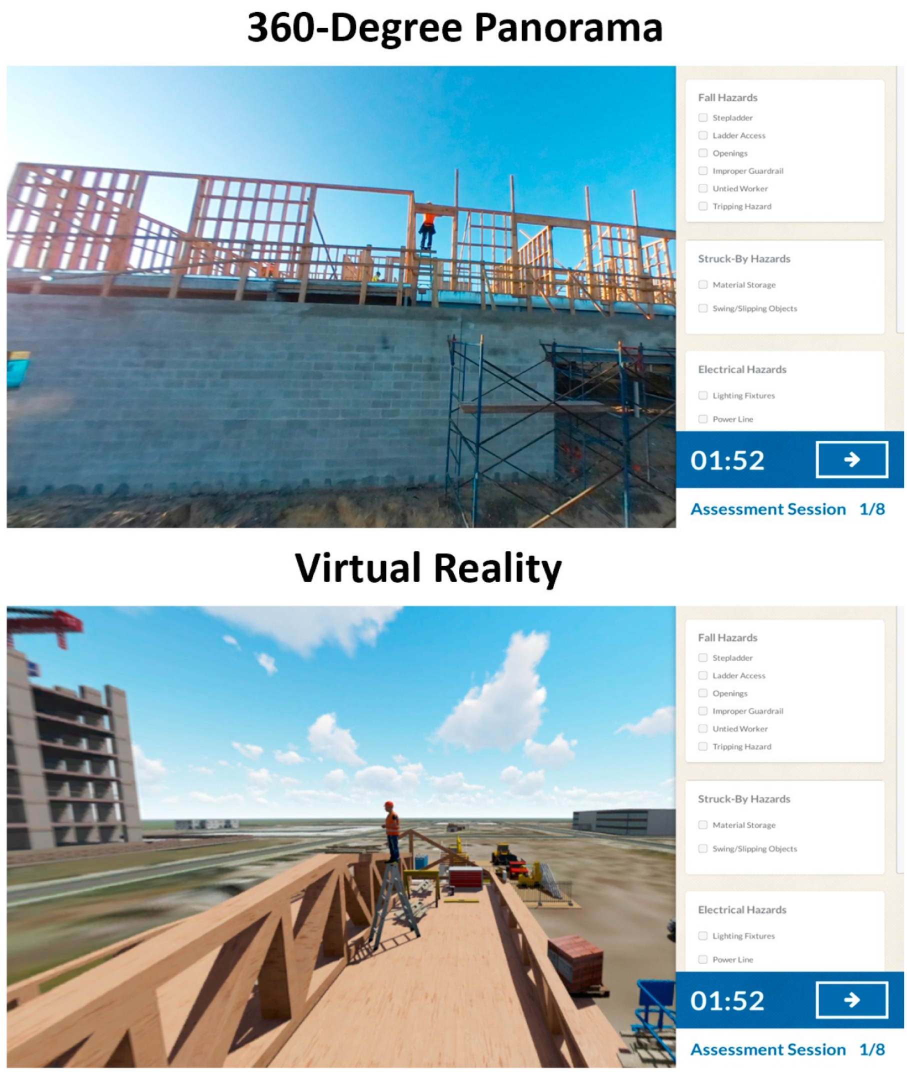

Fig. 5. Assessment module – 360-degree panorama and virtual reality environments.

Table 1
Focus Four hazards contained in the platforms.

Hazard category	Hazard type
Falls	Ladders
	Floor openings/excavations
	Unprotected edges
	Personal arresting gear
	Housekeeping
Struck-By	Falling objects
	Swinging/slipping objects
Electrical	Inadequate wiring
	Overhead power lines
Caught-in/between	Tools and equipment
	Trenches and excavations

Once the hazard-identification tasks were completed in the assessment module, instantaneous feedback was provided to the participants.

In the post-test presence survey, participants completed a questionnaire regarding the sense of presence under each condition. These data were collected to understand how professionals and students perceived the virtual environment in terms of realism. An adapted version of the Slater-Usoh-Steed (SUS) presence questionnaire [29,30] was used to collect the data from the participants. This validated 5-question Likert scale questionnaire is commonly used to evaluate the sense of presence of digital environments in many different contexts [30]. At the end of this questionnaire, a section for open-ended comments was provided to capture additional qualitative data from the users, allowing them to provide descriptions for their score selections.

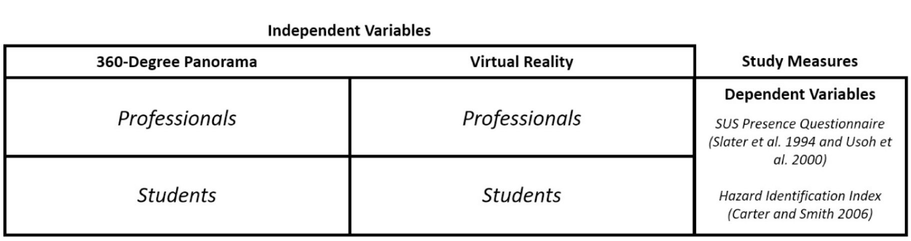

Fig. 6. Experimental design.

Table 2
Summary of questions for the sense of presence instrument.

SUS Presence Questionnaire (Adapted from [28,29])	**Rate:**	**Presence Indicator:**
	Q1. Your sense of being in the space – *(1) Not at all … (9) Very much*	Indicator (1)
	Q2. To what extent were there times during the experience when the construction scene was the reality for you? – *(1) At no time … (9) Almost all the time – Indicator (2)*	Indicator (2) Indicator (2)
	Q3. When you think back about your experience, do you think of the construction jobsite space more as images that you saw, or more as somewhere that you visited? – *(1) Images that I saw … (9) Somewhere that I visited – Indicator (2)*	Indicator (3)
	Q4. During the time of the experience, which was strongest on the whole, your sense of being on the jobsite, or of being elsewhere? – *(1) Being elsewhere … (9) Being on the jobsite – Indicator (2)*	Indicator (3)
	Q5. During the time of the experience, did you often think to yourself that you were actually on the jobsite? – *(1) Not very often … (9) Very much so – Indicator (3)*	

6.3. Study measures: sense of presence and hazard identification index

6.3.1. Sense of presence

The effectiveness of virtual environments for engaging and motivating users is associated with the concept of presence. In [31], presence is defined as "*the subjective experience of being in one place or environment, even when one is physically situated in another*". The physicality of presence is an essential component that measures realism in any virtual environment for users to feel engaged in the narrative, activities, or exploration performed in it. The measurement of presence is well established by using three self-assessed indicators: (1) the user's sense of "*being there*", (2) the extent of the virtual environment to represent reality, and (3) the thought of visiting a place rather than observing images of it [28]. For this study, the SUS presence questionnaire [28,29] was adapted to measure how study participants felt when they experienced the jobsite scenes. To measure the sense of presence, a 5-question Likert scale instrument was used that contained a 9-point measure for the participants to rank their experiences in the digital environments. Table 2 presents a summary of the questions asked in the instrument to measure realism in both platforms and their correspondence with Slater's presence indicators that contain the different aspects of presence.

6.3.2. Hazard identification index (HII)

The evaluation of hazard-recognition skills was performed using the HII developed by [27]. As participants completed the assessment module on each platform, the HII was computed and stored. The HII (Eq. (1)) provides a quantitative measurement of the hazard-identification ability of the participants by scoring their ability to find hazards in the provided context or scenario. The HII is calculated for each participant and was computed as the following ratio:

$$HII_j = \frac{H_i}{H_{total}} \tag{1}$$

where H_i is the number of identified hazards and H_{total} is the total number of hazards present in a given scenario. The ratio of these two quantities allows for the computation of the HII_j, which is the identification score for a scenario *j*. The number of hazards identified by the user (H_i) is directly affected by the user's hazard-recognition skills and the level of conceptual comprehension the participants gained during the training module. To compute the average hazard identification index ($\overline{HII}$, Eq. (2)) across all the scenes for the particular platform user, the mean is computed by adding each previously computed index (HII_j) and dividing it by the total number of scenes (N), as in:

$$\overline{HII} = \frac{\sum_{j=1}^{N} HII_j}{N} \tag{2}$$

6.4. Data analysis

Nonparametric Mann-Whitney U and Kruskal-Wallis, in conjunction with Dunn post hoc tests, were carried out to identify any statistically significant differences between the populations and each experimental condition. These tests were selected due to the observed non-normality of the collected data in a preliminary analysis of the data. For the presence measurements, the data were analyzed in a way similar to previous research methodologies [29–31] by aggregating all values from the presence questionnaire (bounded between the minimum of 5 and the maximum of 45 points) and standardizing them to a range from 0 to 1. The resulting compounded and standardized value represents the sense of presence for a given user. Using these standardized compounded scores for presence provided by the participants, multiple Mann-Whitney *U* tests were conducted across the different independent populations and conditions to observe statistical differences among the conditions. For the HII, multiple Mann-Whitney U tests for each independent population and condition were performed. Moreover, an in-depth analysis was performed for each Focus Four component of the HII using a Kruskal-Wallis analysis, and a data correlation analysis was performed using Spearman rho techniques. For this study, the statistical analysis employed the empirical standards for significance with alpha levels of 5% ($p = .05$), as used in current human-computer interaction literature [32]. The data preprocessing and statistical analysis was performed using the IPython command shell [33] with the Scipy [34] and Statsmodels [35] libraries.

7. Results and discussion

7.1. Participants

In this study, a total sample of 76 participants was collected from two populations: 38 professionals and 38 students. The participants were balanced in terms of experimental exposure by halving the populations—19 individuals from each population per condition (360-degree panorama and virtual reality). The resulting demographic information is displayed in Table 3. The participants were between 31 and 51 years old for the professional population (50%), while the students were between 21 and 30 years old (79%). Most participants were male for both populations (professional: 87%; students: 63%) and had obtained a bachelor's degree (63% and 100% for professionals and students, respectively). The professional population had between 5 and 20 years of experience (55%), while most of the students had less than five years of experience (82%). Overall, only 13% of the professionals did not hold an OSHA training certificate (10-hour, 30-hour, or 500-hour), but almost half of the students (45%) did not have an OSHA training certificate. Finally, the amount of experience with VR/AR was between none and some both for professionals (57%) and students (58%). However, the experience with 360-degree panorama was higher, as almost half of the professionals felt fair or competent using this technology (45%), while a smaller proportion of the students did (34%).

Table 3
Demographics of the participants.

Variable	Category	Frequency (percentage)	
		Population	
		Professionals	Students
Age	21 to 30 years	15 (39%)	30 (79%)
	31 to 41 years	13 (34%)	7 (18%)
	42 to 51 years	6 (16%)	1 (3%)
	51 to 62 years	4 (11%)	0 (0%)
Sex	Male	33 (87%)	24 (63%)
	Female	5 (13%)	14 (37%)
Highest academic rank obtained	High school diploma	5 (13%)	0 (0%)
	Bachelors	24 (63%)	0 (0%)
	Masters	3 (8%)	16 (42%)
	Ph.D.	6 (16%)	22 (58%)
Experience in construction	< 5 years	8 (21%)	31 (82%)
	5 to 10 years	11 (29%)	5 (13%)
	10 to 20 years	10 (26%)	2 (5%)
	20 to 30 years	3 (8%)	0 (0%)
	Over 30 years	6 (16%)	0 (0%)
OSHA certification	No Certification	5 (13%)	17 (45%)
	OSHA 10-Hour	2 (5%)	2 (5%)
	OSHA 30-Hour	31 (82%)	19 (50%)
	OSHA 500-Hour	2 (5%)	0 (0%)
Experience with VR/AR	None	7 (18%)	3 (8%)
	Some	15 (39%)	19 (50%)
	Fair	11 (29%)	14 (37%)
	Competent	5 (13%)	2 (5%)
Experience with 360-degree panoramas	None	8 (21%)	4 (11%)
	Some	13 (34%)	21 (55%)
	Fair	1 (3%)	11 (29%)
	Competent	16 (42%)	2 (5%)

7.2. Sense of presence

The participants' responses to the presence questionnaire were analyzed descriptively and statistically for each population group. Table 4 illustrates descriptive statistics for the responses to each question in terms of the average scores for the population. The average score of questions 1 through 4 was higher for the 360-degree panorama condition than that for the VR condition across populations. Based on the indicators of presence proposed by [27], the average score results suggest that participants perceived 360-degree panorama as having better representation of "*being there*" and as more representative of reality than VR. However, question 5 presented the inverse trend, with higher scores on the virtual reality condition than the 360-degree panorama condition. The disagreement between questions 4 and 5 suggests that the participants had different perceptions of visiting a place than observing a scene for the 360-degree panorama and virtual reality conditions.

Table 4
Descriptive statistics of the SUS presence questionnaire variables.

Variable	Population	Experimental condition			
		360-degree panorama		Virtual reality	
		Average	STD	Average	STD
Q1	Professionals	6.9	1.6	6.2	1.4
	Students	7.8	1.5	7.3	1.0
Q2	Professionals	5.2	2.8	5.1	2.4
	Students	7.3	2.0	6.3	2.2
Q3	Professionals	5.2	2.4	4.4	2.8
	Students	7.1	2.2	6.0	1.9
Q4	Professionals	5.9	2.2	5.6	2.3
	Students	7.4	1.9	6.8	2.0
Q5	Professionals	4.2	2.8	4.7	2.0
	Students	6.3	2.5	6.5	2.2

The results for each question were then compounded and unitarized into a presence score, analogously to previous research methodologies [29–31]. First, the overall participant data were explored as shown in Fig. 7-a. Across populations, the 360-degree panorama condition presented a higher presence score ($\mu = 0.70$; $\sigma = 0.21$) than the virtual reality presence score (0.65; 0.19). Further analysis was performed by computing the presence scores for each population, as shown in Fig. 7-b. For the professionals (0.61; 0.20) and students (0.79; 0.18), the same trend was observed, reporting higher scores for the 360-degree panorama condition. In contrast, professionals (0.57; 0.20) and students (0.72; 0.15) had lower presence scores in the virtual reality condition than in the 360-degree panorama condition.

For the computed presence scores, statistical analyses were performed to detect differences between and within the experimental conditions. The results of the multiple Mann-Whitney *U* tests across the independent conditions are shown in Table 5. For the between experimental exposures across all participants, no significant differences were detected ($p > .05$); thus, the null hypothesis (1) "*360-degree panorama and virtual reality conditions are equal in terms of presence*" cannot be rejected. After further analysis of the different populations for the between experimental conditions, it was found that the student population had significant differences between the 360-degree panorama and virtual reality conditions ($p < .05$, p value = .049). No differences between the conditions were found for the professional population ($p > .05$).

The results of the statistical analysis indicate that, for the students, the null hypothesis (1) can be rejected in favor of the alternate hypothesis, indicating differences in the sense of presence for the population. Notably, students consistently had a higher feeling of presence with the 360-degree panorama condition than with the VR condition. However, the professionals did not display this trend, and as a result, the null hypothesis (1) cannot be rejected, indicating that the sense of presence is not different between the conditions for this population. Finally, the differences within the experimental condition were computed for the different populations, yielding significant differences for professionals ($p < .05$, p value = .00239) and students ($p < .05$, p value = .01168). These results suggest that professionals and students felt differently in terms of presence for both conditions, which might be explained by the age and amount of experience of each population.

7.3. Hazard identification index

Initially, for each study population, the training and recognition times were analyzed descriptively. The results of this analysis are shown in Table 6. Overall, it was found that both professionals and students spent more time on average training in the virtual reality condition than in the 360-degree panorama condition. However, the opposite was found for both populations in the assessment, where more time was spent on average evaluating the scenes for the 360-degree panorama condition than for the virtual reality condition.

Open-ended comments support this behavior, as the assessment scenes were not annotated. One participant noted that, for the 360-degree panorama condition, *"[the scenes are] immersive, but sometimes unclear"*. These comments might be related to the nature of 360-degree panorama, as they depict the real complexity of jobsites, with multiple stimuli displayed at once that might distract the participants and extend their assessment time. However, another participant noted that, for the virtual reality condition, "*more details [on the scenes] would make it more realistic*". This comment indicates that, unlike the 360-degree panorama condition, the more simplified stimuli of the virtual reality assessment might have made it easier for the participants to focus on the hazards presented, reducing the time required to assess the scene.

Subsequently, an in-depth descriptive and statistical analysis was performed between the experimental conditions for the hazard-identification responses of each population group. Table 7 displays the

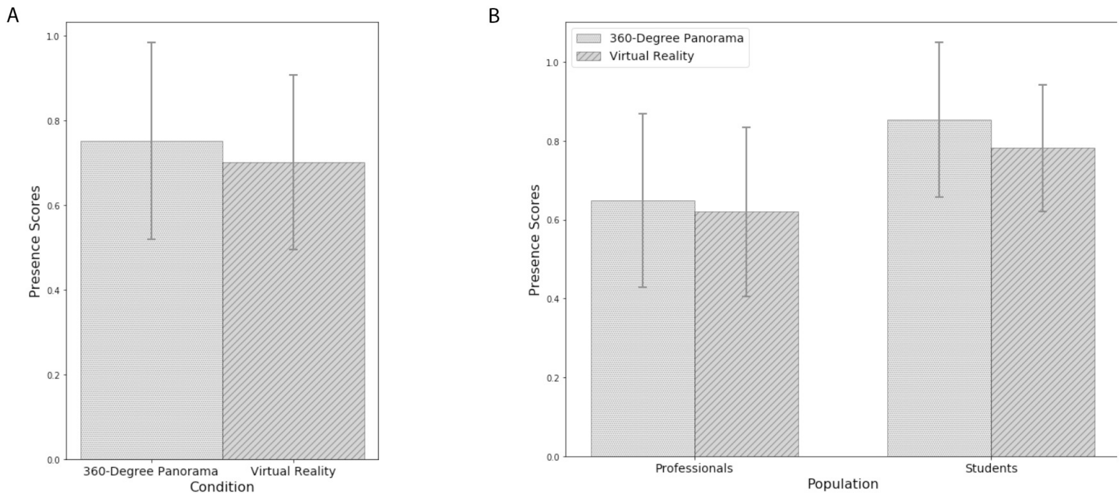

Fig. 7. SUS presence for 360-degree panorama and virtual reality.

Table 5
Statistical analysis results for the SUS presence questionnaire.

Experimental condition		Mann-Whitney U	
		Statistic	p value
Between	*Across All Participants* – 360-Degree Panorama vs Virtual Reality	610.0	0.123110
	Professionals – 360-Degree Panorama vs Virtual Reality	170.0	0.385050
	Students – 360-Degree Panorama vs Virtual Reality	123.5	0.04917*
Within	*360-Degree Panorama* – Professionals vs Students	83.5	0.00239*
	Virtual Reality – Professionals vs Students	102.5	0.01168*

* Indicates a significant difference between the compared conditions ($p < .05$).

Table 6
Completion time for the training and assessment sessions.

Experimental condition	Type of session	Time for completion (minutes)			
		Professionals		Students	
		Average	STD	Average	STD
360-degree panorama	Training	4:36	1:48	6:37	1:35
	Assessment	10:20	2:21	14:42	2:28
Virtual reality	Training	4:43	2:00	6:57	1:59
	Assessment	9:25	3:08	10:10	2:05

Table 7
Descriptive statistics for the HII variable.

Variable	Population	HII score (%)			
		360-degree panorama		Virtual reality	
		Average	STD	Average	STD
HII	Professionals	77.5	13.1	88.5	6.3
	Students	69.2	14.5	85.3	11.4
HII – Fall only	Professionals	40.4	7.2	44.3	5.9
	Students	35.2	9.5	41.5	10.2
HII – Struck-by only	Professionals	18.2	4.3	12.3	2.8
	Students	16.0	5.2	12.8	3.1
HII – Electrical only	Professionals	7.9	3.0	18.2	2.9
	Students	8.8	2.5	17.8	3.0
HII – Caught-by/ between only	Professionals	11.0	3.0	13.7	2.4
	Students	9.2	2.5	13.2	2.4

descriptive statistics for the overall HII of each condition and each population. Additionally, the HII score was broken down by the Focus Four hazards under the experimental conditions for each population group to obtain a more refined understanding of the effects on the individual hazard categories.

It was found that the average HII scores across all the Focus Four categories were consistently higher for the virtual reality condition for the professional (88.5) and student (85.3) populations than for the average HII scores for the 360-degree panorama condition for the professionals (77.5) and students (69.2). This tendency was also found for the fall hazards, electrical hazards, and the caught-by/between hazards for both populations. However, the opposite trend was found for struck-by hazards; the 360-degree panorama condition presented higher average HII scores for professionals (18.2) and students (16.0) than the virtual reality condition for professionals (12.3) and students (12.8). It is worth noting that, within the conditions, professionals had higher average HII scores than students overall, with a few exceptions (virtual reality – stuck-by; 360-degree panorama – electrical).

The statistical analysis results are shown in Table 8. First, a between-condition analysis was performed across all the study participants using a Mann-Whitney *U* test. The average HII scores across all the Focus Four hazards presented significant differences between the experimental conditions ($p < .05$; p value = 9.61E−06). This pattern was also found for each of the individual Focus Four hazard categories, with significant differences obtained between the experimental conditions. As a result, the null hypothesis (2) can be rejected in favor of the alternate: "*The means of the hazard identification index for users under 360-degree panorama and virtual reality environments conditions are not equal*".

Further analysis was performed to understand the effect of the experimental condition on each population using a Kruskal-Wallis test. As a result, significant differences were found for the average HII scores across all Focus Four hazards and for each individual hazard category. This outcome further supports the rejection of the null hypothesis (2). A post hoc analysis was performed to detect the between- and within-condition differences for the average HII scores. For the professionals, the between experimental condition comparison indicated that significant differences existed in the overall average HII score ($p < .05$; p value = .020136). Additionally, significant differences were found for struck ($p < .05$; p value = 2.79E−04), electrical ($p < .05$; p value = 2.52E−07) and caught-by/between ($p < .05$; p value = 4.80E−05) hazards, but no differences were found for fall ($p > .05$) hazards. The same trend was found between experimental conditions for students; the compounded average HII score and the individual HII for each category had significant differences. For the

Table 8
Statistical analysis results for the HII variable.

	Between – across		Between and within – professional and students					
	Mann-Whitney U		Kruskal-Wallis		Dunn Post Hoc			
	Statistic	p value	Statistic	p value	P-360 vs P-VR	S-360 vs S-VR	P-360 vs S-360	P-VR vs S-VR
HII	310.5	9.61E−06*	21.38	8.76E−05*	0.020136*	0.001516*	0.129773	0.482558
FALL	444.5	1.91E−03*	10.89	0.012329*	0.199208	0.042655*	0.223236	0.522971
STRUCK	295	2.35E−06*	22.79	4.46E−05*	2.79E−04*	0.024016*	0.240523	0.701189
ELECTRIC	24	7.49E−14*	54.81	7.53E−12*	2.52E−07*	9.90E−07*	0.849677	0.892766
CAUGHT	154	4.44E−10*	38.59	2.12E−08*	4.80E−05*	2.60E−05*	0.507216	0.566848

* Indicates a significant difference between the compared conditions ($p < .05$).

within-population analysis of the conditions, no differences were found within the populations for any experimental condition.

Finally, a correlation analysis was performed to assess the relationship between the presence score and the average HII score across all the participants and conditions using the Spearman rho analysis. An inversely proportional correlation was found between the presence scores and HII scores (coeff. = −0.19, $p < .05$, p value = .09717); that is, as presence score increased, the average HII score decreased. These findings are supported by the previously presented observations from the descriptive and statistical analysis in this section. The inverse relationship between the presence and HII scores can be observed in Fig. 8. Fig. 8-a presents an overview of all data across conditions, which display a decreasing trend, with low strength, as observed from the correlation coefficient in the Spearman rho analysis. Moreover, Fig. 8-b illustrates the inverse relationship between the average presence scores and the average HII scores across participants. It is important to note that the slope of the average HII score is more pronounced than that of the average presence score, which indicates that gains in realism have a detrimental effect on the hazard recognition by participants.

7.4. Discussion

The results obtained from the analysis indicate that participants experienced challenges in identifying hazards in 360-degree panorama environments. Although the 360-degree panorama condition was perceived as more realistic, as it is a true representation of real-world jobsites, the complexity in the displayed scenes had increased. The hazard-identification challenges experienced by the trainees may be explained by the multiple simultaneous stimuli present in real-world scenes and the widely varying scenarios in the Focus Four conditions. As a result, lower average HII scores can be observed in the 360-degree panorama condition across all Focus Four hazards. In contrast, the virtual reality condition presented higher average scores across all the categories and presented significant differences. The higher scores in the virtual reality condition indicate that participants found it easier to identify hazards as the VR condition presented a simpler, less complex version of a real jobsite. These findings are consistent with the correlation analysis, which displayed inversely proportional relations between the presence scores and the HII scores for the participants across conditions. Additionally, it was found that the participants presented uniform HII scores for each platform, i.e., they were independent of the population sampled, with low variability within the conditions.

The results observed in this research provide indications that VR training environments might be beneficial for less experienced trainees, such as students, as the reduced complexity of the scenarios facilitates the hazard-recognition tasks, although it does not fully represent the real-world conditions of the jobsite. For advanced trainees with more practical field experience, such as professionals, 360-degree panorama might present a more suitable experience that would proactively challenge their safety knowledge and motivate them to identify the hazards from more realistic scenarios. The overall results found in this research are consistent with a previous pilot study conducted by the research team [21], in which students who trained using both platforms perceived virtual reality as a cleaner but less realistic learning environment than the messier and more complex 360-degree panorama learning environment.

8. Research limitations

8.1. Training design, professional sampling, and population size

This research had limitations in three areas associated with the experimental methodology: (1) the training design for comparing the conditions, (2) the sampling method for the professional participants, and (3) the size of the population under each experimental condition.

First, the full replication of the hazards across conditions was infeasible, constraining the training design to the comparison of the two simulation approaches. Ideally, the conditions captured from the real-

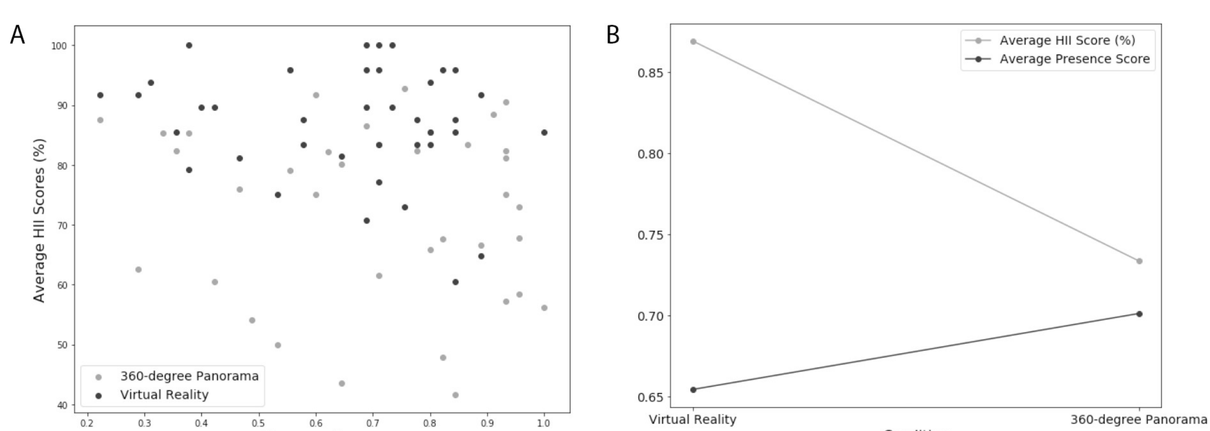

Fig. 8. Relationship between the presence score and the average HII score.

world scenarios in the 360-degree panorama condition would have been comprehensively duplicated in the VR environment for a perfect comparison. However, this would require geometrically modeling each observable element in the scenes and assembling them into a virtual world, which proved to be impossible for the researchers due to the long development times and high computational costs. For this research, the capturing process of the 360-degree panorama scenarios was performed by two photographers, which required visits to 8 jobsites for 2-hour sessions, totaling 16 h of capture time. Furthermore, two modelers spent approximately 35 h replicating the hazard scenarios, using Revit®, SketchUp®, and Infraworks®, from which some models, such as those for workers, machinery, and environmental elements (e.g., trees, stockpiles, electrical lines), were retrieved from online sources (e.g., SketchUp® Warehouse, BIMobject®). For both approaches, additional post-processing time was required to create the equirectangular projection from the data captured or generated with the corresponding software. The post-processing tasks added 3–5 h to the overall workflow. Because of these long workflow processes, the researchers based the generation of VR content on the hazard situations from the 360-degree panorama captures. The virtual representations created in this study aimed to produce environments in VR analogous to those from the 360-degree panorama, instead of providing a full replication, while maintaining a consistent detailed depiction of the hazard conditions across conditions (e.g., workers on the top cap of a stepladder, material stored on elevated surfaces, rotating equipment that can potentially strike workers). These consistency measures also included augmentations in the form of text and markers in both platforms.

Second, the data collection for the professional population sample was performed in situ, lowering the amount of experimental control the research team had over the participants. Although efforts were made to maintain laboratory-like conditions in the offices visited to collect the data, it was impossible for the research team to maintain entirely uniform conditions. Some of the strategies used by the researchers to maximize data collection uniformity were isolating the participants from external distractions, asking participants to turn off their phones, and making sure that participants did not communicate with each other.

Third, the sample size of the population under each discretized experimental condition was small. This is a result of the design considerations for the experimental procedure of the study – targeting two populations for each condition (19 professionals and 19 students). The analysis performed in this study includes both compounded and discretized measures of the participant groups to provide understanding and insights into the potential behavior of the variables presented in the study in relation to the two computer-based safety training techniques. The analysis presented illustrates how the variables considered in this study interact with the overall sampled populations.

8.2. Platform usability

A few usability issues persisted, as pointed out by the participants. Some participants reported being uncomfortable navigating the scenes, as they felt "*[the mouse] movement and zoom was inverse of what they should be*" and "*navigation was opposite of Google Earth controls*". Other participants reported that the scenes provided "*no sense of depth*", while others reported that "*multiple view locations for each scene could add clarity*". These comments correspond to one of the constraints set in the study, wherein only static vantage points were used in both conditions to enable the exploration of the data by visual rotation. As a photographic technology, 360-degree panorama technology is inherently static, which requires it to be replicated in a virtual reality environment to make the conditions comparable. Finally, a few participants reported future improvements that could be made to the platform, such as "*audio associated with the scenes would be beneficial*", "*click on the scene when identifying issues [instead of using a checklist interface]*", and "*create a better feeling of being in the jobsite by using a head-mounted-display*".

9. Conclusion and future research

In this study, the 360-degree panorama was proposed as an alternative to traditional modeled VR-based safety training, which suffers from long development times and high computational costs. Unlike the computer-generated context of VR environments, 360-degree panorama provided a true-to-reality representation of the environments. To compare these approaches, two safety training platforms for Focus Four construction hazards were developed based on similar scenarios: one employing 360-degree panorama and the other employing VR. This comparative user-centered study focused on assessing the effectiveness and differences of the two platforms in terms of realism and hazard identification. Seventy-six participants — 38 construction students and 38 construction professionals — participated in an experiment that trained and assessed hazard recognition. It was found that students perceived the 360-degree panorama condition as more realistic than the VR condition. However, no significant differences were observed for construction professionals between the conditions. In terms of hazard identification, significant differences were found under each condition, and the average HII score for all participants was higher for the VR conditions than for the 360-degree panorama conditions. These HII score results might have been caused by the virtual reality representation being perceived as a cleaner but less realistic alternative to the 360-degree panorama. Moreover, it was observed that the most affected Focus Four categories were struck-by, electrical, and caught-by/between hazards. Finally, it was observed that there was an inverse correlation between the presence scores and the average HII scores for the participants in the study.

Future research should further investigate the perception of realism using different levels of immersion with other devices to deliver the training content (e.g., tablets, CAVE systems, head-mounted-displays). Realism must also be compared across the spectrum of traditional, VR, and MR instructional methods (e.g., 2D photography, CAVE, AR) to comprehensively determine the most beneficial approaches for each hazard type and industrial setting, the cost-effectiveness of training, and the requirements for trainees' level of expertise. Furthermore, the sense of realism of construction professionals must be re-evaluated with a larger sample population and under laboratory conditions. Further study of construction professionals will provide a good understanding of how field experience has an impact on safety training using digital construction sites. Moreover, a detailed investigation must be conducted on the risk perception of trainees under 360-degree panorama and virtual reality conditions. Potentially, the differences in realism could impact how trainees perceive the severity of the hazards and their associated risks on real-world sites. Finally, the sample population of workers should also be explored, as this was not within the scope of this study. The study of construction workers would require an in-depth investigation of how this population perceives hazards in different digital sites and how their ethnicity and literacy levels might have affected the results.

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.

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