Using 360-Degree Virtual Reality Technology for Training Construction Workers about Safety Challenges of Drones

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Abstract: Integrating drones into already dangerous construction sites could expose workers to additional risks and make construction sites more dangerous than before. Several studies have identified various safety challenges of using drones on jobsites. However, limited studies have focused on educating construction workers about the safety challenges of the drone presence in their working environment. This study is the first effort to develop a 360-degree virtual reality (360VR) environment providing a semi-immersive training experience about drone applications in construction, potential safety challenges of working with or near drones, and proposed countermeasures for their safe integration. A repeated measures study design was used to assess the effectiveness of the 360VR training, followed by a system usability assessment. The results indicate that the developed 360VR training significantly improved users' safety knowledge about drones and that the 360VR platform proved to be a sufficiently usable delivery mechanism for this training. The main contribution of this study is to provide a better understanding of 360VR capabilities, as an emerging learning technology, to create virtual learning environments for construction education and training, and, in particular, enhancing trainees' knowledge about working safely with drones. **DOI: 10.1061/JCCEE5.CPENG-5140.**

Author keywords: Drones; 360-degree virtual reality (360VR); Construction safety; Training.

Introduction

In recent years, the use of drones has grown dramatically for a wide variety of applications in construction, such as project planning, progress monitoring, jobsite inspection, structural health monitoring, and maintenance assessment (Albeaino et al. 2019; Chen et al. 2014; Dupont et al. 2017). With the predicted increase in construction activities to address the nation's growing infrastructure needs, it is expected that there will be more use of drones in construction and subsequently increased interaction between them and human workers. The popularity of drones in construction results from the numerous benefits these flying robots provide, which include their ability to accomplish tasks faster, safer, and at a reduced cost (Albeaino et al. 2019; Mosly 2017). However, along with these benefits, the integration of such flying robots can also bring a wide range of new challenges such as technical barriers (Mosly 2017); privacy-, ethics-, and legal-related issues (DeCamara and McMillan 2019; Wang et al. 2016); and safety concerns (Jeelani and Gheisari 2021; Xu et al. 2020). Among these challenges, the rise of new safety concerns caused by drones is most concerning because it might lead to fatal and nonfatal injuries on already dangerous construction sites (Bademosi and Issa 2021; Gheisari and Esmaeili 2019).

Although there has been significant research about different drone applications in construction, only a handful of studies have explored the novel risks posed by drones in the construction industry (Albeaino et al. 2022c; Jeelani and Gheisari 2021, 2022; Khalid et al. 2021; Namian et al. 2021; Xu et al. 2020). The safety challenges of drones in construction can be categorized as physical risks (e.g., being struck by drones), attentional cost (distraction), and psychological impacts (emotional distress from drones monitoring worker activities) (Jeelani and Gheisari 2021). To remedy such challenges, safety training for the workforce is considered an essential intervention (Xu et al. 2020). Because drones are expected to have a greater influence on the construction industry (DroneDeploy 2022), employees who have to work around and interact with drones need to be adequately trained in drone operation (Jeelani and Gheisari 2021); for example, what drones do, how and where drones work, the risks drones bring in, and how to work safely with or around them. Moreover, recent research indicates that there are no Occupational Safety and Health Administration (OSHA) standards or guidelines specifically targeted at drones' utilization on construction sites (Cheng et al. 2022), which makes training workers even more critical. Drone-safety training is an unavoidable and urgently needed intervention to assist construction workers in coping with the safety challenges of drone integration in construction (Albeaino et al. 2022a, c).

Although there have been some efforts to develop drone-focused training programs in construction, much of it focuses on integrating drones within different construction management activities with limited to no focus on the safety issues that arise from such integration. For example, a previous study (Pereira et al. 2018) introduced the

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use of drones integrated with photogrammetry and building information modeling (BIM) in a construction management course to provide an opportunity for students to obtain hands-on experience of how drones could be integrated into construction tasks. Another similar effort included a drone-based activity within a construction surveying curriculum (Williamson and Gage 2019). Studies have also focused on using virtual environments for developing drone-based training, such as a flight training simulator (Albeaino and Gheisari 2021) and a two-dimensional (2D)–based flight behavior visualization platform for training drone pilots to perform building inspection tasks (Eiris et al. 2021a).

Although beneficial, these studies have focused on training drone operators to minimize errors but not on the workers who are not directly involved with drone operations and would be exposed to the risks posed by drones by sharing their work environment with them. A thorough search of the relevant literature showed no current training that focuses explicitly on educating construction workers about the safety challenges of drones on construction jobsites. However, to take appropriate countermeasures against different hazards, workers must be trained to assess the risks correctly (Carter and Smith 2006). As such, it is critical that workers learn the consequences of these hazards, which is barely possible to be demonstrated to workers in real life without placing them in danger (Jeelani et al. 2020). Although training delivery modalities such as presentations, animations, and videos can be used to exhibit such effects, the impact is diminished because the trainee is watching it from a distance and is not part of the experience (Jeelani 2019). The 360-degree virtual reality (360VR) environment provides an excellent opportunity to present the trainee with a real-life situation allowing them to visualize potential accidents caused by drones to better understand the risks and use their knowledge and abilities to control those risks.

Therefore, this study aims to bridge the gap by developing a 360-degree virtual training environment that provides a semi-immersive learning experience about drone applications in construction, potential safety challenges of their integration, and proposed countermeasures for their safe integration. VR has proved useful for various types of drone-focused training. For example, Sakib et al. (2021) investigated the reliability of using the drone operator's physiological indexes and self-assessments to predict performance, mental workload (MWL), and stress in immersive virtual reality training and outdoor deployment. More recently, a game was designed to provide a simulated experience of piloting a drone for construction site inspection and educating users on the effectiveness of using drones for this task (Lawani et al. 2022).

The current study builds on the outcomes of a pilot study that evaluated the usability and feasibility of using 360VR for training about usage on construction jobsites (Cheng et al. 2022). In that pilot study (Cheng et al. 2022), an early-version prototype of a 360VR system with limited training content about drone usage in construction was created. The main goal of that study was to focus on the usability aspect of the 360VR system and its feasibility of being used as an effective educational tool. The usability and feasibility assessment outcomes demonstrated the great potential of such a 360VR approach for training purposes. Building on the lessons learned from the pilot study (Cheng et al. 2022), this study significantly increased the training scope, systematically adopted engaging pedagogical strategies for different training content requirements, and enhanced the quality of 360VR content. This study also provides a clear framework for developing and adopting such device-agnostic 360VR training content for construction or other similar high-risk industries. Moreover, a repeated measures study design was used to assess construction workers' and professionals' in-depth perceptions of the 360VR system and its effectiveness and challenges in providing training about working safely with drones.

Research Background

Drones in Construction

Drones are aerial robots that can be remotely controlled or fly autonomously using software-controlled flight paths and do not have a human pilot onboard (Gheisari et al. 2014). These robots were first used for military purposes but have since been widely adopted by various industries, including construction. According to a 2018 analysis on commercial drone trends by DroneDeploy, the use of drones in construction increased by more than 200% in a year (DroneDeploy 2018), making the construction industry the fastest-growing commercial adopter of drones. A more recent report also pointed out that 12% of all drone applications are associated with construction operations (Drone Industry Insight 2022). The global market for construction drones is predicted to grow from $4.80 billion in 2019 to $11.96 billion by 2027 (Chinchane et al. 2020), demonstrating the huge potential and rapid integration of drones for construction applications. Drones can accomplish different construction tasks more effectively, swiftly, safely, and at a reduced cost, especially in difficult-to-reach places (Albeaino and Gheisari 2021). As such, drones have been used for a wide range of applications in construction, including progress monitoring (Chen et al. 2018; Unger et al. 2014), site planning (Hammad et al. 2021; Jiang et al. 2020), site surveying and mapping (Martinez et al. 2021; Neitzel and Klonowski 2011), building inspection (Liu et al. 2021; Mader et al. 2016; Mutis and Romero 2019), building maintenance (Chen et al. 2021; Hallermann et al. 2015), and safety inspection (Gheisari and Esmaeili 2019; Martinez et al. 2020; Mutis and Romero 2019).

Although drones present several advantages, their widespread use in construction also comes with some challenges: for example, liability and legal concerns, technical-integration concerns (e.g., unfamiliarity or lack of knowledge about drones, reticence to adopt new technologies), weather-related constraints, and security or safety concerns (Albeaino et al. 2022b). Among these, the safety challenges posed by drones are perhaps the most critical, because construction is already struggling with poor safety performance, resulting in hundreds of thousands of accidents every year. As a result, studies have begun to explore the safety impacts of integrating drones into construction jobsites (Jeelani and Gheisari 2021; Namian et al. 2021) to identify ways to overcome these challenges. The following section provides an overview of the safety challenges of drone integration in construction.

Safety Challenges of Drone Integration in Construction

Safety has been one of the major issues with which the construction industry has been dealing for decades (Jin et al. 2019). Construction workers work in hazardous settings characterized by heavy manual labor and temporary, dynamic, and rapidly changing work environments requiring them to work at heights and/or with and around dangerous machinery (Mohammadi et al. 2018). In 2019, the US construction industry reported 1,061 fatal and more than 200,000 nonfatal occupational injuries, accounting for nearly 20% of all fatal workplace injuries in the United States (US BLS 2019). The rapid integration of drones into this already hazardous work environment will likely introduce novel safety challenges that might make the construction industry more dangerous than before. These risks might arise from unintended physical contact between drones and human workers (e.g., struck by) or due to the cognitive interaction between workers and drones that may affect workers' attentional and psychological states. Drones, being physical entities on a construction site, pose a risk of collision with workers or other construction entities (Jeelani and Gheisari 2021; Khalid et al. 2021;

McCabe et al. 2017; Namian et al. 2021; Xu et al. 2020; Yahya et al. 2021). Drones can also distract workers, affecting their ability to work safely and putting them or their coworkers at risk (Irizarry et al. 2012; Jeelani and Gheisari 2021; Khalid et al. 2021; Xu et al. 2020; Yahya et al. 2021). Finally, working with or around drones equipped with data recording sensors (e.g., cameras, microphones) can adversely impact workers' psychological or emotional states and trigger specific unfavorable physiological responses (Jeelani and Gheisari 2021; Khalid et al. 2021; Xu et al. 2020). Workers at heights are particularly exposed to the health and safety risks posed by drones because (1) drones fly closer to their work environment and, as such, have a stronger influence; and (2) according to a recent US Bureau of Labor Statistics report, workers on heights already have the highest fatality rates (US BLS 2022) and drones can aggravate their already risky environment and increase the likelihood of falls (Jeelani and Gheisari 2021; Mendes et al. 2022).

Although there has been a significant amount of research on drone applications in construction, most of the current research on drone integration in construction has primarily focused on the benefits that drones bring to the construction industry (Gheisari and Esmaeili 2019). Only a few studies have focused on the safety implications of drone use in construction to some degree. For example, in an exploratory study (Xu et al. 2020), Heinrich's two-factor safety causation model was used to identify some potential adverse safety risks and outcomes associated with drone-assisted construction management, which were classified as unsafe environments (e.g., system failure and operation error) and unsafe behaviors (e.g., distraction and stress). The study proposed some countermeasures based on the hierarchy of controls (HoC) for safety management. Similarly, extensive literature reviews and expert surveys were conducted to identify potential risks that drones pose for construction workers, including contact with properties, contact with humans, and distraction (McCabe et al. 2017; Namian et al. 2021). Jeelani and Gheisari (2021) used inferential analysis and VR visualization techniques to provide a comprehensive overview of the potential health and safety challenges of drones on construction jobsites. The study categorized those potential challenges as follows:

- Physical risks: When operating drones on construction sites, there is a risk of unintentional physical interaction, contact, or collision between drones and other entities or humans, potentially leading to accidents or injuries. This category includes different types of risks, such as being struck by flying objects, being struck by falling objects, being caught in accidents, indirect or secondary accidents, and dust and particulate emissions.
- Attentional costs: As relatively newly introduced entities on construction sites, the sight or sound of drones can distract workers and cause an interruption to their tasks. This category includes different types of attentional costs, such as visual distractions, auditory distractions, and cognitive distractions.
- Psychological impacts: Sharing the work environment with flying robots capable of recording worker activities might have some negative psychological impacts on workers. These psychological impacts may result from workers' perception of being watched and constant visual and audio distraction by drones on sites, resulting in stress and sensory overload.

Despite these novel safety challenges introduced by drones in the construction industry, there are no specific regulations on the safety of drone usage in construction. Although the US Federal Aviation Administration (FAA) has published some general rules to regulate the operation of drones over people (FAA 2021), most of the rules focus on the qualification of drone operators and the specific conditions or areas where drones cannot be operated (e.g., drones may not fly over humans unless the FAA grants a waiver, drones may not fly at night or in civil twilight unless equipped with anticollision lights). These regulations may reduce the safety risk of operating drones on construction sites, such as reducing the operation error by regulating pilots' qualification (DeCamara and McMillan 2019; FAA 2021). However, these regulations only address the safety issues from drone operations' perspectives and do not account for construction workers' unsafe behavior while working with or near drones, the distraction caused by drones, and psychological impacts on construction workers who work in the vicinity of drones. Similarly, there is also a lack of specific regulatory oversight from OSHA that focuses on the safety implications of drones on construction sites. Currently, the only technical manual from OSHA that somewhat applies to drone safety is *Industrial Robot Systems and Industrial Robot System Safety* (OSHA 2021). However, this manual is for robots in general and does not specifically address drone operation on construction sites or account for specific safety challenges that such flying robots pose for workers on a jobsite. In the absence of regulations to protect workers from risks posed by drones and to help them work safely with drones, construction workers may be exposed to the aforementioned safety challenges.

To overcome these safety challenges, it is critical to prepare workers for the inevitable ubiquity of drones on construction jobsites. Although the emerging literature has explored the potential safety risks that drones could introduce to construction jobsites, there is a research gap in creating effective safety training content and delivery strategies for construction workers and professionals who work in a drone-populated work environment (Cheng et al. 2022). As of June 2022, aside from the pilot study created by the research team, no training content is specifically designed for educating construction workers about the safety challenges when working with drones on their jobsites (Cheng et al. 2022). Therefore, this paper aims to bridge this gap and create effective training material to educate construction workers about drone use in construction, different safety challenges that drones could pose on jobsites, and effective ways to safely work with and around drones on construction jobsites.

Construction Safety Training in Virtual Reality

An immersive virtual environment presents a great opportunity for safety training because it provides a risk-free environment that allows trainees to experience risky situations and learn about hazards and countermeasures without adverse consequences (Jeelani et al. 2017). As a result, immersive technology such as VR is getting popular in construction, especially for safety training purposes (Elghaish et al. 2021; Kandi et al. 2020; Le et al. 2015; Wang et al. 2018). Previous study found that construction safety training is the second largest application area of VR in construction engineering education and training (CEET), accounting for 18% of all related literature (Wang et al. 2018). For example, researchers developed a virtual environment that contains stereo-panoramic scenes captured from real construction sites and a virtual construction site developed to improve the hazard recognition and management performance of trainees (Jeelani et al. 2020). The result of the study demonstrated the effectiveness of VR-based training in improving trainees' safety performance.

In another study (Le et al. 2015), an online social VR system was developed to educate students about the causes of accidents on construction sites and safety theories through hazard inspection and allowed students to interact and play the safety training game in a game-based virtual environment. The result concluded that the game-based collaborative VR platform could improve the effectiveness of safety training.

Other research has also investigated the effectiveness of VR technologies being used in construction safety training by comparing them with traditional methods. For example, a study compared the learning effectiveness of safety training between participants receiving traditional classroom training and those training using a three-dimensional (3D) immersive VR power wall (Sacks et al. 2013). The results found that there is a significant advantage for VR training while the trainees are doing stone cladding work and for cast-in-situ concrete work safety training, but there is no significant difference while receiving general safety training. The study also indicated that VR training was more effective in terms of maintaining trainees' attention and concentration.

Another study also conducted a construction safety education study between two groups of trainees: one using the traditional learning method with real construction field trips and the other using a mobile learning method with virtual field trips on an interactive VR platform (Pham et al. 2018). The results indicated a better learning outcome by using the VR platform as the construction safety education tool.

Although increasing evidence has shown the advantage of adopting VR technology as a tool for construction safety training, there are still several challenges. One significant challenge is the need for costly hardware and high-end computational devices for VR development and rendering. Specifically, traditional VR technology requires trainees or trainers to have VR headsets or VR power walls to access the training. Another issue with traditional VR is its limitation of accessibility. Because traditional VR may require specific hardware and specific software or platform access, it is often challenging to distribute the training widely to workers, which is one of the most critical requirements that training must fulfill. These challenges must be addressed to use VR technology as an effective and accessible tool to provide construction safety training.

With the advances in VR technology, 360VR has recently seen rising popularity (Snelson and Hsu 2020; Ye et al. 2020). It is an audiovisual simulation of a real or virtual environment that surrounds the user, allowing them to look around in all directions. The 360VR can provide a device-agnostic VR experience that can be accessed on a wide range of hardware devices (e.g., tablets, smartphones, computers, head-mounted displays) (Wang et al. 2018; Wen and Gheisari 2021), broadening the delivery alternatives. The 360VR content can also be accessed through several popular social media and video sharing platforms (e.g., YouTube, Facebook), making such training content more accessible to the public (Wen and Gheisari 2021).

Research Method

In this study, a 360VR training environment was created to provide trainees with a semi-immersive experience of working with drones on a virtual construction jobsite while educating them about working safely with drones. In this virtual learning experience, a virtual human (i.e., a virtual drone-safety trainer) led trainees to explore the virtual construction jobsite while providing an on-the-site learning experience about drone applications in construction, potential safety challenges of their integration, and proposed countermeasures for their safe integration. The goal of this study is to educate construction workers about the safety challenges of drone presence in their working environment using the 360VR. To achieve this goal, first the training content was created based on a detailed review of safety literature as well as drone- and safety-related regulations (e.g., OSHA, FAA). Then a 360VR virtual construction site with different virtual entities such as buildings, equipment, workers, drones, and a virtual drone-safety trainer was created based on the training content requirements identified in Phase 1. Finally, a user-centered assessment phase was conducted to assess the effectiveness of the 360VR training in enhancing trainees' knowledge about working safely with drones. This phase also assessed other aspects of the training experience, including system usability, sense of presence, and virtual reality sickness. The following subsections further discuss these three phases.

Training Content Development

The main goal of this phase was to generate the necessary content to achieve the following learning objectives of the training:

1. Define drones and discuss their applications in the construction industry,
2. Discuss potential safety challenges of drone integration on construction jobsites, and
3. Discuss potential countermeasures for the safe integration of drones on construction jobsites.

A virtual human (i.e., a virtual drone-safety trainer) would lead the trainees to explore the virtual construction jobsite while providing on-the-site training about these learning objectives.

To achieve these learning objectives, a comprehensive review of safety literature was conducted that included publications on drone applications in construction, human–robot interaction, safety challenges of working at heights, working with machines, and worker distraction. Moreover, the OSHA technical manual regarding industrial robot system safety and regulations regarding fall protection and working with equipment (e.g., OSHA 2020a, b, 2021), as well as FAA regulations regarding the use of drones [e.g., 14 C.F.R. 107 (2016)], were reviewed. This review identified the requirements for the necessary virtual scenes and scenarios required for the training and generated the script for the virtual drone-safety trainer to lead on-site training.

To cover the first learning objective, an introduction to drones and their types was provided and the drone applications in construction were discussed under the four general categories of inspection, safety, material delivery, and assisting with building (Jeelani and Gheisari 2021, 2022) (Table 1).

To cover the second learning objective, an introduction to the safety challenges of drone integration was provided using three categories: physical risks, attentional costs, and psychological impacts (Jeelani and Gheisari 2021, 2022). Each of those risk types was further discussed using detailed scenarios where different related risk outcomes were demonstrated (Table 2). The majority of these scenarios were defined for construction activities at height (e.g., ladders, scaffolds, roofs), mainly because (1) workers at heights are most prone to being affected by drones, which also fly at height; and (2) falling from height is the leading cause of serious injury and death in the construction industry (US BLS 2022).

Finally, to cover the last learning objective, a series of countermeasures were suggested to address the potential hazards discussed in the previous learning objectives. OSHA and FAA regulations were reviewed to provide suggestions regarding the countermeasures to address the potential hazards (FAA 2021; OSHA 1995, 2015, 2020a, b, 2021). Currently, OSHA does not have a specific regulation or technical manual regarding the safe integration or use of drones on construction jobsites, and the FAA regulations (FAA 2021) are not construction specific and only provide general rules on operating drones near or over people. As a result, the HoC (NIOSH 2015) was selected as a framework to propose a series of countermeasures to address the potential hazards of workers working with or near drones on construction jobsites. HoC is a five-level control system recommended by OSHA (Chapter IV of the technical manual *Industrial Robot Systems and Industrial Robot System*

Table 1. Training elements and narrative summary for Learning Objective 1

Learning objective	Training sections	Training elements	Training narrative summary
Define drones and discuss their applications in the construction industry	Introduction	—	The virtual drone-safety trainer introduces themself and the purpose of the training.
	Drone definition	Drone application in construction	The virtual drone-safety trainer introduces common drone application areas in the construction industry.
		Drone size	The virtual drone-safety trainer introduces different sizes of drones and the most commonly used drone size.
		Drone types	The virtual drone-safety trainer introduces different types of drones based on their wings and how they are used in the construction industry.
		Flight control types	The virtual drone-safety trainer introduces different levels of autonomous control of drones.
		Drone sensors	The virtual drone-safety trainer introduces commonly used sensors that can be mounted on drones.
	Drone applications	Inspection	The virtual drone-safety trainer explains how drones can do construction inspections.
		Safety	The virtual drone-safety trainer explains how drones can be utilized for construction safety.
		Delivery	The virtual drone-safety trainer explains how drones can perform delivery tasks on site.
		Building	The virtual drone-safety trainer explains how drones can assist with building tasks.

Table 2. Training elements and narrative summary for Learning Objective 2 according to Jeelani and Gheisari (2021)

Learning objective	Training elements		Training narrative summary
Discuss potential safety challenges of drone integration on construction jobsites	Physical risks	Struck by flying objects	The virtual drone-safety trainer discusses or shows the drone colliding with a worker.
		Struck by falling objects	The virtual drone-safety trainer discusses or shows the drone itself or its parts falling on workers due to technical malfunction.
		Caught in accidents	The virtual drone-safety trainer discusses or shows workers' hands getting caught in the rotors or other moving parts of drones.
		Indirect or secondary accidents	The virtual drone-safety trainer discusses or shows the drone colliding with other powerlines or physical entities, which in turn strike workers.
		Dust and particulate emissions	The virtual drone-safety trainer discusses or shows how fast-moving rotors of drones can cause significant dust emissions on construction sites.
	Attentional costs	Visual distraction	The virtual drone-safety trainer explains how the drone sight could distract workers from their current tasks.
		Auditory distraction	The virtual drone-safety trainer explains how the noise generated by the drone could distract workers, which can have secondary safety implications.
		Cognitive distraction	The virtual drone-safety trainer explains how knowledge about potential drones around workers could cause a cognitive distraction.
	Psychological impacts	Acute stress	The virtual drone-safety trainer explains how being watched by drones might result in workers' anxiety and stress.
		Higher cognitive demand	The virtual drone-safety trainer explains how working in a drone-dominated site might increase the work pace or time pressure, resulting in an increased workload on human workers.
		Sensory overload	The virtual drone-safety trainer explains how constant distraction and noise generated by drones might cause sensory saturation, resulting in fatigue and a negative emotional state.

Safety) to control occupational hazards. The HoC was found to be useful in addressing the potential risks induced by drones on construction jobsites (Xu et al. 2020). The five levels of HoC were discussed in the context of the safe integration of drones on construction jobsites (Table 3).

Development of 360VR

Once the content was finalized, the next phase focused on the technical development of 360VR training. The 360VR training environment was created through the integration of (1) the virtual construction site where the training happened; and (2) the virtual drone-safety trainer who led the training (Fig. 1).

Creation of Virtual Construction Site

The first phase of 360VR development was focused on creating a virtual construction site that includes the required objects and scenes in the training narrative. The virtual construction site was created using 3D models of different construction entities (e.g., buildings, equipment, temporary structures, virtual workers, drones) and arranging and animating them based on the learning objectives identified in the previous phase (Fig. 2).

First, the 3D models of required objects to develop the construction site were imported into the Unity game engine. These objects can be classified into three categories: static objects, dynamic equipment, and virtual workers. Static game objects such as buildings, ladders, and scaffolds were placed in the environment to create an

Table 3. Training elements and narrative summary for Learning Objective 3

Learning objective	Training elements		Training narrative summary
Discuss potential countermeasures for the safe integration of drones on construction jobsites	Hierarchy of controls	Elimination	The virtual drone-safety trainer discusses how to physically remove people from areas where drones are working (if possible) as the best countermeasure.
		Substitution	The virtual drone-safety trainer explains the meaning of substitution in the drone-safety context as the next best strategy.
		Engineering controls	The virtual drone-safety trainer discusses how to put physical barriers between workers and drones to avoid drone-related hazards.
		Administrative controls	The virtual trainer discusses how to avoid drone-related hazards by following basic safety rules when working with drones.
		Personal protective equipment (PPE)	The virtual drone-safety trainer discusses the importance of PPE and how PPE can mitigate the hazard of drones.
	Closure of the training		The virtual drone-safety trainer concludes the training.

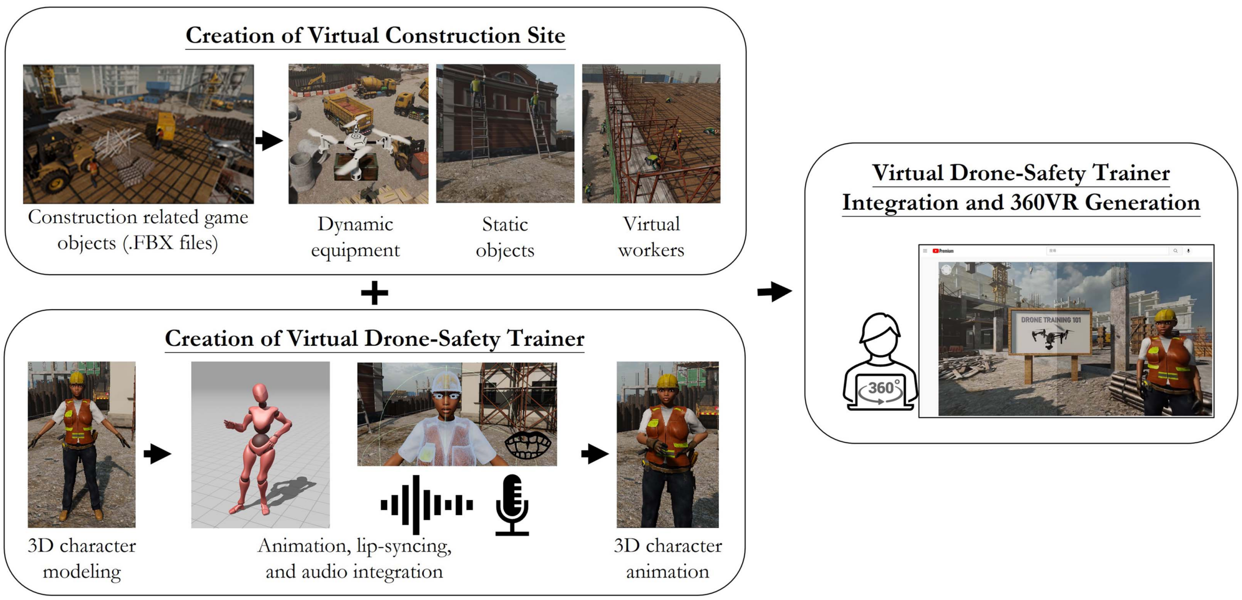

Fig. 1. Development of 360VR.

immersive feeling of being on an actual construction site. The dynamic game objects, such as moving cranes or flying drones, were also programmed with a predefined path in the virtual environment to increase the realism of the dynamic virtual construction site with drones working on site. Finally, virtual workers with various predefined movement paths and working animations (e.g., hammering, inspecting, sweeping) were added to represent workers working on the virtual construction site.

Then, considering the requirements of the three learning objectives as well as the required objects and scenes identified in the previous phase, further development was conducted to cover each of those learning objectives. For example, for Learning Objective 1 (drones and their applications in construction), different types of drones were built and programmed to show different drone applications (e.g., safety surveillance, quality inspections, painting walls, material delivery). For Learning Objective 2 (potential safety challenges of drone integration), different accident animations were created to demonstrate the potential accidents involving drones on the jobsite (e.g., drones falling on workers, drones striking workers or equipment on site, workers on heights getting distracted by drones and falling afterward, workers' fingers getting caught in the drone propellors while getting close to them during delivery). And finally, for Learning Objective 3 (potential countermeasures for the safe integration of drones), various visual contents were created to illustrate how workers can manage and control different hazards posed by drones on their jobsites.

Creation of Virtual Drone-Safety Trainer

In this phase, a virtual human (i.e., a virtual drone-safety trainer) was created who led the trainees to explore the virtual construction jobsite while providing them with on-site training about drone applications in construction, potential safety challenges of their integration, and proposed countermeasures for their safe integration. A 3D humanoid character was used to create the virtual drone-safety trainer because it provided the advantages of full control and easy iterations (compared with a human trainer) while providing rich nonverbal behaviors (compared with an audio or text-based narration). Previous literature shows that such verbal and nonverbal behaviors (e.g., facial expression, gestures, body orientation, movement, and eye contact) can form a virtual avatar's personality and lead it to be more likable and thus more enjoyable to learn with (Park 2016; Salem and Earle 2000). The creation of the virtual drone-safety trainer involved three steps: (1) 3D character modeling of the drone-safety trainer, (2) integration of audio and lip-syncing, and (3) integrating animation into the 3D character (Fig. 3).

The 3D character model was used in the Unity game engine to create the human physical body of the drone-safety trainer. A realistic-looking African American female 3D character was selected

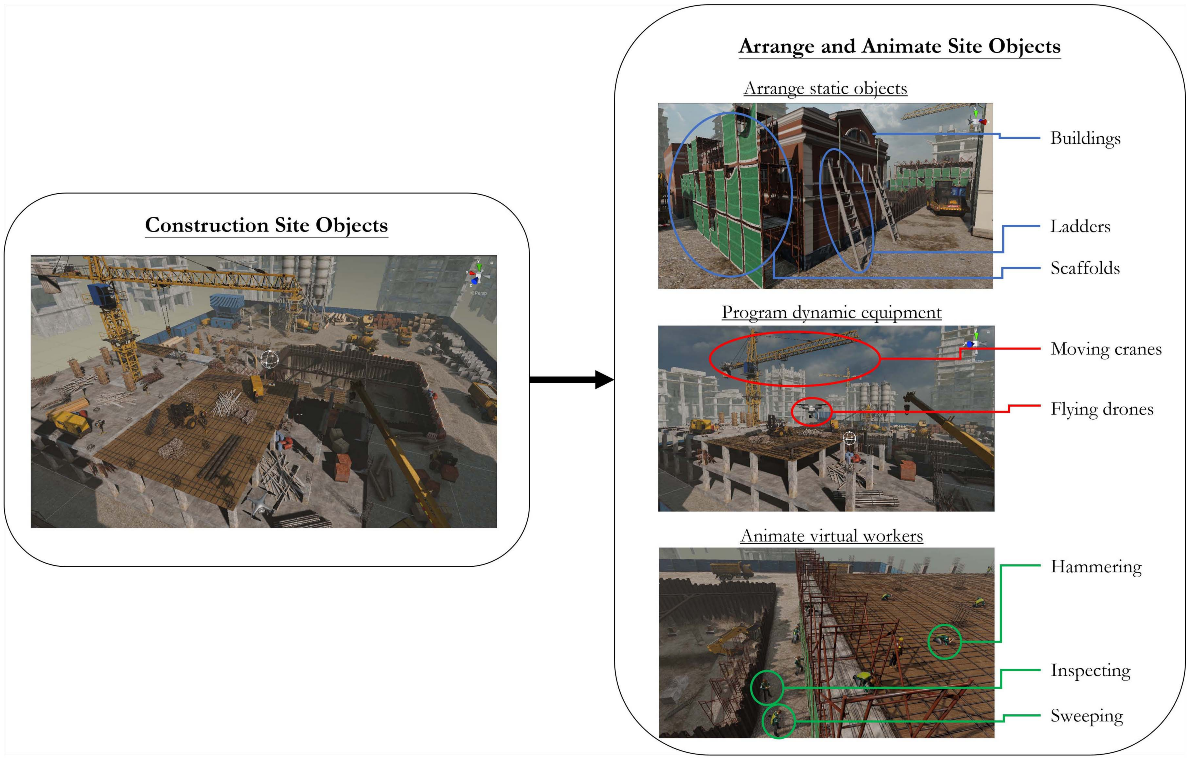

Fig. 2. Creation of virtual construction site.

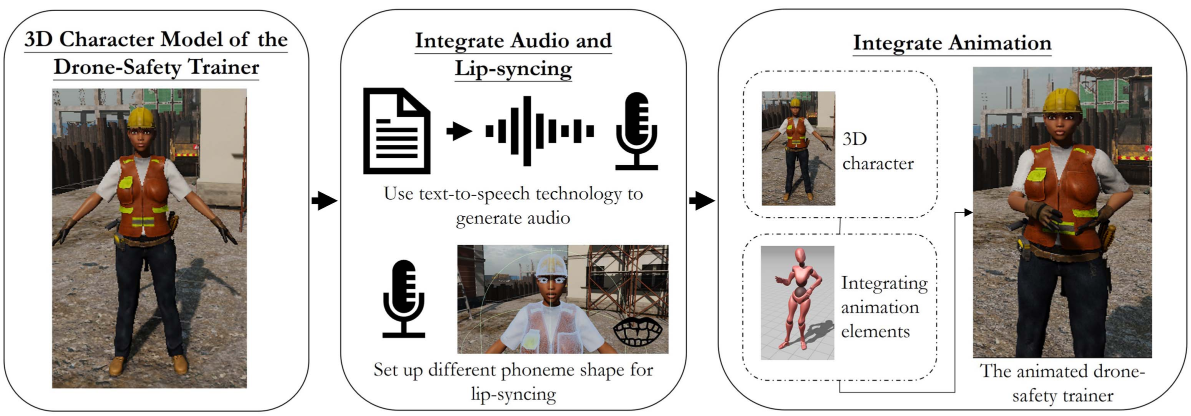

Fig. 3. Creation of virtual drone-safety trainer.

as the drone-safety trainer. Considering virtual agents' gender, ethnicity, and realism are important factors during pedagogical agent design, and previous research (Baylor and Kim 2004) shows that students would have a greater transfer of learning when the agents have more realistic images and when agents in the expert role are represented nontraditionally. Then, based on the training narratives developed in the previous phase, the narrative audio was generated using the Google Cloud text-to-speech API. Then the required lip-syncing was done to create a more natural and realistic drone-safety trainer. Lipsync Pro was used to create the facial animation and a core mouth shape corresponding to the words from the audio source while controlling facial expressions and eye contact of the virtual drone-safety trainer (Huang et al. 2019; Rogo Digital 2020). Finally, the proper animation elements such as gestures, body orientation, and movement were generated using a built-in Animator asset in Unity (Unity Learn 2020) and integrated with the 3D character model. Previous research shows that enriching verbal and nonverbal behaviors can help increase users' sensation of being with the virtual avatar, encourage social exchanges, and further improve users' satisfaction (Bulu 2012; Wen and Gheisari 2021).

Virtual Drone-Safety Trainer Integration and 360VR Generation

In the last step of 360VR development, the virtual drone-safety trainer was integrated into the virtual construction site. This required properly placing the virtual drone-safety trainer at designated positions in the virtual environment, considering the training content requirements at each specific time. Based on the training content requirements, the virtual drone-safety trainer was integrated into the virtual site in three general ways:

1. Conceptual learning: the virtual drone-safety trainer used a display board to introduce the topics or explain nonsituated conceptual contents (e.g., drone definition, safety challenge types, hierarchy of controls definition) [Fig. 4(a)]. The virtual environment should offer a setting that is familiar to users in order to provide an immersive learning experience for trainees (Usoh et al. 2000). As a result, a display board was employed to provide an experience more akin to a traditional classroom delivery setting, with which trainees are already familiar. This strategy was used in a few instances where it was required to discuss nonsituated conceptual content.
2. Situated learning: the virtual drone-safety trainer used the 360-degree scene on the site to explain related training contents (e.g., physical risks, attentional cost) [Fig. 4(b)]. Situated learning focuses on the "relationship between learning and the social situation in which it occurs" (Lave and Wenger 1991). This strategy allows trainees to acquire knowledge in realistic settings and learn how to apply the knowledge within similar contexts (Lave and Wenger 1991; Schell and Black 1997). Previous research about applying situated learning in VR shows that such a strategy could also enhance trainees' motivation (Mei and Sheng 2011). This strategy was frequently used throughout the training session; for example, putting trainees in different situated learning scenes to show the potential safety risks while working with or near drones on the site without exposing them to those real risks.
3. Bird's-eye view: a bird's-eye view of the virtual site was provided, showing different types of drones and their flight paths as well as various construction-related tasks on the site, while the virtual drone-safety trainer's voice-over was used to better explain those specific views and the necessary training content. [Fig. 4(c)]. Previous literature has found that the use of bird's-eye views can arouse students' motivation and help construction students better understand construction site information (Mutis and Antonenko 2022). This strategy was used in a few instances where it was required to demonstrate the application of different types of drones on the jobsite.

Finally, the virtual training experience was exported as a 360-degree omnidirectional video format using Video Capture Pro, and then the generated 4K 360-degree video was published on YouTube to make it easily available to trainees using a web link. Such 360-degree omnidirectional videos are compatible with various tools (e.g., laptops and desktop computers, tablets, smartphones) and social media platforms (e.g., YouTube, Facebook) (Wen and Gheisari 2021). Once users access the 360-degree omnidirectional video, there are several ways to interact with the online video with different immersive levels. For example, users can use a mouse and keyboard to pan and explore the virtual environment on a laptop and desktop computer. Another option is to watch the video on mobile devices, such as smartphones or tablets, and use a finger to pan or directly tilt the device in the direction they want to look. Finally, the video can also be watched on a smartphone integrated with a mobile VR headset (e.g., Google Cardboard) to provide a more immersive experience.

User-Centered Assessment

Assessment Procedure

This phase aimed to assess the usability, user experience, and effectiveness of the proposed 360VR training experience to help the audience understand the safety challenges of working with or near drones on construction jobsites. A repeated measured experiment design was adopted in this study to achieve this goal. The repeated measures design assesses different independent variables from the same group of participants before and after an intervention and is commonly used for retrieving intuitive and initial evidence for the influence of an intervention (Robson et al. 2001; Wen and Gheisari 2021). The proposed assessment protocol was evaluated and approved by the University of Florida Institutional Review Board (IRB # 202002549). In this assessment, the participants first responded to a demographic survey followed by pretraining knowledge questions to assess their initial knowledge about drones and the safety challenges they impose on construction jobsites. Then trainees watched the 360VR training video and responded to the post-training knowledge questions to assess how their knowledge might have changed after experiencing the 360VR training. The post-training knowledge questions were followed by a series of surveys on system usability, sense of presence, and virtual reality sickness (Fig. 5). At the end of each survey, there was an open-ended section where users could provide their qualitative feedback about each study measure. The pre- and post-surveys and the 360VR training experience were distributed using the Qualtrics online surveying platform. The Appendixes S1–S4 provide a paper-based version of all the surveys and questions used in this study.

Study Metrics

This section discusses the study metrics used in the assessment procedure.

Knowledge Test. A set of 12 questions was created to assess users' knowledge level before and after the training (Appendix S1). These questions covered the three learning objectives of the training to evaluate user knowledge about (1) drones and their applications in the construction industry, (2) potential safety challenges of drone integration on construction jobsites, and (3) potential countermeasures for the safe integration of drones on construction jobsites.

System Usability. This metric was adapted from the System Usability Scale (SUS) developed by Brooke (1996) (Appendix S2). It is a validated tool to effectively differentiate usable and unusable systems and can generate a reliable result with a small sample size (Gallavin 2014). The SUS was built to assess the three components of usability: (1) effectiveness (user's ability to complete tasks using the system), (2) efficiency (consumed resource level when performing tasks), and (3) satisfaction (user's reactions to the system) (Brooke 2013). This is a widely used standardized questionnaire for assessing the perceived usability (Lewis 2018), with references in more than 1,300 articles and publications.

Sense of Presence. This metric was adapted from Slater et al. (1994) and Usoh et al. (2000) (Appendix S3). The sense of presence has long been considered an important characteristic of VR and is defined as the ability to create the feeling of being or acting in a place even when one is physically situated in another location (Regenbrecht et al. 1998; Schwind et al. 2019). For this study, the sense of presence was measured to assess whether the level of user presence in the virtual construction site was high enough to create an experience similar to that of a real-world construction site. This questionnaire is based on six questions covering three main aspects: (1) the sense of being in the virtual environment, (2) the extent to which the virtual environment becomes the dominant reality, and (3) the extent to which the virtual environment is remembered as a place (Usoh et al. 2000).

Virtual Reality Sickness. It is known that exposure to a virtual environment can have adverse side effects on participants (Sagnier et al. 2020) (Appendix S4). Different terms have been used in the literature to refer to these side effects, such as cyber sickness, visually induced motion sickness, virtual simulation sickness, and virtual reality sickness (Rebenitsch and Owen 2016; Saredakis et al. 2020). In this research, the virtual reality sickness questionnaire (VRSQ) was used (Kim et al. 2018). The VRSQ consisted of nine items: general discomfort, fatigue, headache, eye strain, difficulty

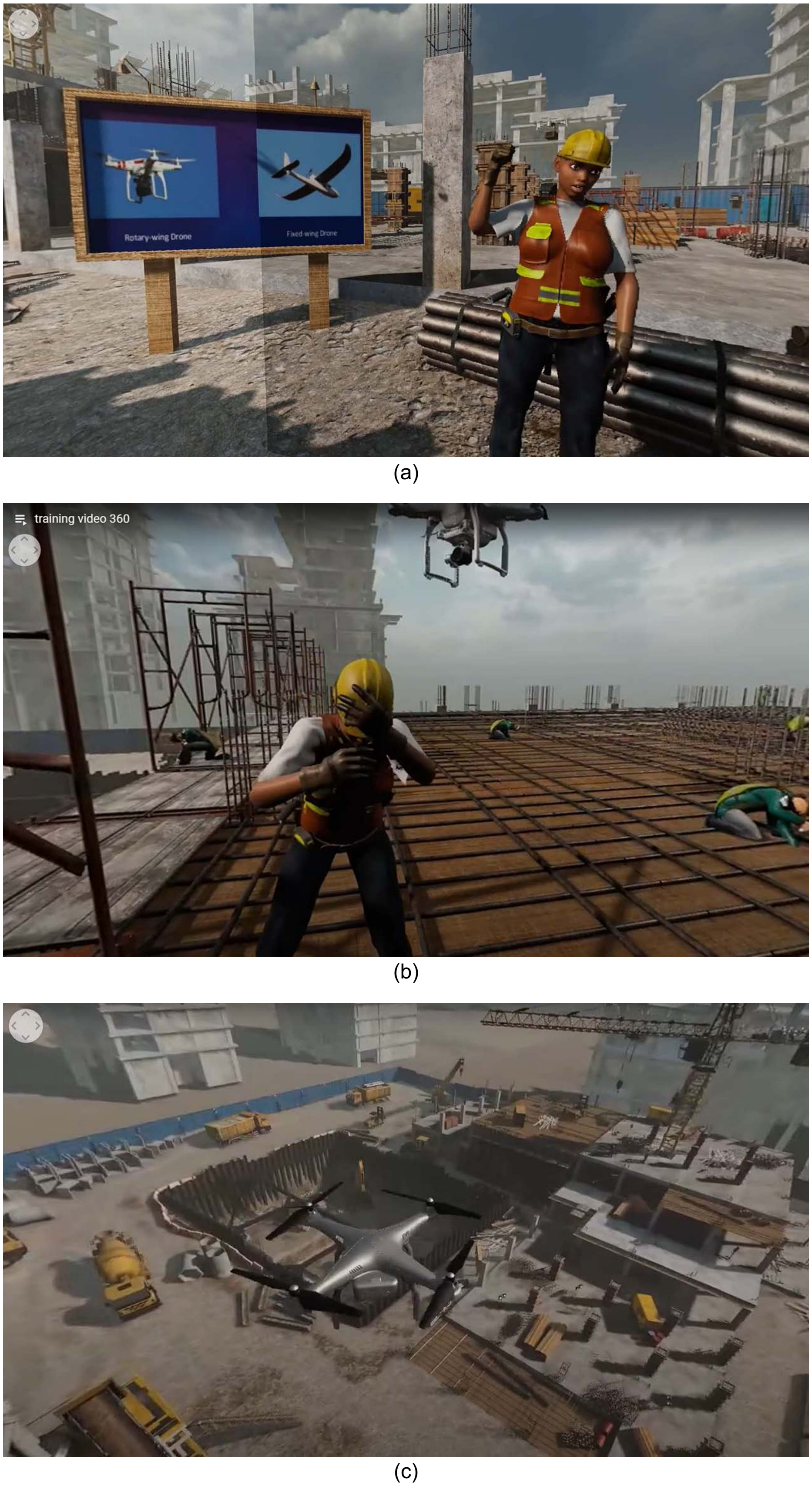

Fig. 4. Different ways of the virtual drone-safety trainer integration into the construction site: (a) conceptual learning; (b) situated learning; and (c) bird's-eye view.

Fig. 5. Assessment procedure.

Table 4. Demographics of the subjects

Variable	Category	Number	Percentage
Gender	Male	39	76
	Female	12	24
Age	≤30	16	31
	31–40	28	55
	41–50	4	8
	≥51	3	6
Education	High school diploma	6	12
	Associate's	14	27
	Bachelor's	10	20
	Master's	17	33
	Ph.D.	4	8
Experience in the construction industry	None	0	0
	<1 year	3	6
	1–2 years	8	16
	3–4 years	13	25
	Over 4 years	27	53
Types of construction	Building	37	73
	Heavy industry	12	24
	Light industry	7	14
	Infrastructure	7	14
	Other	1	2
Trades	Roofer	20	39
	Operating engineer	19	37
	Laborer	7	14
	Pipe fitter	7	14
	Carpenter	5	10
	Electrician	4	8
	Sheet metal worker	2	4
	Ironworker	2	4
	Painter	1	2
	Other	8	16

focusing, fullness of the head, blurred vision, dizziness with eyes closed, and vertigo (Kim et al. 2018). VR sickness could adversely influence users' intention to use VR (Sagnier et al. 2020). Therefore, VRSQ was used to properly assess various adverse side effects of the proposed 360VR training approach.

Results and Discussion

Fifty-one participants were recruited to evaluate the training content. Table 4 provides the demographics of the study participants. Most participants were males (76%), under the age of 40 (86%), with at least a high school diploma or an undergraduate degree (59%), and had more than 3 years of construction experience (78%) and working in the building industry (73%).

Most participants had experience working at height (e.g., roofs, ladders, scaffolds), and only 22% had never worked on a construction project where drones were not used (Table 5). More than 84%

Table 5. Participants' background

Variable	Category	Number	Percentage
Experience working at height	Work on roofs	33	65
	Work on ladders	30	59
	Work on scaffolds	27	53
	None of the above	7	14
Experience working on projects that used drones	Never	11	22
	1–5 projects	18	35
	6–10 projects	19	37
	Over 10 projects	3	6
Previous safety training	Not certified	5	10
	OSHA: 10 h	22	43
	OSHA: 30 h	21	41
	Other	3	6
Understanding of construction safety	None	0	0
	Low	6	12
	Medium	20	39
	High	25	49
Understanding of 360 videos	None	5	10
	Low	14	27
	Medium	19	37
	High	13	25
Understanding of drones	None	3	6
	Low	8	16
	Medium	22	43
	High	18	35

of participants had received OSHA training, and most perceived themselves to have a medium to high level of understanding of construction safety (88%), 360-degree videos (63%), and drones (78%).

Moreover, Cronbach's alpha tests were conducted (Table 6) to assess the internal consistency (reliability) of the results of the study surveys (Tavakol and Dennick 2011). A Cronbach's alpha of greater than 0.70 was considered acceptable reliability: the higher its value, the greater its reliability (Taber 2018; Tavakol and Dennick 2011). The analysis shows that all metrics in this study reached the acceptable Cronbach's alpha value, which indicates the results of these metrics are reliable. The following subsections provide detailed discussions of the study results.

Knowledge Test

A pre- and post-training knowledge test was used to evaluate the effectiveness of training in improving users' knowledge of drones, the safety challenges they introduce, and how to work safely with or around drones. Before training, users were tasked with completing a baseline knowledge assessment test that evaluated their baseline knowledge about drones, their application in construction, and the safety issues of working with drones in construction. Following training, participants were again tasked with completing a similar

Table 6. Cronbach's alpha reliability analysis of the post-training surveys

Post-training surveys	Mean (SD)	Maximum	Minimum	Cronbach's alpha
System usability	66% (17%)	100%	37%	0.80
Sense of presence	4.8 (1.1)	7.0	1.7	0.85
Virtual reality sickness	28.8 (27.6)	85.0	0.0	0.94

Table 7. Knowledge test results

Training component	Pretraining mean (SD)	Post-training mean (SD)	Two-sample t-test	
			p-value	Power
Learning Objective 1	2.8 (1.2)	3.7 (1.2)	$p < 0.01$	1.00
Learning Objective 2	1.5 (0.6)	2.3 (0.9)	$p < 0.01$	1.00
Learning Objective 3	0.9 (0.4)	1.1 (0.3)	$p < 0.01$	0.85
Total	5.1 (1.5)	7.2 (1.9)	$p < 0.01$	1.00

knowledge assessment to evaluate the effectiveness of the training content in achieving the required learning objectives. The Shapiro-Wilk normality test was adapted to test the normality of the knowledge assessment result (Shapiro and Wilk 1965). The obtained p-value was 0.08, which was more than 0.05, validating the normality assumption. Therefore, a paired two-sample t-test was used to evaluate if there was a significant improvement in the scores after the training.

The knowledge assessment consists of three sections covering the three learning objectives of this training: (1) drones and their application in construction, (2) safety challenges of drone integration on construction jobsites, and (3) countermeasures for the safe integration of drones on construction jobsites. The overall result indicates that the participants' knowledge scores significantly increased from 5.1 to 7.2 after the training (Table 7). Although most participants (78%) had a medium to good level of understanding of drones (Table 5), the knowledge test results for Learning Objective 1 show that the proposed training significantly increased their understanding of drones and their different applications in construction (from 2.8 to 3.7). For Learning Objective 2, the increased results from 1.5 to 2.3 indicate that participants were more significantly aware of the risks posed by drones on their jobsites after going through the training, which is the first step to effective safety management. And finally, for Learning Objective 3, the increased results from 0.9 to 1.1 indicate that participants' knowledge of the countermeasures to deal with the safety challenges of drones significantly increased after going through the training. This increased knowledge could ultimately help the trainees work safely with and around drones.

System Usability

The System Usability Scale (Brooke 1996) was used to evaluate the usability of the developed 360VR training (Table 8). The overall system usability score of this 360VR training was 66%, which is considered acceptable (Brooke 2013). The specific results showed that trainees strongly agreed that they would use the 360VR training frequently (4.2), most people would learn to use this very quickly (4.1), and they are confident in using it (4.0). For example, one trainee stated that "the 360 video is very useful, especially for the workers who might not be familiar with drones and safety training." The results also showed that trainees agreed that the 360VR training was easy to use (3.8) and that various functions within it were well integrated (2.4), although they disagreed that they would need the support of a technical person to be able to use it (2.7). However, the trainees neither agreed nor disagreed that the 360VR training was unnecessarily complex (3.0), contained too much inconsistency (2.9), was very awkward to use (2.5), or they needed some previous knowledge to use the 360VR training (2.8). Limited familiarity with the 360VR type of virtual experience, as well as 360VR's limited amount of interactivity, could be some of the reasons behind such neutral ratings of these factors. One user reflected on 360VR's limited interactivity by indicating that the system could be enhanced by "provide[ing] more interactions, more information popups than a purely vocal explanation."

The 360 videos offer three degrees of freedom, which provides a limited stationary view of the area surrounding the user. Unlike the traditional VR environments with six degrees of freedom, 360 videos are not capable of allowing users walk around to explore the virtual environment, and users are merely observers in such a 360VR experience. However, previous research shows that although the interactivity of VR learning material could affect participants' engagement in learning, attention, and focus on learning material, it does not significantly affect users' learning gains (Zhang et al. 2019). Although the limited interactivity of 360VR videos was expected, it was envisioned that 360VR would provide a device-agnostic VR experience that could be accessed on a wide range of hardware devices that could ultimately broaden the delivery alternatives and make the VR experience more available to users. It is recommended to conduct a detailed interactivity and accessibility analysis for selecting specific versions of VR while considering training's different needs and goals.

Sense of Presence

The sense-of-presence metric (Table 9) was adapted from Slater et al. (1994) and Usoh et al. (2000). Participants reported somewhat positively on all five statements of sense of presence, and their overall average rate for this 360VR training was 4.8, which shows they

Table 8. System usability results

System usability statements[a] (Brooke 1996)	Mean[b](SD)
1. I think that I would like to use this 360VR training frequently.	4.2 (0.9)
2. I found the 360VR training unnecessarily complex.	3.0 (1.3)
3. I thought the 360VR training was easy to use.	3.8 (1.1)
4. I think that I would need the support of a technical person to be able to use this 360VR training.	2.4 (1.2)
5. I found the various functions in the 360VR training were well integrated.	3.8 (1.1)
6. I thought there was too much inconsistency in this 360VR training.	2.9 (1.1)
7. I would imagine that most people would learn to use this 360VR training very quickly.	4.1 (1.0)
8. I found the 360VR training very awkward to use.	2.5 (1.3)
9. I felt very confident using the 360VR training.	4.0 (1.0)
10. I needed to learn a lot of things before I could get going with this 360VR training.	2.8 (1.3)

[a]Statements 1, 3, 5, 7, and 9 are worded positively; and Statements 2, 4, 6, 8, and 10 are worded negatively.
[b]Likert scale: 1 = strongly disagree; and 5 = strongly agree.

Table 9. Sense-of-presence results

Sense-of-presence statements (Usoh et al. 2000)	Likert scale	Mean (SD)
1. I had a sense of being there in the construction jobsite.	1: Not at all 7: Very much	5.2 (1.5)
2. There were times during the experience when the construction jobsite was the reality for me.	1: At no time 7: Almost all the time	4.4 (1.4)
3. The construction jobsite seems to me to be more like . . .	1: Image that I saw 7: Somewhere that I visited	4.7 (1.5)
4. I had a stronger sense of . . .	1: Being elsewhere 7: Being on the jobsite	4.9 (1.5)
5. I think of the construction jobsite as a place in a way similar to other places that I've been today.	1: Not at all 7: Very much so	4.5 (1.6)
6. During the experience, I often thought that I was really standing in the construction jobsite.	1: Not very often 7: Very much	4.8 (1.5)

Table 10. Virtual reality sickness results

VRSQ symptoms[a] (Kim et al. 2018)	Mean (SD)
General discomfort	0.8 (1.1)
Fatigue	1.0 (0.9)
Headache	0.8 (1.0)
Eye strain	1.1 (1.0)
Difficulty focusing	0.8 (1.1)
Fullness of the head	0.8 (1.1)
Blurred vision	0.8 (1.0)
Dizziness with eyes closed	0.8 (1.0)
Vertigo	0.7 (1.0)

[a]Likert scale: 0 = not at all, 1 = slightly, 2 = moderately, and 3 = severe.

thought that the training provided a slight sense of presence. More specifically, the trainees had a somewhat high sense of being there on the construction jobsite (5.2) and slightly thought that they had a stronger sense of being on the jobsite (4.9) or really standing on the construction jobsite (4.8). Trainees also slightly thought that the virtual environment was more like a place that they had visited (4.7) and in a way similar to a place that they visited that day (4.5).

During the 360VR training, participants provided a neutral feeling of sensing that the construction jobsite was reality to them (4.4). Some trainees referred to the low level of immersion provided in this desktop VR experience as well as the quality of the VR model as issues that potentially might have led to these mainly average ratings of sense of presence. For example, one participant indicated that "I think the sense of presence would come from having a VR headset on, not necessarily just watching a 360-degree video." While 360 videos might provide a better sense of presence compared with traditional 2D videos (Hendriks Vettehen et al. 2019), viewing them in more immersive delivery methods (e.g., Google Cardboard headsets) could improve their sense of presence (Rupp et al. 2019). In this study, we mainly focused on desktop VR to be able to widely distribute the training to construction workers via a YouTube link, with no need for specific types of hardware or head-mounted displays to view it. Also, previous research shows that the effects on knowledge gain, self-efficacy, and engagement are comparable between desktop VR and immersive VR (a head-mounted display with a narrow field of view and a three-degrees-of-freedom tracker) (Buttussi and Chittaro 2018).

Some of the participants also suggested that "improving the VR modeling" could have increased their sense-of-presence ratings. Such feedback might be related to some of the VR modeling issues, such as some unnatural movement of the virtual drong-safety trainer or other virtual humans. Due to the limited number of elements in the integrated animation database, the movements of the virtual drone-safety trainer and other virtual humans might not have been as realistic as real humans. To address this issue, more detailed animation development should be conducted, but this might significantly increase the virtual human development time. Also, previous literature shows that the higher appearance fidelity of virtual humans might not necessarily lead to higher learning gains and engagement (Eiris et al. 2021b). A detailed sense-of-presence analysis should be conducted for different VR delivery methods and fidelity requirements while considering training's different needs and goals.

Virtual Reality Sickness

VRSQ was analyzed to properly assess various adverse side effects of the proposed 360VR training (Table 10). Trainees reported slight symptoms in all nine VRSQ categories: general discomfort (0.8), fatigue (1.0), headache (0.8), eye strain (1.1), difficulty focusing (0.8), fullness of the head (0.8), blurred vision (0.8), dizziness with eyes closed (0.8), and vertigo (0.7). One important reason behind such ratings of VR sickness could be the somewhat long duration of the training in 360VR (roughly 20 min). For example, one user indicated that the video was "a little bit long and [I] hardly focused [on it] over time." Previous literature has demonstrated that the long duration of VR content could be one of the causes of VR sickness (Chang et al. 2020). Several studies also found that more than 10–15 min of exposure to VR can lead to symptoms of sickness, and the longer the exposure time, the greater the degree of VR sickness (Chang et al. 2020; Munafo et al. 2017). Providing the 360VR training experience in shorter periods (e.g., 10-min periods) and providing rest time in between (Clark et al. 2021; Kim et al. 2018) could decrease or even eliminate the VR sickness symptoms.

Conclusion

In this study, a 360VR training environment was created to provide a semi-immersive training experience about drone applications in construction, the potential safety challenges of working with or near drones, and proposed countermeasures for their safe integration. This 360VR training environment was ultimately assessed using a repeated measures study design to measure trainees' learning, sense of presence, and virtual reality sickness, as well as the system's usability. The main contribution of this study is to provide a better understanding of the effect of 360VR training in enhancing trainees' knowledge about working safely with drones through a combination of quantitative and qualitative approaches. This study also contributes to the core body of knowledge by providing a framework for developing device-agnostic 360VR training environments in construction or similar high-risk industries.

The overall result indicates that the participants' knowledge scores significantly increased after the training, with significant increases in all three training sections of (1) drones and their application in construction, (2) safety challenges of drone integration on the construction jobsites, and (3) countermeasures for the safe integration of drones on construction jobsites. For the system usability, it was found that the 360VR training was an acceptable system, and the trainees would like to use it frequently and found it simple to follow and felt confident using it. The results also showed that the 360VR training provided a slight sense of presence, and participants also reported slight symptoms of virtual reality sickness. One of the main reasons behind these ratings, as well as some of the usability issues, could be the technological limitations of the implemented 360VR approach. The 360VR technology provides a limited amount of immersion in the implemented desktop VR delivery mode while offering a limited degree of freedom. The 360VR technology and desktop delivery mode were specifically selected to enhance training's accessibility to a wide population of trainees. A detailed comparative analysis of various levels of immersion, degrees of freedom, fidelity requirements, and VR delivery modes should be conducted while considering training needs and requirements (e.g., interactivity, accessibility, cost).

The other important limitation of this study was the lack of sample diversity. Demographic analysis showed that most trainees had some level of higher education with medium to high knowledge of drones and 360VR. Workers and professionals with no higher education or with limited or no familiarity with drones and 360VR should be included in future phases of this study. The other limiting factor was that the training was only in English. It is recommended to develop other training versions for non-English-speaking construction workers and professionals, which account for nearly 30% of construction workers in the United States (CPWR 2018). The other limitation of this study was that only the short-term impact of the proposed training was explored. Although the immediate boost in knowledge level is evident, it is uncertain whether the training benefit will be sustained in the long term. And finally, another study limitation relates to the knowledge content of the training. The content was designed as scenario-based training, mainly focusing on workers at height who might be more exposed to the health and safety risks posed by drones. More comprehensive scenarios and training content should be created to include different kinds of working situations affected by drones.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

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Supplemental Materials

Appendixes S1–S4 are available online in the ASCE Library (www.ascelibrary.org).

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