Safety Science 179 (2024) 106631

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/safety

Enhancing safety training engagement through immersive storytelling: A case study in the residential construction

Josiane Isingizwe [a,*], Ricardo Eiris [a,*], Ahmed Jalil Al-Bayati [b]

[a] School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ, USA

[b] Department of Civil and Architectural Engineering, Lawrence Technological University, 21000 West Ten Mile Road, Southfield, Michigan, 48075-1058, USA

ARTICLE INFO

Keywords:
Immersive storytelling
Residential construction
Safety training
Learning engagement
Fall hazards
Eye-tracking

ABSTRACT

Virtual safety training environments are increasingly utilized to support the development of safety knowledge and increase hazard identification skills in construction. One of the emerging techniques for virtual safety training is immersive storytelling. However, current studies have not explored how the inclusion or exclusion of storytelling within immersive safety training systems produces learning gains. Specifically, this study explores learning through the lens of engagement – behavioral, cognitive, and emotional. The residential construction industry was used as a case study to explore this research gap. Residential workers were assessed through a between-subject experimental design. Two safety training conditions were employed for this evaluation using a between-subject experiment – (1) immersive storytelling; and (2) immersive non-storytelling. The experimental comparison revealed that using immersive storytelling led to increases in behavioral learning and cognitive learning, allowing trainees to effectively identify openings and scaffold fall hazard categories. On the other hand, trainee emotional learning engagement did not change between immersive storytelling and immersive non-storytelling conditions. This study contributes to the existing body of knowledge by providing evidence on how using or not using storytelling can affect learning in the context of safety for fall hazards in residential construction. Practical implications for academicians and industry practitioners for the implementation of storytelling in immersive training systems are provided in the study.

1. Introduction

High rates of fatal and non-fatal injuries continue to be recorded in the U.S. construction industry (Nadhim et al., 2016; Hasanzadeh et al., 2018; Albert et al., 2020; Al-Bayati, 2021). Construction safety training programs try to ameliorate the occurrence of these accidents by equipping workers with knowledge that allows them to be proactive when facing unsafe work conditions. Training directly increases safety awareness and hazard identification at job sites, aiming to prevent and decrease rates of fatal and non-fatal incidents on job sites (Demirkesen & Arditi, 2015, Harris et al., 2023). Traditional construction safety training programs are often conducted in standardized formats (such as OSHA 10- or 30-hours training courses) (e.g., Caban-Martinez et al., 2018; Garcia, 2018; Namian et al., 2022). Even though traditional training is commonly used in construction, previous research has associated it with numerous limitations. A major limitation with traditional training is the use of passive learning contents (e.g., texts, videos, pamphlets, slides, images). These passive learning contents have been found to reduce trainees' learning engagement during safety training (Burke et al., 2006; Wilkins, 2011; Zuluaga et al., 2016). Consequently, traditional safety training has difficulties to effectively transfer safety knowledge to workers which translates into the continuous occurrence of safety accidents in construction (Wilkins, 2011; Bhandari & Hallowell, 2017).

Emerging studies are exploring the utilization of immersive virtual environments to address the passive nature of traditional training for improving construction worker safety (e.g., Li et al., 2018; Yu et al., 2022; Rokooei et al., 2023). 360-degree panorama is one of the emerging techniques that has been increasingly used to create engaging construction training. It is defined as a reality capturing technique that provides a true-to-reality, full field-of-view of a location in a virtual setting that can be augmented with data such as graphics, texts, pointers, and audios (Eiris et al., 2018; Eiris et al., 2020-b; Eiris et al., 2021; Shinde et al., 2023). Researchers have found that 360-degree panoramas used in construction safety training are effective because they offer high sense of immersion and realistic representations of construction sites

* Corresponding authors.
E-mail addresses: jisingiz@asu.edu (J. Isingizwe), reiris@asu.edu (R. Eiris), aalbayati@ltu.edu (A. Jalil Al-Bayati).

https://doi.org/10.1016/j.ssci.2024.106631
Received 19 January 2024; Received in revised form 10 June 2024; Accepted 29 July 2024
Available online 9 August 2024

(Lee et al., 2022-a; Shinde et al., 2023; Eiris & Gheisari, 2023). Increasingly, 360-degree panoramic construction safety training leverages the use of storytelling (also called immersive storytelling) to support learning safety contents (Eiris et al., 2018; Eiris et al., 2020-b). Existing immersive storytelling employs virtual humans (i.e., human-like characters to draw attention to hazardous situations) as story narrators for describing high-risk and unsafe operations (Eiris & Gheisari, 2017). Preliminary results on the use of immersive storytelling for safety training demonstrate some aspects of how storytelling is effective for learning (Din & Gibson Jr., 2019; Eiris et al., 2020-a; Arif et al., 2021; Babalola et al., 2023; Man et al., 2023), but these approaches only compare the storytelling technique against traditional paper-based methodologies. Therefore, there is an existing research gap for the current experimental designs that limit the understanding of how including or excluding storytelling within immersive safety training systems produces gains in learning.

Consequently, this study contributes to the current body of knowledge by providing new evidence on how using or not using storytelling can affect learning in the context of safety. Specifically, this study explores learning through the lens of engagement. The concept of engagement as part of learning remains largely unexplored within this type of safety training intervention (Burke et al., 2016; Eiris et al., 2020-a; Seo et al., 2021; Babalola et al., 2023; Isingizwe et al., 2024-a). Prior studies that evaluate engagement explore traditional safety training methods (e.g., lecture, videos, hands-on activities) (Burke et al., 2016), test virtual reality from the usability (Seo et al., 2021), or compare the virtual reality systems against the traditional safety training lectures (Eiris et al., 2020-a; Babalola et al., 2023; Isingizwe et al., 2024-a). Therefore, there is lack of exploration of the effects of engagement as part of the learning process in safety training using immersive training technologies. Given the gaps in knowledge, this study focuses on investigating the effects of immersive safety storytelling to enhance learning engagement.

To evaluate the inclusion of immersive storytelling and its effects on safety training learning engagement, a case study was conducted within the residential construction context. This context was selected for investigation due to the high fall accident rates among residential construction workers as reported by the Center for Construction Research and Training (CPWR) (Brown et al., 2020). To investigate learning engagement produced by immersive storytelling safety training, a set of story narratives were crafted based on the four leading causes of fall incidents (i.e., ladders, scaffolds, openings, working at elevation around unprotected edges). To represent these fall hazards incidents, 360-degree panoramas were captured from active residential job sites. A comparative study was conducted to measure learning engagement by contrasting two experimental conditions:

- Experimental – Immersive Storytelling (IS) Safety Training; and
- Control – Immersive Non-Storytelling (INS) Safety Training

A set of validated surveys, eye-tracking data, and verbal responses were recorded to measure behavioral, cognitive, and emotional learning engagement during each experimental condition. Accordingly, this study focuses on advancing the understanding of immersive storytelling as a tool to deliver learning engagement to workers and providing an alternative safety training method.

2. Literature review

2.1. Residential construction, fall incidents, safety training

Current research shows that falls constitute the largest percentage of fatal incidents (Hasanzadeh et al., 2018; Al-Bayati and York, 2018; Harris et al., 2023). From all construction industry sectors, the highest proportions of fatal falls occur in the residential sector (Johnson et al., 1998; Hu et al., 2011; Dong et al., 2014; Kang, 2018; Al-Bayati and York, 2018; Brown et al., 2020). Researchers trace these fall accidents within residential construction to multiple variables including high-risk practices, limited resources, and unsafe culture. Enforcement and compliance of fall safety practices has been recorded to be poor in the residential construction sector (Johnson et al., 1998; Jeelani et al., 2017-b; Kang, 2018; Al-Bayati et al., 2023a). Moreover, small sized companies with low resources to foster safe practices on job sites are prevalent in residential construction, which often results in more injuries and fatalities due to the reduced availability of training (Evanoff et al., 2016; Al-Bayati and York, 2018). Falls incidents in residential construction also occur due to a lack of a well-established safety culture, with personal protection equipment or systems often not used by workers (Johnson et al., 1998; Hu et al., 2011; Kang, 2018; Al-Bayati et al., 2023b). Consequently, fall incidents among residential workers have remained historically high overall despite efforts to reduce fatalities and injuries in the construction industry (Janicak, 1998; Johnson et al., 1998; Hu et al., 2011; Evanoff et al., 2016; Brown et al., 2020). The main method used to try to reduce fall accidents in residential construction is safety training.

While safety training programs (e.g., OSHA 10- or OSHA 30-hour) are used by residential workers to reduce safety incidents on the job site, falls remains a major concern (Evanoff et al., 2016; Al-Bayati and York, 2018). Many researchers and practitioners argue that traditional safety training contents are not directly tailored to the nature of work performed on residential worksites (Hung et al., 2013; Le et al., 2015-a; Evanoff et al., 2016). Moreover, much of the training done for fall hazards is still passive, as workers often play the role of spectators of the safety training contents (e.g., texts, videos, pamphlets, slides, images), without being given the opportunity to actively interact with the training materials to develop applicable jobsite safety knowledge (Burke et al., 2006; Wilkins, 2011; Hung et al., 2013). Prior studies have found that workers often do not feel engaged during learning of training materials (Hung et al., 2013). For example, workers have highlighted that "a lot of times, videos, [they] get really kind of boring, to be honest, and they would be like the same thing as reading, you kind of just skim through stuff, even though it's important stuff' (Hung et al., 2013). Safety training for residential workers has also been criticized to be unrealistic and unrelated to their field work (Hung et al., 2013; Evanoff et al., 2016). Therefore, the learning outcomes for residential construction safety training has been documented by previous researchers to be low (Hung et al., 2013, Evanoff et al., 2016; Namian et al., 2016).

2.2. Immersive virtual environments for construction safety training

Multiple technologies – such as Building Information Modeling (BIM), Augmented Reality (AR), Virtual Reality (VR), Mixed Reality (MR), and 360-degree panoramas – have been used to produce immersive virtual environments (Li et al., 2018). These immersive virtual environments have been found to produce effective educational experiences for safety training of construction workers (Li et al., 2018). Within these immersive virtual environments, mediated learning simulations are provided for exploring and understanding hazardous conditions in a controlled and replicable manner. These immersive environments have been found to have numerous benefits that include improved task performance, attitude changes towards risk, and increased creativity and engagement (Chittaro et al., 2017; Loup-Escande et al., 2017; Suh & Prophet, 2018). Consequently, researchers have employed the benefits of immersive virtual environments to support learning during construction safety training (Wang et al., 2018; Zhang et al., 2022).

From all the different technologies used to create immersive virtual environments, 360-degree panoramas are being increasingly used for construction safety training. 360-degree panoramas are advantageous because of their low computational-power required, high realism, high sense-of-presence, ease-of-access, and capability of adding information over the obtained background images and videos (Eiris et al., 2018). Additionally, it has been found that using 360-degree panoramas can potentially save time and reduce costs in contrast to 3D-based virtual environments (Moore et al., 2019; Eiris et al., 2020-a, Lee et al., 2022-a). One key component used within 360-degree panorama environments (and other virtual environments) to support safety training are virtual humans. Virtual humans have been shown to be useful in safety training because these digital replicas allow trainees to observe high-risk operations (e.g., working on the top step of a ladder, working at heights without a harness, working at unsecured elevated edges) without exposing real people to physical danger (Brown et al., 2020). By leveraging these features of virtual humans, trainees can experience hazards in a secure, consequence-free platform for understanding incident situations (Li et al., 2018; Eiris et al., 2020-a).

2.3. Learning engagement and construction safety immersive virtual environments

Educational literature points to learning engagement as a crucial factor for successful knowledge acquisition (Lester, 2013; Henrie et al., 2015). Learning engagement is measured across three main dimensions (D'Mello et al., 2017):

- *Behavioral:* the relationship between time and attention dedicated by a learner to the training materials (Henrie et al., 2015; D'Mello et al., 2017).
- *Cognitive:* the mental processes and approaches applied by a learner to make sense of the content during training session (Fredricks & McColskey, 2012; Lester, 2013).
- *Emotional:* the perception of the learner in regard to the personal benefits and usefulness of learning the topic being studied (Peters et al., 2004, Slovic et al., 2013).

Therefore, behavioral, cognitive, and emotional involvement during any learning or training activity determines the overall learning engagement outcomes (Fredricks & McColskey, 2012; Henrie et al., 2015). Learning engagement produces interest, curiosity, satisfaction, and persistence towards the learning task (Skinner at al., 2009; Halverson & Graham, 2019). As a result, engaged trainees or students during learning have an increased desire to complete tasks and are less likely to abandon the learning tasks before full completion (Lester, 2013; Henrie et al., 2015). In construction, enhancing learning engagement during safety training is crucial for promoting safety awareness and proactive hazard recognition (Wilkins, 2011; Evanoff et al., 2016). Researchers have utilized eye tracking data to understand the behavioral engagement of trainees (Hasanzadeh et al., 2018 Lee et al., 2022-a; Shadiev & Li, 2022). Verbal responses have been utilized to collect immediate feedback on cognitive learning engagement processes occurring in the mind of trainees (Le et al., 2015-b; Wong et al., 2020; Ogunseiju et al., 2024). Furthermore, validated surveys such as self-efficacy (Chen et al., 2001) and motivation (Guay et al., 2000) have been utilized in pretest – posttest studies to assess the learner's emotional changes in terms of the learners' perception and confidence to engage in the learning activity (Jeelani et al., 2017-a; Wolf et al., 2022). These multiple connected methods aim to understand learning engagement holistically through various direct and indirect measures.

Various researchers have explored some dimensions of learning engagement within immersive virtual environments (e.g., Li et al., 2018; Pham et al., 2018; Lee et al., 2022a). For example, behavioral learning engagement was measured during construction hazard identification using 360-degree panorama and eye-tracking techniques (Lee et al., 2022a). The study outcome revealed that the characteristics of hazards within a 360-degree panoramic virtual environment influenced visual attention of participants while identifying hazards. In another example, a 360-degree panoramic virtual field trip was created, and a study was conducted to measure cognitive learning engagement of participants (Pham et al., 2018). The study findings revealed that traditional and 360-degree panoramic interventions produced identical cognitive learning engagement (Pham et al., 2018). Similarly, emotional learning engagement in construction safety training was explored using simulations to demonstrate cause and effects of hand injuries (Bhandari & Hallowell, 2017). The study finding has revealed that change in emotional learning engagement influences the ability of workers to perceive and assess risks of injuries.

Literature in construction safety training have employed a variety of indirect and direct approaches to assess learning engagement, including questionnaires (Jeelani et al., 2017-a; Wolf et al., 2022), verbal responses (Le et al., 2015-b; Man et al., 2017; Wong et al., 2020), and eye-tracking technologies (Hasanzadeh et al., 2018, Lee et al., 2022-a; Shadiev & Li, 2022). Indirect approaches often aim to understand cognitive and emotional learning engagement by asking trainees about their experiences. For example, a construction virtual safety system was developed to assess the usefulness of the system for safety training using interviews and test questions. The outcome of the study revealed virtual systems to be effective learning tools for construction site safety (Le et al., 2015-b). Alternatively, direct approaches attempt to evaluate behavioral learning engagement by observing trainee exploration and knowledge gaining processes. Particularly, attention is used as a direct method to assess areas that engage trainees' gaze during learning within virtual environments (Bhoir et al., 2015). In eye-tracking technology, those areas are often referred to as areas of interest (AOI) and gaze data are often segmented into fixations (a steady gaze position within an area of interest lasts between 100 and 200 ms) and saccades (abrupt shifts in gaze between areas of interests) (Ehmke & Wilson, 2007; Hasanzadeh et al., 2018). Fixation count (i.e., how many times participants fixate at each area of interest) and dwell time (i.e., how long a participant fixated each hazard in total) are common metrics used to evaluate behavioral engagement (Hasanzadeh et al., 2018; Shadiev & Li, 2022).

2.4. Storytelling and immersive storytelling for safety training

Storytelling as a learning technique is widespread in traditional construction safety training. Often storytelling is used as part of toolbox talks or videos techniques in construction safety training (Olson et al., 2016). Storytelling in the safety context allows a narrator to share hazardous job site information in a way that the audience can relate to, and it is easy to remember (Kaskutas et al., 2013; McDowell, 2021). The mental processes that occur when a person follows a storytelling scenario positively influence the memory of events described, the understanding of the context, and the identification of safe and unsafe behaviors, allowing the listener to connect with the feelings and experiences of the narrator in a practical sense (Bliss and Dalto, 2018). Although storytelling provides opportunities to enhance learning in traditional construction safety training, this technique is limited due to the lack of visual representation of hazardous situations, characters, and venues of described events (Eiris & Gheisari, 2017; Eiris et al., 2020-b). To overcome this challenge, previous studies have proposed the use of immersive storytelling techniques that leverage 360-degree panorama virtual environments (Eiris et al., 2020-a; Eiris & Gheisari, 2023).

Immersive storytelling (i.e., storytelling combined with virtual environments such as 360-degree panoramas) supports learning in construction safety training by engaging workers during learning using visually rich, context-based, and task-focused set of materials (Eiris & Gheisari, 2023). Prior studies have compared knowledge gained from the traditional safety training (i.e., OSHA 10-Hour) and immersive storytelling, finding no differences in knowledge obtained but gains in learning engagement (Eiris et al., 2020-b). In a more recent study, safety learning outcomes were compared between traditional safety training (i.e., text and images) and online virtual environment training to teach fall hazard identification. The study findings indicated that online virtual environment training was as effective as the traditional safety training in teaching fall hazard recognition, but the virtual environment training was found to increase learning engagement (Eiris et al., 2021). While some studies are finding positive gains in using virtual environments, more research is needed to understand how immersive storytelling supports learning engagement during training interventions. Table 1 summarizes a comparison of existing VR-based construction safety training systems in terms of four components (i.e., type of virtual environment used, use of virtual humans, the use of immersive storytelling, and the evaluation of storytelling to produce learning engagement). As shown in Table 1, no prior papers have explored how including or excluding storytelling within immersive safety training systems produces gains in learning.

3. Research objectives, questions, and hypotheses

This study project builds on previous investigations that use of immersive storytelling (IS) as a tool for safety training (Din & Gibson Jr., 2019; Eiris et al., 2020-b; Arif et al., 2021; Babalola et al., 2023; Man et al., 2023). Although prior studies have advanced the knowledge in the use of immersive storytelling for safety training, two major challenges have been identified in this study that require further exploration. First, the use of immersive storytelling remains poorly understood as a technique to foster learning engagement as part of safety training interventions. Prior studies (e.g., Din & Gibson Jr., 2019; Eiris et al., 2020-a; Arif et al., 2021) have shown that there are some learning benefits during safety training while using immersive storytelling. However, these approaches only compare the storytelling technique against traditional paper-based methodologies. Therefore, there is an existing research gap for the current experimental designs that limit the understanding of how including or excluding storytelling within immersive safety training systems produces gains in learning. Second, residential construction remains largely affected by fall accidents (Dong et al., 2014; Kang, 2018). Consequently, there is a need to design safety training contents that produce learning engagement in residential construction workers. This study contributes to the current body of knowledge by providing new evidence on how using or not using storytelling can affect learning in the context of residential construction safety. It is particularly important to increase the effectiveness of current safety learning materials for enabling residential workers the ability to proactively identify and react to fall hazard conditions. To address these challenges, this study this paper aims to provide evidence on how using or not using storytelling affects learning within the residential construction sector. This objective led to the formulation of a set of research questions and hypotheses as shown on Table 2.

Table 1
VR-based construction safety training system comparison.

References	Type of Environment Used (360° Panorama or 3D)	Use of Virtual Human (Present / Not Present)	Employment of Storytelling (Present / Not Present)	Evaluation of Storytelling to Produce Learning Engagement (Present / Not Present)
Guo et al., 2012	3D	Not Present	Not Present	Not Present
Sacks et al., (2013)	3D	Not Present	Not Present	Not Present
Le et al., (2015-a)	3D	Not Present	Present	Not Present
Le et al., (2015-b)	3D	Not Present	Present	Not Present
Eiris et al., (2018)	360° Panorama	Not Present	Not Present	Not Present
Pham et al., (2018)	360° Panorama	Not Present	Not Present	Not Present
Din & Gibson Jr., (2019)	3D	Not Present	Present	Not Present
Eiris et al., 2020-a)	360° Panorama	Present	Not Present	Not Present
Eiris et al., 2020-b)	360° Panorama	Not Present	Present	Not Present
Arif et al., (2021)	3D	Not Present	Present	Not Present
Lee et al., (2022-a)	360° Panorama	Not Present	Not Present	Not Present
Zhang et al., (2022)	3D	Not Present	Present	Not Present

4. Immersive storytelling safety training: Case study of fall hazards within the residential construction sector

In response to the significant needs to design safety training for residential fall hazard contents that produce learning engagement and the promising but poorly understood effects of immersive storytelling, this study centers on investigating immersive storytelling through a case study in the residential construction sector. To accomplish the evaluation of learning engagement for immersive storytelling within residential construction context, this study followed three phases illustrated in Fig. 1.

During Phase I, story narratives were created based on the four main leading causes of fall hazards for residential construction as identified from real-world accidents reports. In Phase II, an immersive storytelling system was developed using a combination of 360-degree panoramas, narratives audio files, texts and shapes, and animated virtual humans as storytellers. Two digital training platforms – one that used immersive storytelling and the other that only used immersive virtual environments – were developed to conduct residential worker safety training and assessment sessions. Lastly, Phase III was centered in a comparative, between-subject experimental intervention to evaluate the effectiveness of immersive storytelling for enhancing learning engagement. Data were gathered through eye tracking metrics and validated surveys to understand learning engagement. Following is a detailed description of how these three phases were completed to achieve the objective of this study and answer the proposed research questions.

4.1. Phase I – Narratives creation

4.1.1. Fall fatality incident report collection and analysis

In this phase, the goal was to understand the current state of the fatal falls in the residential construction industry. The data collection and analysis guided the development of fall incident narratives that represent how fall safety incidents occur in the real-world within residential construction sites. To accomplish this goal, fatal fall incidents in the residential sector were identified from reports in the Occupational Safety and Health Administration (OSHA) Fatality and Catastrophe Investigation Summaries (FCIS), the National Institute of Occupational Safety and Health (NIOSH) Fatality Assessment and Control Evaluation (FACE) Program, and the Center for Construction Research and Training (CPWR) "stopconstructionfalls.com" fatality databases. Real-world incident narratives were collected and analyzed to understand the

Table 2
Study Research Questions and Hypotheses.

Research Questions (RQ)	Hypothesis (H)
RQ1: What are the impacts of immersive storytelling (IS) and immersive non-storytelling (INS) experiences on behavioral learning engagement?	**H1:** Participants under IS condition have different behavioral learning engagement effects than those in INS condition.
RQ2: What are the impacts of IS and INS experiences on cognitive learning engagement?	**H2:** Participants under IS condition have different cognitive learning engagement effects than those in INS condition.
RQ3: What are the impacts of IS and INS experiences on emotional learning engagement?	**H3:** Participants under IS condition have different emotional learning engagement effects than those in INS condition.

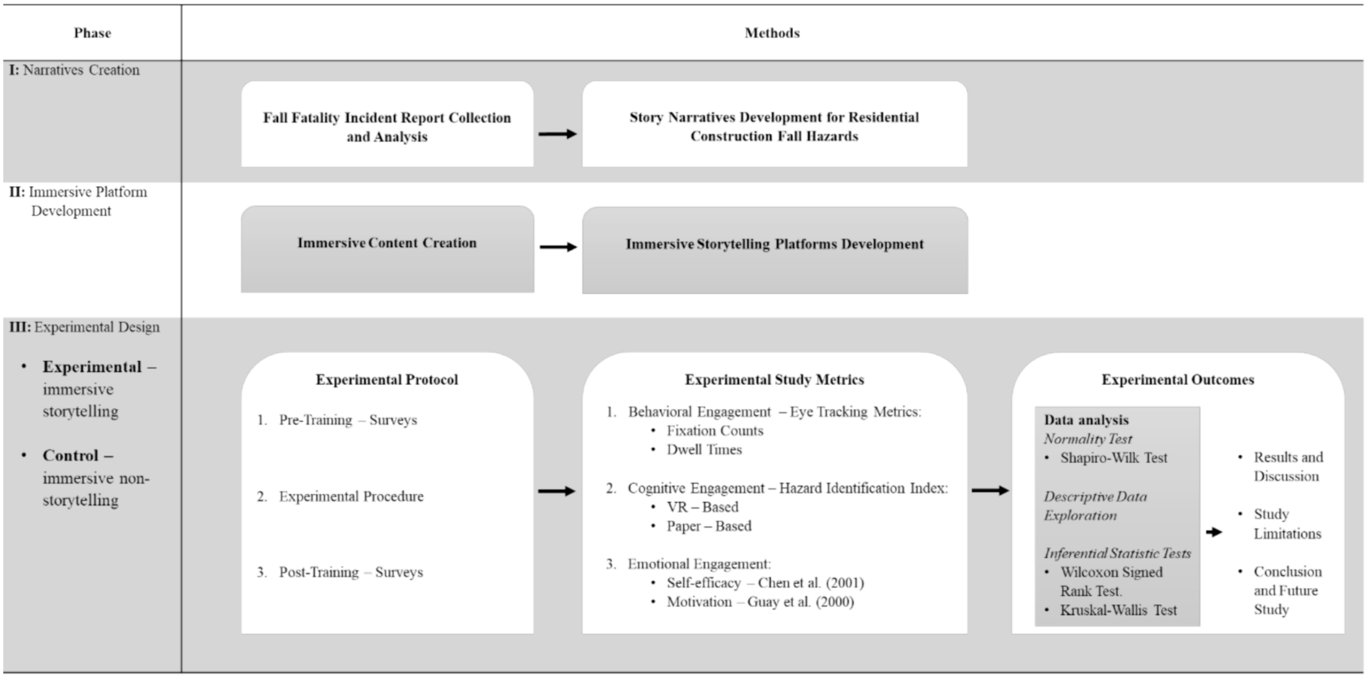


Fig. 1. Overview of the Immersive Storytelling Safety Training Case Study for Residential Construction.

common hazard types, the way these occurred on job sites, and the trades affected by these accidents. Data about the most recent fatality reports were obtained from these databases using the following process:

- *OSHA – FCIS:* The following parameters were used for report filtering in the FCIS data repository – (1) the North American Industry Classification System (NAICS) code was selected for residential building construction using the descriptor “23611”; (2) the keyword “Fall” was used as to outline the accident type; (3) the “fatality-only” filter was employed to guarantee reports that contained only accidents that resulted in worker deaths; and (4) the time range “January 2016 to April 2022”. This time frame was selected to show the five years most recent years from when this study was started.
- *NIOSH – FACE:* The following parameters were used for report filtering in the FACE data repository – The case-studies contained in the database were constrained to the category of “Falls-Construction-Residential”.
- CPWR – *stopconstructionfalls.com:* The following parameters were used for filtering the CPWR interactive map dashboard – (1) the Injury Type filter was set to “Falls, Slips, Trips”; (2) the Focus Four Category filter was set to “Fall to Lower Level”, (3) the Years of Occurrence filter was set to “2016–2022”. The resulting data from this search was manually investigated to include only residential accidents.

A total of 193 reports were found for analysis of the FCIS, FACE, and CPWR databases. Initially, the data was reviewed for completeness. From this analysis, 36 data points were discarded, as they either had large amounts of data missing, were not construction-related, or were not fall accidents. The remaining 157 data points were further analyzed to characterize each report description and classified each accident based on the type of fall hazard, type of occupation of the victim, type of project where the accident occurred, and location where the accident occurred. From the analysis, it was found that most fatal fall accidents occurred from working on elevated surfaces with unprotected edges (36 %), ladders (23 %), scaffolds (18 %), and openings (14 %) (Table 3). Other fall accidents are present within the databases (e.g., slips & trips, collapsed stands, non-specified), but these represent only a small percentage of all the data (10 %).

Table 3
Frequency of Falls by Category.

Types of Falls	Frequency (Counts)	Percentage
Unprotected Edge	56	36 %
Ladders	36	23 %
Scaffold	28	18 %
Opening	22	14 %
Other Falls (Slips & Trip, Collapsed Stand, Non-Specified Falls)	17	10 %
Total	157	100 %

Furthermore, the analysis showed that most fatal fall accidents affected the following occupations: laborers (21 %), carpenters (20 %), roofers (10 %), painters (8 %), construction trades (4 %), and other construction roles (e.g., managers, inspectors, glaziers) (10 %). However, a considerable percentage of the data points collected did not specify the occupation of the accident victim (27 %). Furthermore, the analysis showed that the largest number of fatal fall accidents occurred in single-family/duplex dwellings (33 %) and multi-family residential buildings (17 %). A large percentage of the accident reports did not specify the type of project (49 %), and a minor portion of the accidents occurred in mobile homes (1 %). Finally, it was found that most fatal fall accidents happened outside the building (84 %) in places such as roofs, scaffolds, or trusses. A lower percentage of the accidents occurred inside the buildings (13 %) or were non-specified (3 %). The inconsistency in the information reported in the explored investigations was also highlighted by Al-Bayati et al. (2021). Thus, it is recommended designing a systematic approach for incident investigation to enhance the learning opportunities from incident investigations.

4.1.2. Story narratives development for residential construction fall hazards

Leveraging the data from the fall accident written report descriptions previously analyzed, story narratives were developed under each of the key fall hazard categories contained in Table 3. A total of four stories were created that focused on one of the following fall hazards: ladders, scaffolds, openings, and unprotected edges. The “Hero’s Journey”

(Campbell, 2008) narrative structure was used to craft these stories focusing on each of these four hazards. This story structure was selected for this study due to its simplicity and popularity across many domains such as entertainment, journalism, and education (Delmas et al., 2007; Campbell, 2008). The goal of the "Hero's Journey" storytelling narrative approach is to showcase the transformative journey of a character using three acts as follows: (1) Departure – the character embarks on a journey unaware of upcoming challenges; (2) Initiation – the character encounters difficult challenges along the journey; and (3) Return – the journey is completed by the new experience and knowledge the character gained from resolving the challenges. Prior researchers have recognized the potential to describe safety training contents in an easy and intuitive manner using this storytelling approach (Bliss & Dalto, 2018; Eiris et al., 2020-b).

In this study, the "Hero's Journey" structure was used to create safety training narratives contents for the immersive storytelling experiences using the following approach:

(1) *Departure:* the story begins by describing the contextual jobsite information for a character. The character is introduced to the story audience by describing their jobsite role and tasks and indicating that a safety accident has occurred in connection with their work.
(2) *Initiation:* the character is transported to the location where the fall accident occurred. In that location, the causes and consequences of the fall accident are described to deliver a learning opportunity for the character and the story audience.
(3) *Return:* the character demonstrates the gained safety knowledge within the context of the fall hazard accident. Specific descriptions of the solution to the encountered hazard are provided as story closure.

An illustrative example of how this storytelling approach was used using the three-act framework is shown on Table 4. Typical OSHA investigation summary reports for ladders do not provide a storytelling structure in their descriptions, offering only a short text that resembles an abbreviated initiation act in the "Hero's Journey" (Table 4). To craft the complete structure of a "Hero's Journey" story, this study adapted the patterns and data found across several OSHA investigation reports to demonstrate how the improper use of ladders can produce a fatal fall accident through narratively describing the departure, initiation, and return acts. In this example, six story scenes were created to contain this structure of a ladder fall accident as follows: (1) Departure [Scene 1 & 2] – Trainees learn about an employee named Marcos who is a carpenter. Marcos takes the audience around the jobsite and describes his work. There, Marcos reveals that he suffered a safety accident while installing the soffit at the roof eave. (2) Initiation [Scenes 3 & 4] – Marcos shows the location where he suffered the fall accident while performing jobsite tasks. As he displays the location, he provides the details of the accident (i.e., he fell 14 feet from an extension ladder due to incorrect run-to-height ratio). Marcos also described the consequences of the fall, describing how he was taken to the hospital and the injuries he suffered. Lastly, he indicates that everyone in his social and professional life was affected by his accident (i.e., himself, his family, and his company), offering insights into the injuries and the rehabilitation process. (3) Return [Scene 5 & 6] – Marcos returns to work after recuperating from the fall. As he is at his jobsite, he notices a hazard like the one that caused him to suffer the fall (i.e., improper ladder run-to-height ratio) and immediately informs the manager. Marcos provides a solution by describing how such accidents should be avoided by offering specific insights regarding the necessary actions to be taken.

Table 4
Sample Narrative Crafting for Ladder Residential Fall Hazard.

OSHA Investigation Report	Example Created Narrative Summary *
At 9:00 a.m. on February 4, 2021, an employee ascended an unsecured extension ladder to install wood siding on a two-story residential home. The employee stood near the top of the ladder and attempted to reach out to the right when the ladder slid to the left and the employee fell approximately twelve feet. The employee was killed by unspecified injuries received.	**Scene 1:** Marcos introduces himself as a carpenter. He describes his typical work tasks and showcases the locations where he works. **Scene 2:** Marcos indicates that he suffered an injury recently while working on a ladder. He describes the type of work he was performing that day – installing the soffit at the roof eave. **Scene 3:** Marcos reveals the location where the fall accident happened. He describes that he was using an extension ladder and that it slid down the wall while he was trying to reach the roof eave. He indicates the run-to-height ratio used for the ladder as 5:2. **Scene 4**: Marcos describes how he, his family, and his company were impacted by the fall accident. He emphasizes details about the physical pain and monetary cost from his accident. **Scene 5**: Marcos describes returning to work 5 months later. After returning to his jobsite, he notices a hazardous ladder that was not stabilized using a 5:3 run-to-height ratio. He now knows that the ratio should be 4:1 and described how he reported the situation. **Scene 6**: The hazard solution is presented by offering insights regarding the necessary actions that need to be taken to prevent the accident and the story is closed.
OSHA Investigation Report: Source Inspection Number: 1514875.015 ID#: NAICS: 236118/Residential Remodelers Report ID: 0,950,621	Hero's Journey Structure : Departure : Initiation : Return

* Note: The full narrative is provided as an Appendix.

4.2. Phase II – Immersive platform development

4.2.1. Immersive content creation

In this phase, the goal was to produce a realistic and interactive visual representation of hazardous situations using immersive contents. The immersive contents focused on demonstrating hazard types, characters, and location of events described in scene narratives created in Phase I. To accomplish this goal, 360-degree panorama images were collected to represent the story narratives previously created. Multiple residential construction sites were visited in the U.S. Midwest region, capturing images that encapsulated the ideas presented in the story scenes narratives. A total of nine residential construction site visits were captured using advanced high-precision 360-degree cameras (e.g., Insta360® ONE X2 and Pro 2). The seven single-family/duplex dwellings and two multi-family residential buildings were visited for data collection. A total of approximately 300 images were captured that illustrated potential fall hazards and the surrounding environments. The site selection and the image capturing process was driven on the previously created narratives, attempting to obtain images that resembled the created stories in Phase I.

Subsequently, storyboarding – technique used to illustrate scene by scene how the video will unfold using multimedia components such as shapes, images, and texts of what is said in sequential order based on preconceived ideas (Jantakoon et al., 2019) – was used to match the captured 360-degree images with created narratives. Within these storyboards, indicators for the virtual human movements and dialogue were added to connect the narratives created by the story narrator. It is important to highlight that this process was highly iterative, as the images captured in the real-world did not perfectly match the previously created narratives. Adjustment had to be made in the narratives to seemly integrate the story contents through the storyboarding process. To validate the outcome of the storyboarding process, an online focus group (1-hour in duration) was completed with a safety advisory board of four residential industry professionals with at least five years of experience. These professionals reviewed all the storyboards and provided feedback regarding the created materials to make them representative of the real-world situations and characters based on their prior experiences. A sample of the outcome of the storyboarding outcomes is shown in Fig. 2. Each of the storytelling scenes as part of the "Hero's Journey" three-act framework is represented with a corresponding 360-degree image of a residential site. Within the Return act [Scene 6], the fall hazard is visually represented, showcasing an extension ladder fall hazard as described in the crafted narrative.

4.2.2. *Immersive storytelling platform development*

The validated storyboards created as described in the previous section were developed into an immersive storytelling platform that allows trainees to interactively learn and test their knowledge regarding fall hazards using a head-mounted display (HMD). In this study, immersion is defined as a property of the technology that mediates an experience, with higher level of fidelity in the displays and tracking corresponding to greater levels of immersion (Slater, 2003). Participants used the HMD (HTC VIVE Pro Eye ® HMD) to explore fall hazards within 360-degree images which delivers a field of view of 110 degrees, resolution 1440 x 1600 pixels per eye, and refresh rate 90 Hz. Similar papers used these HMD technology settings to indicate fully immersive experiences (e.g., Azhar et al., 2020; Dhalmahapatra et al., 2021; Liu et al., 2022). Moreover, these prior studies have found that 360-degree panoramas offer full immersion across multiple applications (Szabó et al., 2020; Li et al., 2023). Because of these considerations, this study defined the developed system as a fully immersive experience.

To develop the platform using the HMD fully immersive technology, the Unity® game engine (version 2019.4.38f1) was employed. Previous studies have used the Unity® gaming engine to conduct immersive experiences for a variety of applications in the construction domain. (Albeaino et al., 2021; Hussain et al., 2024; Isingizwe et al., 2024-b). Within the game engine, custom scripts (e.g., Speech_Blend for facial animations; Game_Background_Sound; New_Audio_Player; and the Render_Objects_With_Children C# scripts) were created to enable trainee audio-visual exploration of the fall safety challenges within the story contextualized for residential construction. Code snippets of each of these custom C# scripts are provided in the **appendix**, demonstrating the technology integration process used in this study. As shown on Fig. 3, this game engine was utilized to interconnect four types of immersive contents that composed the storytelling experience including (1) 360-degree panorama environments, (2) augmented information (e.g., text, images, attentional indicators), (3) animated virtual humans, and (4) narrative voice-overs. Following is a description for how each of these components were implemented to develop the immersive storytelling experiences:

(1) *360-degree Panorama Environments:* The 360-degree panorama environment aimed to create immersive, interactive, and visually

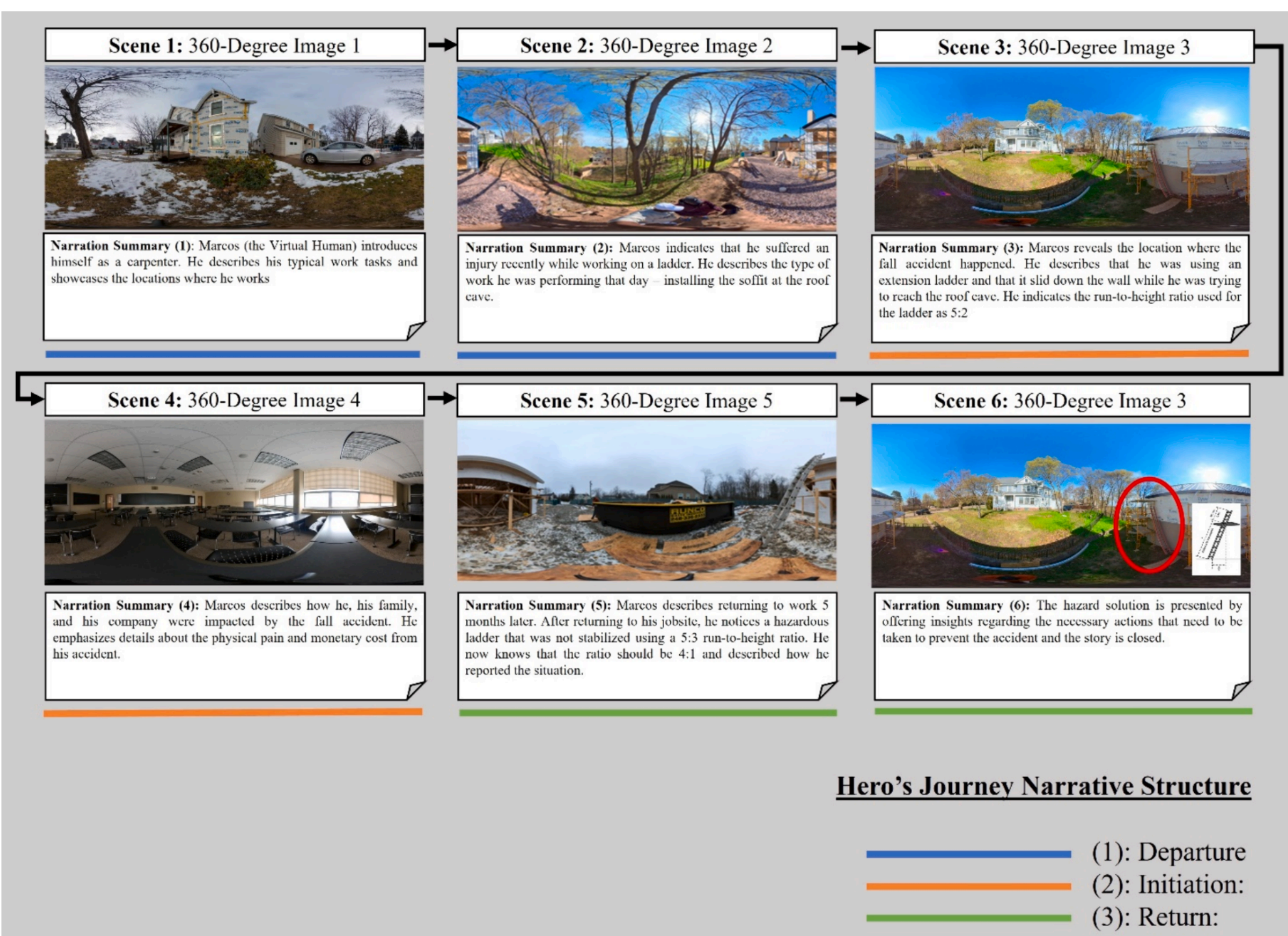


Fig. 2. Storyboard creation process.

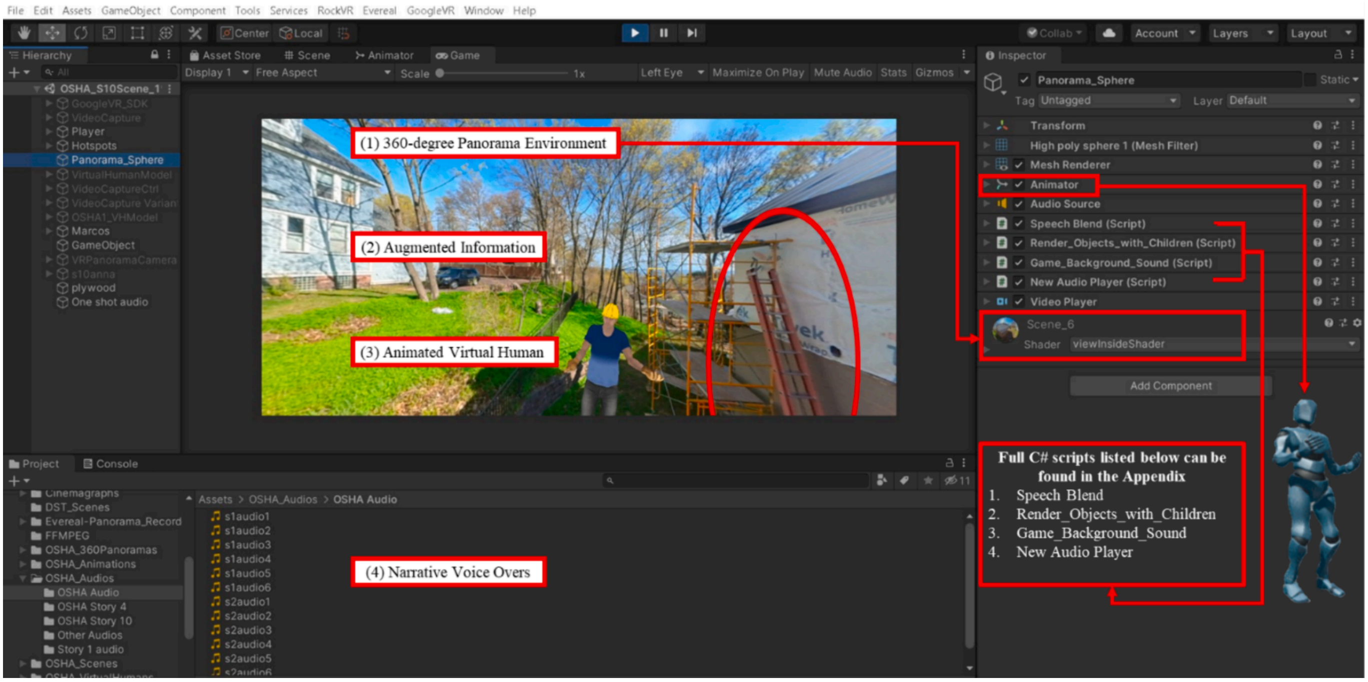


Fig. 3. Immersive Storytelling Content in Unity®.

contextualized environments for engaged learning of safety information in the created story narratives. This environment contained captured 360-degree images of potential fall hazards from real-world residential jobsites, similar to those described in the text story narratives. To create immersive interactive experiences, the 360-degree images were rendered into Unity® game engine as textures sphere and using custom shaders to unfold equirectangular projections into the spherical models.

(2) *Augmented Information:* Information augmentation aimed to elaborate on visual information in the 360-degree panorama by providing a visual representation of the fall hazard knowledge. These visual information augmentations were introduced in the final narrative scene of each story to deliver clear indicators of the hazard issues and solutions by using texts, images, and attentional indicators (e.g., arrows, circles, dots) into background of the 360-degree panoramas.

(3) *Animated Virtual Humans:* The virtual human aimed to provide a method for trainees to connect with the stories through their representation as storyteller characters. The creation of the virtual humans for this game engine was done with the Reallusion® Character Creator 4 software. The Reallusion® Character Creator 4 software enables to create any characteristics for virtual humans (e.g., gender, race, facial features, clothing). Diverse virtual humans in terms of race and gender were created to represent residential construction workers. The animations of the virtual humans were completed using Adobe Mixamo® software to create body movement to animate the virtual humans, while SpeechBlend® Lip-Synch software was used to create facial animations that matched the narrative voice-overs. The body and facial animations were crafted specifically to replicate natural human gestures during the narrative delivery in the immersive storytelling platform.

(4) *Narrative Voice-Overs:* The narrative voice-overs aimed to deliver an audio-based description for the text story narratives. The IBM Text-to-Speech® software was used to produce the audio narratives.

This creation process for each of these four components was completed individually for each "Hero's Journey" narrative scenes (i.e., six scenes for each of the four fall stories), producing approximately twenty-four individual scenes. Fig. 4 shows an example of how this process was done for a single narrative scene by combining the four possible components for the scenes in the game engine. In this scene, the fall hazard is shown in a ladder that has improper run-to-height ratio and that is not extended three feet over the top of the landing section. To show this information, the animated virtual human narrates the text show in the storyboard using audio and the fall hazard is highlighted with a visual image augmentation.

As part of the development of the immersive platform, two sessions – a training session and an assessment session – were established to guide the trainee in the learning and testing of their knowledge regarding fall hazards. Following is a description of what each of these sessions entailed as part of the immersive storytelling experience.

Training Session: The goal of the training session was to learn about residential fall hazards. Trainees gained safety knowledge for jobsite hazard identification within immersive platforms developed in this study. During the training session, each participant was exposed to a total of four immersive stories that covered the fall hazard topics of ladders, scaffolds, openings, unprotected edges. The order in which each of the stories were displayed to each trainee was randomized to eliminate any order effects. Table 5 illustrates the training contents and the 360-degree panorama images shown to each of the trainees during this session. It is important to highlight that these contents were weaved into the story narratives as previously described.

Assessment Session: The goal of the assessment session was to understand the learning engagement through the measurement of fall hazard identification. Within this session, this Hazard Identification Index (HII) was measured using VR-based test that requested the participants to verbally identify a hazard within the virtual setting. This HII data was collected by analyzing video recordings that included the participant view of the immersive experience (as seen in the HTC Vive Pro Eye Head-Mounted Display) and their verbal responses as they identify the hazards. The verbal responses were scored using the HII methodology adapted from Carter and Smith (2006), scoring the HII as a percentage between 0 % to 100 % for each participant. Additionally, the participant completion time and visual attention allocation patterns in

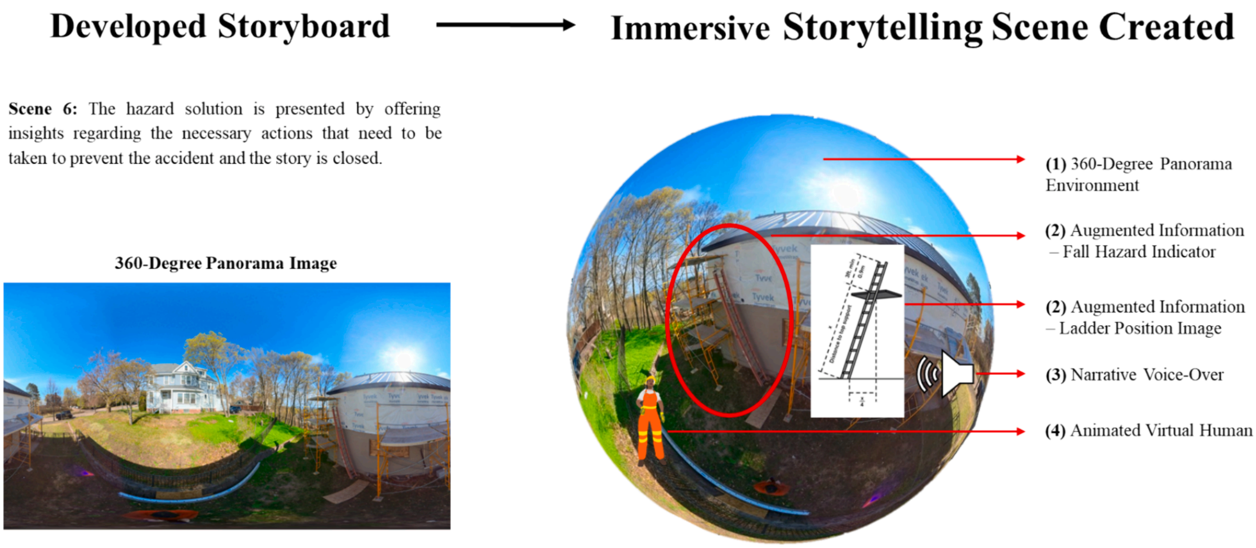


Fig. 4. Immersive Storytelling Scene Creation Process.

the developed immersive platform were collected in the assessment session of this study." The time, and visual attention allocation of participants in the developed immersive platform were collected and analyzed in a similar fashion to prior studies (e.g., Hasanzadeh et al., 2017-a, Liko et al., 2020; Lee et al., 2022-b). Trainees observed two 360-degree images (analogous hazard types observed during the training season, but different images) and were asked to verbally describe any hazards visually identified within the location. The order in which the assessment images appeared to each trainee was randomized to eliminate order effects. Table 5 shows each of the assessment images shown to the trainees.

4.3. *Phase III – Experiment design and measures*

4.3.1. *Research design*

To evaluate immersive storytelling as a method to enhance learning engagement within residential construction safety training, a between-subject research design was employed. The experiment was conducted in a controlled indoor laboratory, without background noises, under standard ambient electric lighting, and at neutral air-conditioned temperature. Participants were required to be seated at all times, with every participant using a rotating chair for ease of virtual space exploration. This research approach enabled the comparison of the two conditions designed for this study as follows: Experimental – Immersive Storytelling, and Control – Immersive Non-Storytelling (Fig. 5). During both conditions, trainees learned the same scope of contents for residential fall hazards (training session) and were assessed within the immersive virtual environment using the same 360-degree panorama (assessment session). Each of these conditions are described in detail below.

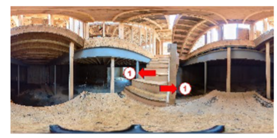
- *Experimental Condition – Immersive Storytelling*: The experimental condition was developed in Unity® as described in section "4.2.2. Immersive Storytelling Platform Development". The "Hero's Journey" structure was used to narrate four fall hazard stories (i.e., ladders, scaffolds, openings, unprotected edges). Each story contained a total of six scenes that followed the three-act narrative framework of the "Hero's Journey". Fig. 5 illustrates the narrative flow and structure for the experimental condition for the ladder fall story.
- *Control Condition – Immersive Non-Storytelling:* Similarly to the experimental condition, the process described in section "4.2.2. Immersive Storytelling Platform Development" was used to develop the control condition employing the Unity® game engine. Differently, from the experimental condition, the storytelling components were removed from this condition. The virtual human was removed, and the voice-overs were simplified to outline only the OSHA regulation for the hazard present in the virtual location. Moreover, the "Hero Journey" scenes for the departure and return were removed to eliminate the story narrative structure. It is important to highlight that the same scope of learning content (i.e., topics, visual demonstrations, concept descriptions) was consistently kept within this condition in contrast to the experimental condition. Fig. 5 illustrates the shortened flow of the control condition for the sample ladder fall story.

4.3.2. *Experimental protocol*

To perform the between-subject comparative study, an experimental protocol was established for guiding the data collection (Fig. 6). Before being exposed to the training and assessment sessions, each trainee completed a set of pre-training surveys. Subsequently, trainees used a head-mounted display (HTC® Vive Pro Eye) to perform the two sessions – training and assessment. First, during the training session, each trainee was exposed to only one of the two training conditions (experimental or control). The duration of the training session lasted for approximately 20 min. Second, each participant completed an assessment session, where a fall hazard identification activity took place. To complete the assessment session, trainees observed 360-degree images to recognize safety hazards. Eye-tracking sensors embedded in the head-mounted display recorded their eye movements and a Zoom® shared screen was used to record the trainee views of the platform and their verbal response audio while performing the assessment session. The duration of the assessment session varied depending on the total amount of time each trainee took to identify the hazards in the images (i.e., trainees could request the researcher to move to the next 360-degree image if they thought they were done identifying the hazard) but was capped to a maximum of 10 min. After completing the experimental procedure, another set of post-training surveys were completed by the participants. The total duration of the study, including the surveys, was approximately 50 min.

All data collected from trainees was fully anonymized based on IRB (#1873063–2) protocols developed for this study. A total of forty-two residential workers trainee datasets were collected for the evaluation. Trainees were randomly assigned to each experimental condition while maintaining an equal balance of participants across conditions (i.e., twenty-one participants per condition). Each trainee received monetary compensation for the time used to participate in the study.

Table 5
Immersive Storytelling Training and Assessment Sessions.

Hazard Category	Training Contents	Training Session Images	Assessment Session Images
Ladder	1. Ladders are not stabilized using a 4:1 run-to-height ratio. 2. Ladders improperly used by a worker standing on the top step. 3. Workers using a bucket as a stepping stool instead of using a proper length ladder.		 
Openings	1. Openings bigger than 2 in. not marked and not covered.		 
Scaffolds	1. Using a non-self-supporting extension ladder as an access point to the scaffold. 2. Using an unacceptable access point to the scaffold. 3. Using unprotected scaffold.		 
Unprotected Edges	1. Roof edge over than six feet high not protected by guardrails. 2. Lack of personal fall arrest system.		 

4.3.3. *Experimental metrics*

To compare learning engagement of trainees across the two conditions (Control: Immersive Non-Storytelling, and Experimental: Immersive Storytelling) of this study, three different categories of metrics – (1) Behavioral Learning Engagement, (2) Cognitive learning Engagement, and (3) Emotional Learning Engagement – were collected as described below:

(1) *Behavioral Learning Engagement*: This metric aimed to understand learning engagement through the analysis of the time and visual attention dedicated by the trainees during their interactions with the safety contents. To measure behavioral learning engagement two eye-tracking metrics were employed – *Fixation Counts*: the number of times a trainee fixated at a hazard during the intervention; and *Dwell Time*: the total time a trainee fixated at a hazard during the intervention. The definition of fixations in this study employed the velocity method as described by Salvucci & Goldberg (2000). The eye-tracking data was collected using the HTC Vive Pro Eye ® head-mounted display at a rate of 120 Hz. To analyze the eye-tracking data for determining fixations and dwell times, Area of Interests (AOIs) were established on each 360-degree assessment session images. The AOIs were selected based on the validation feedback from the expert focus groups previously completed. The AOIs considered the typical trainee behaviors and the position of each fall hazard being studied in the images. The AOIs were delineated using rectangles following the established practices of prior safety analysis papers in the construction domain (e.g., Bhoir et al., 2015; Lee et al., 2022-b; Lee et al., 2022-c). Fig. 7 shows the AOIs annotated for all the assessment session 360-degree panorama images in the assessment session.

(2) *Cognitive Learning Engagement:* This metric aims to assess the approaches applied by the trainees to make sense of the safety content during assessment session. To understand this cognitive involvement of the trainees, two hazard identification tests were

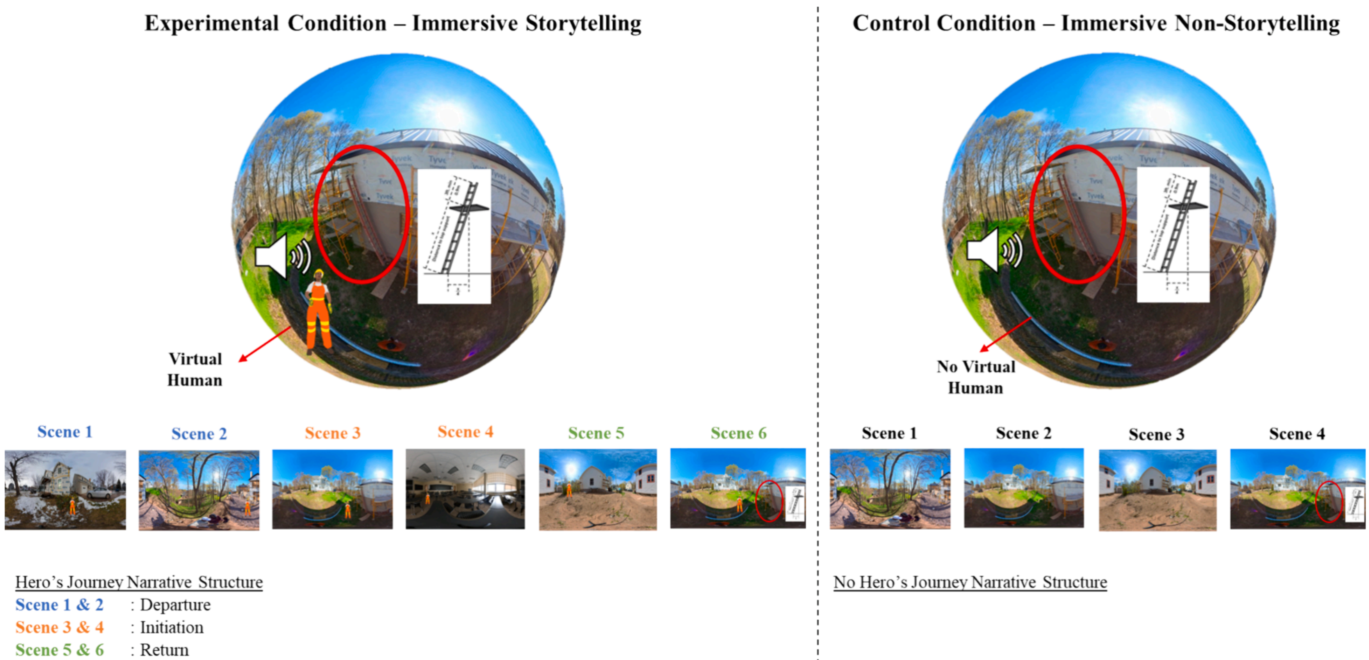


Fig. 5. Research Design – Experimental and Control Conditions.

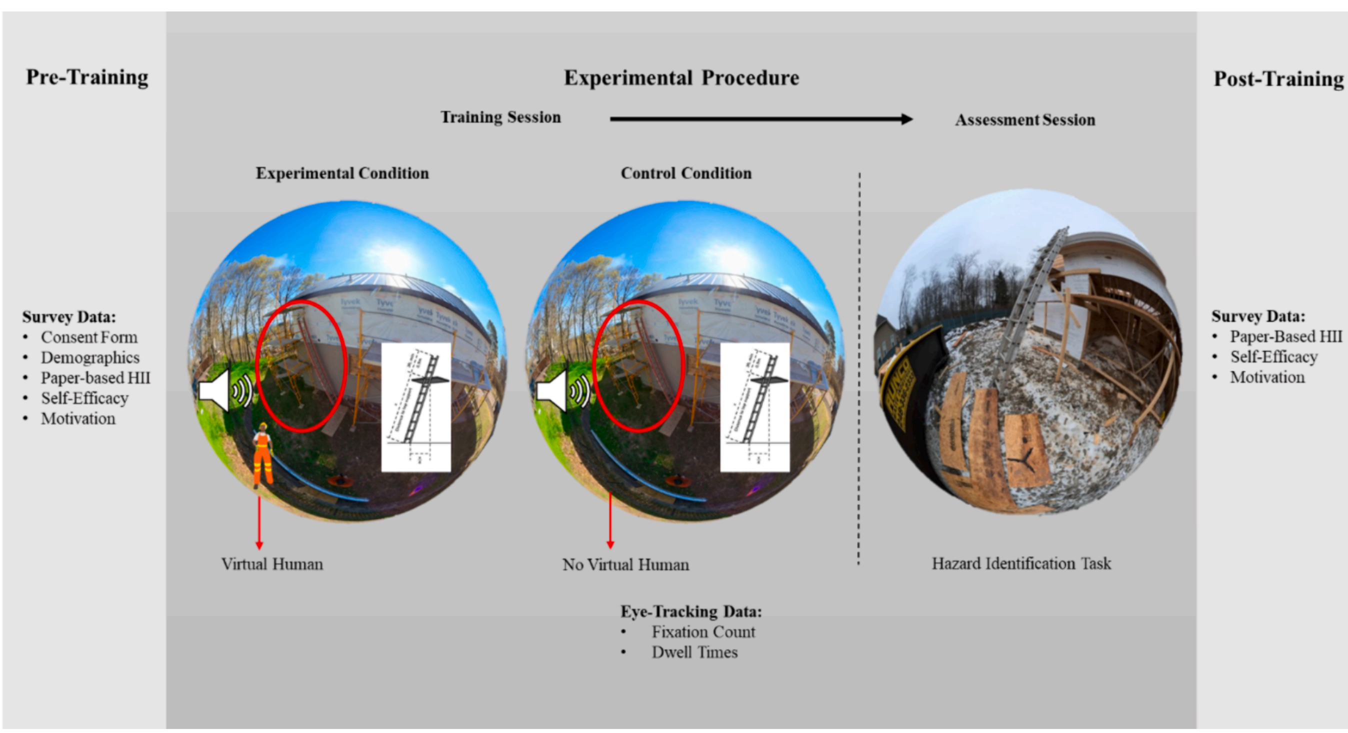


Fig. 6. Experimental Protocol.

used: (1) *Virtual Hazard Identification Test* and (2) *Paper Hazard Identification Test*. (1) *Virtual Hazard Identification Test* – The goal of the virtual hazard identification test was to evaluate in a naturistic way the approach used by the trainees to visually identify hazards in the contextualized setting of fall hazards as demonstrated in Fig. 8. This test took place during the assessment session. Video recording was obtained during the assessment session as trainees were asked to verbalize their thought process as they search and identify the hazards. The videos were then reviewed and scored by the research team. The scores were binary, with a rating of one if the hazard was successfully identified in the virtual fall hazard setting or zero if it was not identified by the trainee. (2) *Paper Hazard Identification Test* – The goal of the paper hazard identification test was to understand how the trainee knowledge translated into traditional testing means that capture retention as shown in Fig. 8. A set of four multiple-choice questions, each containing a written narrative and an image about fall hazard related to the fall categories was used. The

Fig. 7. Behavioral Engagement Metric – Areas of Interests (Hazards) in Red Rectangles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

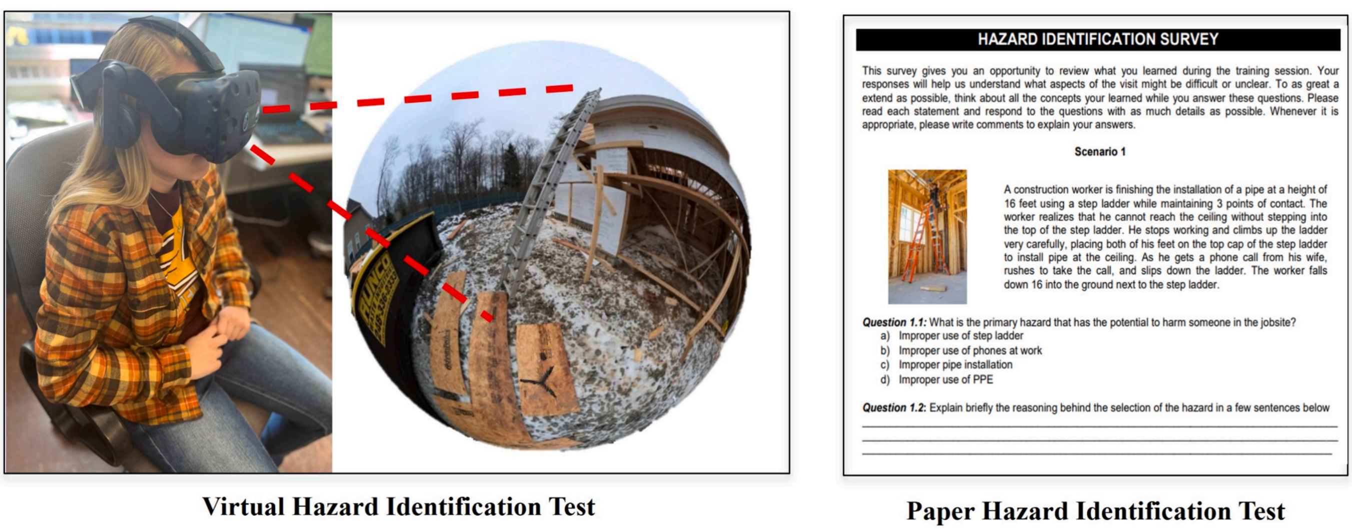


Fig. 8. Cognitive Engagement Metric – Ladder Fall Hazard Category.

created questions were validated for accuracy and correctness by the experts in the focus group previously completed.

(3) *Emotional Learning Engagement:* This metric aimed to understand the trainee's perception regarding the personal benefits and usefulness of the safety training. Two constructs were used to capture the concept of emotional learning engagement: (1) *Self-Efficacy* and (2) *Motivation*. First, *Self-Efficacy* was selected because it provides insights into perceived learning benefits of the safety training intervention. This metric is defined as trainee's belief in his or her capacity to complete the safety training (Chen et al., 2001). A Self-Efficacy Survey was adapted from Chen et al. (2001) to measure this construct – this survey contained 8 five-point Likert scale items from strongly disagree (1) to strongly agree (5). This survey contained questions aimed at explaining the expected outcome of the intervention. The survey asked trainees to rate statements such as "I will be able to achieve most of the goals that I have set for myself"; "When facing difficult tasks, I am certain that I will accomplish them"; or "In general, I think that I can obtain outcomes that are important to me". Second, *Motivation* was selected because it provides insights into the perceived usefulness of the completed safety training intervention. This metric is defined as personal reasons why the safety training intervention is completed (Guay et al., 2000). A Motivation Survey was adapted from Guay et al. (2000) to measure this construct – this survey contained 16 seven-point Likert scale items from not at all (1) to exactly (7). This survey contained statements aimed at describing reasons for completing the intervention. Some of the example statements include "Because I think that this activity is interesting"; "Because I am doing it for my own good"; or "Because I am supposed to do it". Previous researchers have used these surveys to measure emotional learning engagement in healthcare, construction, and education domains (Conchie, 2013; Douglas-Lenders et al., 2017; Wei et al., 2019).

4.3.4. Statistical analysis

To analyze the results from the behavioral, cognitive, and emotional learning engagement metrics described in prior sections, descriptive and inferential analyses were performed. In this study, all dependent variables analyzed were treated as continuous variables similar to prior studies that collected comparable variables (e.g., Carter & Smith 2006; Bhoir et al., 2015; Eiris et al., 2020-a; Lee et al., 2022-b; Lee et al., 2022-c). Using these continuous variables, an appropriate statistical analysis test was selected to show whether there are differences between the two groups of participants across experimental and control conditions. To select a statistical comparison analysis methodology for the two groups of participants, first the normality of collected dataset was tested using a Shapiro-Wilk Goodness of Fit Test (D'Agostino, 2017). The Shapiro-Wilk Goodness of Fit Test was selected in contrast to other normality tests (i.e., Kolmogorov-Smirnov test; Anderson-Darling test; Lilliefors test; Chi-

Square test; D'Agostino-Pearson test) because prior research demonstrate that the Shapiro-Wilk test has the most statistical power for symmetric and asymmetric distribution (Razali & Wah, 2011; Yap & Sim, 2011; Saculinggan & Balase, 2013). The results of this analysis of all dependent variables displayed non-normal distributions. Therefore, the Wilcoxon Signed-Rank Test (Taheri & Hesamian, 2013) was selected for comparing pairs of dependent variables (e.g., comparing control and experimental groups for Ladder Fixation Counts dependent variable) and the Kruskal-Wallis Test (Kruskal & Wallis, 1952; Nwobi & Akanno, 2021) for comparison that required 2 or more dependent variables (e.g., comparing control and experimental groups for HII across all four types of hazards). The results of these analyses are included in the "Study Results" section. Lastly, an additional correlation analysis using a Spearman's Rank-Order Test (van Doorn et al., 2020) was conducted (due to the lack of normality in collected data) that did not result in any statistically significant correlation among dependent variables.

- **Behavioral Learning Engagement Metrics Analysis**: Using the behavioral learning engagement metrics data collected from the experiment, descriptive and inferential analyses were performed. The eye-tracking data in terms of fixation counts (frequency) and dwell times (in seconds) for the assessment session of each experimental condition were analyzed. First, the fixation counts across all AOIs and fall hazard types were aggregated into a single total fixation count and total dwell time for descriptive and inferential analysis between the two conditions. Then, each fall hazard category (ladders, openings, scaffolds, and unprotected edges) fixation count, and dwell time were individually aggregated within the corresponding AOIs for descriptive and inferential analyses. Each category represented a fall hazard within the virtual environment.

In addition to analyzing the raw fixation count (i.e., how many times participants fixate at each area of interest) and dwell time (i.e., how long a participant fixated each hazard in total) aggregated values, the fixation proportions (i.e., ratio of fixation counts inside the AOIs in a 360-degree assessment image over the aggregation of the fixation counts inside and outside the AOIs for a 360-degree assessment image) and dwell proportions (i.e., ratio of dwell time inside the AOIs in a 360-degree assessment image over the aggregation of the dwell time inside and outside the AOIs for a 360-degree assessment image) were investigated. Similarly, to the raw fixation counts and dwell time, proportion across all AOIs and proportions for each individual hazard type AOIs were computed. The use of these proportions for analysis enabled the understanding of the trainee attentional engagement during learning by exploring the relative distribution of fixation and dwell time within the AOIs. Prior research (such as Hasanzadeh et al., 2017-a, Liko et al., 2020; Lee et al., 2022-b) have used similar metric approaches to provide further context for eye-tracking datasets. Because of the behavioral and attentional implications of the fixation and dwell proportions, the analysis of Hypothesis 1 (H1) – Participants under IS condition have different behavioral learning engagement effects than those in INS condition – was done based on the findings for this computed metric.

- **Cognitive Learning Engagement Metrics Analysis:** The cognitive engagement metric was composed of two different tests. The first was a VR-based hazard identification task performance test. A total of 11 hazards were present in the immersive system for participants to identify. Therefore, maximum, full score possible for the VR-based test was 11 points, and the minimum, lowest score was 0 points. Participants obtained these points by correctly identifying hazards through verbal description and visual search patterns within the immersive safety training experience. A binary scoring system for each hazard identified was employed (i.e., a score of one was assigned to a correctly identified hazard and a score of zero was assigned to an incorrectly identified hazard). The second was a paper-based hazard identification test. A total of 4 hazard scenarios were presented to participants to identify hazards on a paper test. The maximum, full score of the paper-based test was 4 points, and the minimum, lowest score was 0 points. Analogously to the VR-based test, a binary scoring system was employed (i.e., a score of one was assigned to a correctly identified hazard and a score of zero was assigned to an incorrectly identified hazard). The resulting assigned points to the participants in both tests were then used to compute the Hazard Identification Index (HII) as defined by Carter and Smith (2006). Each trainee was assigned a HII that was converted into a score (i.e., 0 % is the lowest score, and 100 % the highest score) to simplify the analyses done in this study. To compute the HII score, the ratio of the number of identified hazards by a trainee was divided by the total number of hazards that can be possibly identified (as described in Eiris et al., 2020-a). For example, if a participant identified 7 hazards in the VR-based test from the 11 total possible hazards, an HII score of (7 ÷ 11) computed and covered into a percentage, resulting in a HII score of 63.63 %. The analysis of Hypothesis 2 (H2) – participants under IS condition have different emotional learning engagement effects than those in INS condition – was done based on the findings for this computed metric.
- **Emotional Learning Engagement Metrics Analysis:** Using the emotional learning engagement metrics data for self-efficacy and motivation collected from the experiment, descriptive analysis was performed. A Self-Efficacy Survey was adapted from Chen et al. (2001) – this survey contained 8 five-point Likert scale items from strongly disagree (1) to strongly agree (5). A Motivation Survey was adapted from Guay et al. (2000) – this survey contained 16 seven-point Likert scale items from not at all (1) to exactly (7). For the self-efficacy and motivation data, the average Likert-scale survey responses for each trainee were employed for analysis as a continuous variable.

Further analysis was performed using inferential statistics for the emotional learning engagement data. A between-subject comparison was analyzed for self-efficacy and motivation, between each experimental condition (i.e., pre control vs pre-experimental, and post control vs post experimental). The analysis of Hypothesis 3 (H3) – Participants under IS condition have different emotional learning engagement effects than those in INS condition – was done based on the findings for this computed metric.

5. Study results

5.1. Participants

A total of 42 residential workers trainees participated in this study (Table 6). This total number of participants was selected by reviewing prior similar published studies in the construction safety domain that reported sufficient sample size for statistical analyses and significant results (Eiris et al., 2018; Eiris et al., 2020-b; Dhalmahapatra et al., 2021; Guo et al., 2021; Al-Khiami & Jaeger, 2023; Rokooei et al., 2023). The workers were predominantly male (93 %), with a low percentage of female (7 %). Most participants self-identified as White American (71 %), followed by African American (16 %), and Hispanic were (12 %). The average age of the participants was 35 years, a standard deviation of 12 years. Most participants obtained a high school diploma (40 %), while others had some college (19 %), a bachelor's degree (14 %), a trade certificate (12 %), some high school (7 %), a master's degree (5 %), or some trade school (2 %). Half of the participants indicated that they had over 5 years of experience (50 %), with others indicating that they had 2-to-5 years (19 %), 1-to-2 years (12 %), or less than one year (20 %). Over half of the participants had not obtained either OSHA 10-hour or OSHA 30-hr training (67 %). No prior experience with virtual reality experiences was reported by any participant. This demographic information is provided in this study to clearly delineate the characteristics of the participants involved in the experiments, to avoid

Table 6
Demographics Information for Residential Workers Sample.

Variable		Frequency (Percentage)
Gender	Male	39 (93 %)
	Female	3 (7 %)
Race	White	30 (71 %)
	Hispanic	5 (12 %)
	African American	7 (17 %)
Age	Mean	35 years
	SD	12 years
Education	Some HS	3 (7 %)
	HS Diploma	17 (40 %)
	Some College	8 (19 %)
	BS	6 (14 %)
	Master's	2 (5 %)
	Some Trade School	1 (2 %)
	Trade Certificate	5 (12 %)
Experience	No Experience	2 (5 %)
	Less than 6 months	4 (10 %)
	6 months to 1 year	2 (5 %)
	1 to 2 years	5 (12 %)
	2 to 5 years	8 (19 %)
	Over 5 years	21 (50 %)
Type of Work (Single person can have multiple answers)	Laborer	10 (24 %)
	Carpenter	3 (7 %)
	Roofer	2 (5 %)
	Other (e.g., Pipefitters, Skilled Trade, Maintenance)	31 (74 %)
Prior Safety Training	Yes	14 (33 %)
	No	28 (67 %)
Prior Experience with Virtual Reality	Yes	0 (0 %)
	No	42 (100 %)

overgeneralization of this study findings, and to ensure that future scholars and practitioners can replicate this study findings.

5.2. Results for IS and INS experiences on behavioral learning engagement

The results of the statistical analysis show significant behavioral learning engagement differences between the two conditions for the opening fall hazards only. The control group had significantly higher fixation proportions (p-value = 0.0004) and longer dwell proportions (p-value = 0.0001) only for the openings fall hazards (Table 8). The descriptive analysis of fixation counts, and dwell times showed higher rates of total fixation counts for all hazards and fixation counts for each hazard individually in the experimental condition in comparison to the control condition. Lower rates of dwell times were observed in the experimental condition for all hazards and for each fall hazard type. However, no significant differences were found using inferential analyzes for either the fixation counts or the dwell times for all hazards or across each individual hazard type (Table 7).

The descriptive analysis of fixation and dwell proportions showed similar fixation proportion percentages between experimental and control conditions for all hazards and for each hazard individually, except for the openings fall hazard type (Table 8). For the openings fall hazard, higher fixation proportions (Mean = 21.95 %) in the control condition were found when compared to the lower fixation proportions (Mean = 14.94 %) in the experimental condition. Statistical analysis of the fixation proportions shows significant differences for the openings fall hazard ($p < 0.05$; p-value = 0.0004) between the control and experimental conditions. Similarly, higher dwell proportions (Mean = 23.31 %) in the control condition were observed when compared to the lower dwell proportions (Mean = 16.00 %) in the experimental condition. Statistical analysis on the dwell proportions also shows that these differences were significant ($p < 0.05$; p-value = 0.0001). However, no significant differences were found for the fixations or dwell proportions for all hazards or any other individual fall categories (Table 8).

Previous literature shows that higher fixation often indicates

Table 7
Behavioral Learning Engagement – Fixation Counts and Dwell Times.

Hazard Type	Metric	Condition		Significance? (p-val) Kruskal-Wallis Test*/ Wilcoxon Signed Rank Test**
		Control Mean (Standard Deviation)	Experimental Mean (Standard Deviation)	
All	Fixation Count (#)	1153.76 (472.39)	1280.24 (546.41)	No (0.43 > 0.05) *
	Dwell Time (seconds)	333.85 (924.09)	135.41 (31.83)	No (0.34 > 0.05) *
Ladders	Fixation Count (#)	447.62 (180.32)	514.67 (199.41)	No (0.26 > 0.05) **
	Dwell Time (seconds)	255.03 (926.01)	57.24 (15.64)	No (0.34 > 0.05) **
Openings	Fixation Count (#)	233.90 (142.76)	240.48 (71.23)	No (0.85 > 0.05) **
	Dwell Time (seconds)	23.52 (10.79)	23.36 (5.68)	No (0.95 > 0.05) **
Scaffolds	Fixation Count (#)	167.62 (85.35)	186.24 (132.51)	No (0.59 > 0.05) **
	Dwell Time (seconds)	19.54 (8.34)	18.82 (8.17)	No (0.78 > 0.05) **
Unprotected Edges	Fixation Count (#)	324.26 (119.68)	352.62 (191.71)	No (0.57 > 0.05) **
	Dwell Time (seconds)	37.78 (10.06)	37.74 (13.76)	No (0.99 > 0.05) **

Table 8
Behavioral Learning Engagement – Fixation and Dwelling Proportions.

Hazard Type	Metric	Condition		Significance? (p-value) Kruskal-Wallis Test*/ Wilcoxon Signed Rank Test**
		Control Mean (Standard Deviation)	Experimental Mean (Standard Deviation)	
All	Fixation Proportion (%)	32.35 (4.79)	33.02 (6.68)	No (0.71 > 0.05) *
	Dwell Proportion (%)	35.28 (15.78)	33.89 (5.69)	No (0.70 > 0.05) *
Ladders	Fixation Proportion (%)	53.59 (14.25)	55.67 (11.92)	No (0.61 > 0.05) **
	Dwell Proportion (%)	58.09 (21.35)	59.44 (11.44)	No (0.80 > 0.05) **
Openings	Fixation Proportion (%)	21.95 (7.23)	14.94 (3.54)	Yes (0.0004 < 0.05) **
	Dwell Proportion (%)	23.31 (6.98)	16.00 (3.39)	Yes (0.0001 < 0.05) **
Scaffolds	Fixation Proportion (%)	18.91 (5.89)	19.39 (11.95)	No (0.87 > 0.05) **
	Dwell Proportion (%)	18.34 (6.93)	18.22 (7.84)	No (0.95 > 0.05) **
Unprotected Edges	Fixation Proportion (%)	23.17 (5.89)	23.82 (6.28)	No (0.72 > 0.05) **
	Dwell Proportion (%)	24.25 (6.61)	25.04 (6.10)	No (0.69 > 0.05) **

increased attention with the viewed content (Holmqvist et al., 2011; Underwood et al., 2011). However, the specific learning engagement mechanisms that explain these higher fixations are still somewhat debated, as it can associated to two potential notions: (1) trainees with higher fixations wanted to spend more cognitive resources on this area because it was interesting and useful; or (2) trainees with higher fixations needed additional cognitive resources to understand, decipher, and process information because the content was difficult for them (Shadiev & Li, 2023). On the other hand, consensus is more general regarding dwell, indicating that lower dwell is associated with faster understanding of content and higher hazard identification skills (Hasanzadeh et al., 2017-a). Therefore, the results from Table 8 for dwell proportion might suggest that workers in the experimental condition were able to identify the opening hazards using IS more effectively. However, lower fixation can potentially indicate that either the trainees were not highly engaged with the opening hazards or that they required less cognitive resources to understand them in the IS context. These results for IS provide evidence to not reject hypothesis for behavioral learning engagement (*H1*), indicating that participants under IS condition have different behavioral learning engagement effects than those in INS condition. Further investigation is required to determine the mechanism that prompted this phenomenon to occur within IS.

5.3. Results for IS and INS experiences on cognitive learning engagement

The results of the statistical analysis show significant cognitive learning engagement differences between the two conditions only for the opening and scaffolds fall hazards. The experimental group had significantly higher HIII scores for openings on the paper-based test (p-value = 0.0100) and significantly higher HIII scores on scaffolds (p-value = 0.0010) on the VR-Based test and (p-value = 0.0020) the paper-based test (Table 9).

Table 9
Cognitive Learning Engagement – HII for Virtual and Paper Tests.

Hazard Type	Metric	Condition		Significance? (p-value) Kruskal-Wallis Test*/ Wilcoxon Signed Rank Test**
		Control Mean (Standard Deviation)	Experimental Mean (Standard Deviation)	
All	HII – Virtual Test (%)	58.82 (22.91)	71.49 (11.80)	No (0.0518 > 0.05) *
	HII – Paper Test (%)	71.25 (31.70)	94.05 (13.47)	Yes (0.0064 < 0.05) *
Ladders	HII – Virtual Test (%)	62.74 (23.22)	63.16 (18.90)	No (0.9541 > 0.05) **
	HII – Paper Test (%)	85 (36.63)	90.47 (30.07)	No (0.6050 > 0.05) **
Openings	HII – Virtual Test (%)	58.82 (34.42)	63.16 (26.97)	No (0.6795 > 0.05) **
	HII – Paper Test (%)	70.00 (47.02)	100 (0)	Yes (0.0100 < 0.05) **
Scaffolds	HII – Virtual Test (%)	58.82 (36.38)	94.73 (15.76)	Yes (0.0010 < 0.05) **
	HII – Paper Test (%)	60 (50.26)	100 (0)	Yes (0.0020 < 0.05) **
Unprotected Edges	HII – Virtual Test (%)	54.90 (33.21)	64.91(20.70)	No (0.2942 > 0.05) **
	HII – Paper Test (%)	70 (47.016)	85.71 (35.86)	No (0.2384 > 0.05) **

The descriptive analysis of hazard identification index (HII) scores obtained in virtual and paper tests showed differences between control and experimental conditions (Table 9). Higher HII scores were observed in the experimental condition for the virtual test and paper test in comparison to the control condition for all hazards and for each hazard individually. Higher HII scores among workers in the experimental condition in comparison to control condition in virtual and paper tests may suggest that hazard identification knowledge is gained more effectively in the IS training method. Additionally, an inferential statistical analysis for the cognitive learning engagement HII score metrics was performed. The statistical analysis showed significant differences between control and experimental conditions (Table 9). It was found that the HII score for the paper tests were significantly different across experimental conditions ($p < 0.05$; p-value = 0.0064), with significant higher HII scores in the experimental condition (Mean = 94.05 %) when compared with the control condition (Mean = 71.49 %). While no significant difference was found for the virtual test for all hazards, the inferential analysis displayed borderline significance ($p > 0.05$; p-value = 0.0518).

Upon further examination within each individual fall hazard category, it was found that the HII paper test scores were significantly different for the openings category on the paper test ($p < 0.05$; p-value = 0.0100), and for the scaffolds category for the virtual ($p < 0.05$; p-value = 0.0010) and paper tests ($p < 0.05$; p-value = 0.0020). For the openings category, it was observed that the paper test experimental condition (Mean = 100 %) was significantly higher than the control condition (Mean = 60 %) HII score results. For the openings category, it was observed that the virtual test had higher experimental condition HII scores (Mean = 94.73) than control condition HII scores (Mean = 58.82 %), and the paper test had also higher condition HII scores (Mean = 100 %) than control condition HII scores (Mean = 60).

5.4. Results for IS and INS experiences on emotional learning engagement

The results of the statistical analysis show no significant emotional learning engagement differences between and within the two conditions for self-efficacy (p-value = 0.44) and motivation (p-value = 0.61). The descriptive statistics show that trainees perceive high self-efficacy after both conditions, with Likert-scale scores over four points from a maximum of five. Slight increases were observed for the control condition (Pre-Mean = 4.45; Post Mean = 4.60), but decreases were observed for the experimental condition (Pre-Mean = 4.53; Post Mean = 4.49) (Table 10). On the other hand, the trainees perceived a moderate score for motivation, with Likert-scale scores over four points from a maximum of seven. Mostly unchanged scores for motivation were observed for the control (Pre-Mean = 4.25; Post Mean = 4.26) and experimental (Pre-Mean = 4.37; Post Mean = 4.37) conditions pre-post experiment (Table 10).

Upon further examination, statistical analysis of emotional learning

Table 10
Emotional Learning Engagement (Pre- & Post- Training Comparisons) – Self-Efficacy and Motivation.

Condition	Metric	Pre-Training Mean (Standard Deviation)	Post-Training Mean (Standard Deviation)
Control	Self-Efficacy[¤]	4.45 (0.54)	4.60 (0.55)
	Motivation[¤¤]	4.25 (0.70)	4.26 (0.65)
Experimental	Self-Efficacy[¤]	4.53 (0.41)	4.49 (0.40)
	Motivation[¤¤]	4.37 (0.66)	4.37 (0.77)

[¤] The self-efficacy scale ranges from 1-Strongly Disagree to Agree 5-Strongly Agree.
[¤¤] The motivation scale ranges from 1-Not at All to 7-Exactly.

engagement data (Self-Efficacy and Motivation) was performed between the control and experimental conditions as shown in Table 11. When comparing emotional engagement between control and experimental conditions, no statistically significant differences were found pre- or post-intervention across control or experimental conditions for self-efficacy and motivation. Ultimately, the Hypothesis 3 (H3) – participants under immersive storytelling condition have different emotional learning engagement effects than those in immersive non-storytelling condition – was rejected.

6. Discussion

The use of immersive safety storytelling is increasingly being explored to support the development of safety knowledge and increase hazard identification skills. This study reveals how the inclusion of storytelling techniques within immersive training systems supports learning. Specifically, engagement as part of learning was evaluated, assessing its behavioral, cognitive, and emotional dimensions (Fredricks & McColskey, 2012; Henrie et al., 2015). Both physiological and psychological mechanisms were explored as part of immersive storytelling and learning engagement in this study. Consistent with the definition of physiological mechanisms by Kim et al. (2021), eye-tracking measurements were used to evaluate the participants' physical responses and biological signals resulting from exposure to a hazard. These eye-tracking metrics were collected during the assessment session portion of the experimental design, supporting the characterization of visual attention behaviors (Hasanzadeh et al., 2017-a). Existing theories for eye movements (i.e., fixations and saccades) indicate that trainees process learning information during visual search patterns that occur as part of hazard identification performance (Xu et al., 2019). Moreover, the definition of psychological mechanisms by Habibnezhad et al. (2016) was used to assess the processes that occur in the participant's mind during decision-making processes for hazard identification. Think-aloud protocols within the immersive learning experiences and paper tests were employed to measure these decision-making processes. Think-aloud protocols provide immediate feedback on cognitive activities occurring in the trainee's mind during the processing and learning of contents (Ogunseiju et al., 2024). The Eye-Mind Hypothesis by Just & Carpenter (1980) connects both physiological and psychological mechanisms, positing that the duration eyes remain fixated on a given stimuli relates to cognitive processing and effort required to understand knowledge which leads to individual's knowledge gains (Wu et al., 2022). The following sections describe how each the implications of each the engagement dimensions as observed in the results for this study.

6.1. *What are the impacts of IS and INS experiences on behavioral learning engagement?*

Findings from the behavioral engagement data analysis (fixation counts and dwell times eye tracking metrics) demonstrated significant statistical differences between the two conditions for the openings fall hazards. Participants in the IS condition had lower fixation counts and lower dwell times when compared to those in the INS condition. The findings in this research highlight that learning about identification of openings fall hazards benefit from IS. Previous literature shows that higher fixation often indicates increased attention with the viewed content (Holmqvist et al., 2011; Underwood et al., 2011). However, the specific learning engagement mechanisms that explain these higher fixations are still somewhat debated, as it can associated to two potential notions: (1) trainees with higher fixations wanted to spend more cognitive resources on this area because it was interesting and useful; or (2) trainees with higher fixations needed additional cognitive resources to understand, decipher, and process information because the content was difficult for them (Shadiev & Li, 2023). On the other hand, consensus is more general regarding dwell, indicating that lower dwell is associated with faster understanding of content and higher hazard identification skills (Hasanzadeh et al., 2017-a). Therefore, the results from Table 8 for dwell proportion might suggest that workers in the experimental condition were able to identify the opening hazards using IS more effectively. However, lower fixation can potentially indicate that either the trainees were not highly engaged with the opening hazards or that they required less cognitive resources to understand them in the IS context. These findings are consistent with Just & Carpenter's (1980) Eye-Mind Hypothesis, as more time spent on given stimuli relates to higher cognitive processing and effort required to understand knowledge. Therefore, it can be inferred that the lack of storytelling in immersive systems required additional attentional efforts to process the information as the fixation and dwell participants is significantly higher for openings. Contrary, ladders, scaffolds, and unprotected edges fall hazards do not show attentional differences across the IS and non-storytelling conditions. These results for IS provide evidence to not reject hypothesis for behavioral learning engagement (H1), indicating that participants under IS condition have different behavioral learning engagement effects than those in INS condition. Further investigation is required to determine the specific properties of ladders, scaffolds, and unprotected edges that prompted this phenomenon to occur within IS.

6.2. *What are the impacts of IS and INS experiences on cognitive learning engagement?*

Findings from the cognitive engagement data analysis (VR-based and Paper-based HII) indicated significant statistical differences between the two conditions. The observed results in the virtual and paper tests indicate that workers using the IS had an increased ability to identify hazards in the openings and scaffolds 360-degree images. These findings align with other studies that point to cognitive learning engagement gains from IS training (Eiris et al., 2020-c). Importantly, it shown that both think-aloud protocols and paper test displayed a congruence of the cognitive activities occurring in the trainee's mind, evidenced by the learning outcomes. Moreover, the results are consistent with Eye-Mind Hypothesis (Just & Carpenter, 1980) as the results for opening fall hazards were found to be higher across the behavioral and cognitive engagement measurements. However, the behavioral and cognitive measures for the scaffold fall hazards were not consistent with this theory, requiring further study to understand this phenomenon. Ultimately, it was found that participants under the IS condition have different cognitive learning engagement effects than those in INS condition and the hypothesis for cognitive learning engagement (H2) is not rejected.

6.3. *What are the impacts of IS and INS experiences on emotional learning engagement?*

The result for emotional learning engagement indicates that the worker perception regarding their personal benefits and usefulness of learning from the safety training is potentially similar across IS and INS conditions. Even though findings from the emotional engagement data analysis (motivation and self-efficacy) revealed no significant differences, moderate to high scores were found across self-efficacy and motivation, indicating that trainees perceived training as important and useful for their personal goals and safety. Additionally, it is important to highlight that emotional learning engagement encompasses more than

Table 11
Emotional Engagement Between Conditions – Self-Efficacy and Motivation.

Comparison		Metric	Significance? (p-value)
Control/Experimental	Pre-Pre	Self-Efficacy	No (0.59 > 0.05)
	Pre-Pre	Motivation	No (0.59 > 0.05)
	Post-Post	Self-Efficacy	No (0.44 > 0.05)
	Post-Post	Motivation	No (0.61 > 0.05)

just self-efficacy and motivation metrics including affective arousal and valence with respect to prior injury exposure (Bhandari & Hallowell, 2017; Hasanzadeh et al., 2017-b). Finally, further study is needed for IS, as other effects might be produced that were not investigated within the scope of this study.

7. Limitations and future study

This research study had four limitations inherent to the research design selections for this investigation as follows: (1) limited number of fall hazard types; (2) residential construction as study context; (3) storytelling narratives are crafted, and not real; and (4) training material are limited to head-mounted display devices. Following is a detailed description of each of these limitations and future venues for research:

- Safety training materials and the hazard recognition tasks in this research project were constrained to only ladders, openings, scaffolds, and unprotected edges. No other type of hazard in the residential sector was explored. While these fall hazards are critical within the residential industry, other fall hazards (Dong et al., 2014; Kang, 2018) and non-fall hazard are present in the residential sector which require study to understand how IS safety training affects learning engagement. Future study of these other types of fall hazards is needed to evaluate how the findings obtained in this study can potentially change.
- The context of safety hazard studied in the research was limited to being within the residential construction industry. While construction literature shows that residential construction fall hazards are prevalent (Dong et al., 2014; Kang, 2018), other industry sector also suffers from these types of hazards. Therefore, the findings of this study might not generalize to all the other construction sectors (e.g., commercial, industrial, heavy civil) as their context for fall hazards might be different. Further study is required to understand how different construction sectors can leverage IS for safety training and what are the effects of learning engagement for the workers of those domains.
- This study crafted narratives based on real-world incident reports found in the OSHA, NIOSH, and CPWR databases. However, due to the crafting process, the stories in this study are an amalgamation of multiple reports that might not fully represent all the details of real-world fall accidents. The use of real-world interviews from workers that suffered a fall accident and survived can potentially produce more realistic stories and represent the intricacies in terms of personal experiences that occur from a fall accident. This study was unable to capture those details and was limited by the story crafting process to portray realistic fall accident narratives. Future studies that interview workers can enhance the process presented in this study to enhance the realism of the story narratives. On the other hand, it is recommended that the storyteller be an expert safety or construction practitioner. This will certainly enhance the trainees' engagement.
- This study was limited to displaying safety training materials using head-mounted displays. The effects of learning engagement in other devices such as smartphones, tables, desktop computer might be different due to the limited immersion afforded by those delivery methods. It is important to highlight that head-mounted displays for safety training approaches requires access to high-end computers and costly devices (e.g., Oculus Quest, HTC Vive) that are not always available for large numbers of residential construction workers (Huang et al., 2019). This limitation greatly reduces the accessibility of the created training materials. Future studies should evaluate how learning engagement is affected over these alternative approaches to democratize access to safety training.

8. Practical implications

Three major practical implications of this study have been identified guide academicians and industry practitioners regarding the utilization of storytelling and 360-degree panoramas in immersive safety training systems:

- **Utilization of Storytelling for Immersive Safety Training Systems:** This study reveals potential storytelling techniques within immersive safety training to support engagement and learning. Academicians and practitioners that wish to implement immersive safety storytelling should carefully consider the nature of the hazards shown within the training. The findings in this research highlight that training applications that include fall hazards such as scaffolding and openings benefit from IS. These types of fall hazards benefit from the storytelling technique because participants under the IS condition displayed higher levels of behavioral and cognitive learning engagement when compared to those in the INS conditions. On the other hand, the exclusion of storytelling should also be considered as a valid option to deliver immersive safety training engagement and learning, as it was found not to be different from the IS method in ladder and elevated surface hazards. The selection of using or not using storytelling is significative for academicians and practitioners due to the significant number of technical and knowledge resources required to create such immersive learning experiences as described in this paper. Although the use of any immersive safety training experiences (including or not storytelling) requires significant creation time commitments and has limited dissemination opportunities due to their HMD nature, new research shows how alternatives ways for these immersive experiences can be easily disseminated by recording 360-degree panoramic videos that can be shared in easily accessible platforms such as Vimeo® and YouTube® (Isingizwe et al., 2023). These new techniques can use immersive contents such as the created in this research to be accessible in any platform independent of the level of immersion afforded by the technologies used by the learners (e.g., desktop computers, mobile phones, HMDs).
- **Designing Data-Driven Story Narratives for Safety Training:** This research illustrates how a data-driven approach can be employed to create safety training story narratives. Data sources such as OSHA, NIOSH, and CPWR can be analyzed to extract narrative components of the most recent fatality reports to develop realistic safety stories. While the focus of this study centered on the most common causes of fall hazards fatalities, this same process can be leveraged by academicians and practitioners in construction and other domains with similar databases to create any type of safety story. The story narrative development process as described in this paper has the potential to be streamlined and simplified by employing new generative artificial intelligence large language models (e.g., OpenAI ChatGPT®, Meta Llama®), which can significantly accelerate the conceptualization, storyboarding, and creation of these stories. While the "hero's journey" was the focus of this paper, any other type of narrative structure such as the "drama triangle'', "three-act-structure", and the "fabulator" (Karpman, 1968; Barros & Musse, 2005; Campbell, 2008) can utilize the same data-driven approaches. Ultimately, the data collection parameters and frameworks used in this paper can inform and guide safety academicians and practitioners who wish to develop engaging story narratives that are based on real-life narratives to produce effective storytelling safety training.
- **Capturing Real-World Residential Hazards for Immersive Safety Training:** This study showcases a viable methodology for capturing residential construction safety hazard situations using 360-degree panorama technologies. It is important to highlight that the site selection and the image capturing processes need to be driven by the learning goals of the training system. For this study, residential fall

hazards were the main knowledge objective to obtain images, but similar 360-degree capturing methodologies can leveraged for any type of hazard across safety domains. While other reality capturing methods exist such as laser scanning and photogrammetry, the 360-degree panorama approach as illustrated in this study is recommend to academicians and practitioners due to its ease of collection and implementation. Lastly, as quality of the 360-degree panorama cameras increases and the equipment price decreases, this technique is becoming prevalent in the safety domains as a method to easily display hazard information in virtual environments.

9. Conclusions

This study evaluated the use of immersive storytelling (IS) to enhance learning engagement within a case study of fall hazard training in the context of residential construction. Two safety training conditions were employed for this evaluation using a between-subject experiment – (1) immersive storytelling (IS); and (2) immersive non-storytelling (INS). A total of 42 residential construction workers experienced one of these two conditions. Residential workers were assessed across three learning engagement dimensions – behavioral, cognitive, and emotional. Metrics were collected pre-, during, and post-experiment using surveys and eye-tracking data. Descriptive and statistical differences were evaluated from the data across the experimental conditions. Trainees behavioral learning engagement showed significantly lower fixations and time spent on the openings hazard when using IS. These results suggest that trainees using the IS were able to identify opening fall hazards more effectively. In terms of trainees cognitive learning engagement, it was found that the HII virtual test scores were significantly different for the scaffolds fall hazard categories, with higher scores in the experimental condition compared to the HII scores of the control condition. No other significant differences were identified for other types of hazards for the HIII virtual test. Moreover, it was found that the HII paper test scores were significantly different for the openings and the scaffolds categories of fall hazards. Moreover, trainees overall cognitive learning engagement (measured through virtual and paper hazard identification tests) was higher overall for IS. However, trainees emotional learning engagement in terms of self-efficacy and motivation did not change across conditions. It was concluded that IS supported learning engagement and hazard identification knowledge gained with respect to INS experiences. Particularly, IS was found to be significantly more beneficial in knowledge acquisition of certain types of fall hazards including openings and scaffolds for the residential construction sector.

CRediT authorship contribution statement

Josiane Isingizwe: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ricardo Eiris:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ahmed Jalil Al-Bayati:** Writing – review & editing, Visualization, Validation, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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.

Acknowledgments

This publication was made possible by CPWR – The Center for Construction Research and Training—through cooperative agreement number U60 OH009762 (CFDA #93.262) from the National Institute of Occupational Safety and Health (NIOSH). Its contents are solely the authors' responsibility and do not represent the official views of the CPWR or NIOSH. The research team expresses its sincere gratitude to Howard Hipes, the Director of Apprenticeship & Training at the Michigan Bricklayers & Allied Craftworkers (BAC) Union Training Centers for helping in the study experimental data gathering. Lastly, the research team expresses its sincere gratitude to the four residential safety experts that participated in the focus group to validate the safety learning contents in this study.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ssci.2024.106631.

References

Al-Bayati, A.J., 2021. Impact of construction safety culture and construction safety climate on safety behavior and safety motivation. Safety 7, 41. https://doi.org/10.3390/safety7020041.
Al-Bayati, A. J., Alghamdi, A., and Abydayyeh, O. (2023b) "Improving the Safety Culture and Climate of Smaller Construction Firms: A Necessary Addition to the OSH Intervention Model." Journal of Civil Engineering and Construction, 12(4). Doi: 10.32732/jcec.2023.12.4.187.
Al-Bayati, A.J., York, D., 2018. Fatal injuries among Hispanic workers in the US construction industry: Findings from FACE investigation reports. J. Saf. Res. Elsevier. https://doi.org/10.1016/j.jsr.2018.09.007.
Al-Bayati, A.J., Bilal, G.A., Esmaeili, B., Karakhan, A., York, D., 2021. Evaluating OSHA's fatality and catastrophe investigation summaries: Arc flash focus. Saf. Sci. Elsevier 140 (105287). https://doi.org/10.1016/j.ssci.2021.105287.
Al-Bayati, A.J., Rener, A.T., Listello, M.P., Mohamed, M., 2023a. PPE non-compliance among construction workers: An assessment of contributing factors utilizing fuzzy theory. J. Saf. Res. Elsevier. https://doi.org/10.1016/j.jsr.2023.02.008.
Albeaino, G., Eiris, R., Gheisari, M., & Issa, R. R. (2021). Development of a VR-based drone-mediated building inspection training environment. In Computing in Civil Engineering 2021 (pp. 1401-1408).
Albert, A., Pandit, B., Patil, Y., 2020. Focus on the fatal-four: Implications for construction hazard recognition. Saf. Sci. 128, 104774.
Al-Khiami, M.I., Jaeger, M., 2023. Safer working at heights: exploring the usability of virtual reality for construction safety training among blue-collar workers in Kuwait. Safety 9 (3), 63.
Arif, M., Nasir, A.R., Thaheem, M.J., Khan, K.I.A., 2021. ConSafe4All: A framework for language friendly safety training modules. Saf. Sci. 141, 105329.
Azhar, S., Han, D., Dastider, S.G., 2020. Immersive VR modules for construction safety education of generation Z students. EPiC Ser. Built Environ. 1, 482–490.
Babalola, A., Manu, P., Cheung, C., Yunusa-Kaltungo, A., Bartolo, P., 2023. A systematic review of the application of immersive technologies for safety and health management in the construction sector. J. Saf. Res. 85, 66–85.
Barros, L. M., & Musse, S. R. (2005, June). Introducing narrative principles into planning-based interactive storytelling. In Proceedings of the 2005 ACM SIGCHI International Conference on Advances in computer entertainment technology (pp. 35-42).
Bhandari, S., Hallowell, M.R., 2017. Emotional engagement in safety training: impact of naturalistic injury simulations on the emotional state of construction workers. J. Constr. Eng. Manag. 143 (12), 04017090.
Bhoir, S. A., Hasanzadeh, S., Esmaeili, B., Dodd, M. D., & Fardhosseini, M. S. (2015). Measuring construction workers attention using eye-tracking technology.
Bliss, M.M., Dalto, J., 2018. Storytelling in safety training. Prof. Saf. 63 (10), 34–35.
Brown, S., Brooks, R. D., & Dong, X. S. (2020). New Trends of fatal falls in the construction industry. CPWR Data Bulletin, Sept 2020. Retrieved from https://stacks.cdc.gov/view/cdc/107027 (Last accessed on April 20th, 2024).
Burke, M.J., Sarpy, S.A., Smith-Crowe, K., Chan-Serafin, S., Salvador, R.O., Islam, G., 2006. Relative effectiveness of worker safety and health training methods. Am. J. Public Health 96 (2), 315–324.
Caban-Martinez, A.J., Santiago, K.M., Stillman, J., Moore, K.J., Sierra, D., Chalmers, J., Baniak, M., Jordan, M.M., 2018. Physical exposures, work tasks and OSHA-10 training among temporary and payroll construction workers. J. Occup. Environ. Med. 60 (4), e159–e165.
Campbell, J. (2008). *The hero with a thousand faces* (Vol. 17). New World Library.
Carter, G., Smith, S.D., 2006. Safety hazard identification on construction projects. J. Constr. Eng. Manag. 132 (2), 197–205.
Chen, G., Gully, S.M., Eden, D., 2001. Validation of a new general self-efficacy scale. Organ. Res. Methods 4 (1), 62–83.

Chittaro, L., Sioni, R., Crescentini, C., Fabbro, F., 2017. Mortality salience in virtual reality experiences and its effects on users' attitudes towards risk. Int. J. Hum Comput Stud. 101, 10–22.
Conchie, S.M., 2013. Transformational leadership, intrinsic motivation, and trust: A moderated-mediated model of workplace safety. J. Occup. Health Psychol. 18 (2), 198.
D'Agostino, R. B. (2017). Tests for the normal distribution. In Goodness-of-fit-techniques (pp. 367-420). Routledge.
Delmas, G., Champagnat, R., & Augeraud, M. (2007). Bringing interactivity into Campbell's hero's journey. In Virtual Storytelling. Using Virtual Reality Technologies for Storytelling: 4th International Conference, ICVS 2007, Saint-Malo, France, December 5-7, 2007. Proceedings 4 (pp. 187-195). Springer Berlin Heidelberg.
Demirkesen, S., Arditi, D., 2015. Construction safety personnel' s perceptions of safety training practices. Int. J. Project Manage. 33 (5), 1160–1169.
Dhalmahapatra, K., Maiti, J., Krishna, O.B., 2021. Assessment of virtual reality-based safety training simulator for electric overhead crane operations. Saf. Sci. 139, 105241.
Din, Z.U., Gibson Jr, G.E., 2019. Serious games for learning prevention through design concepts: An experimental study. Saf. Sci. 115, 176–187.
D'Mello, S., Dieterle, E., Duckworth, A., 2017. Advanced, analytic, automated (AAA) measurement of engagement during learning. Educ. Psychol. 52 (2), 104–123.
Dong, X.S., Wang, X., Largay, J.A., Platner, J.W., Stafford, E., Cain, C.T., Choi, S.D., 2014. Fatal falls in the U.S. residential construction industry. Am. J. Ind. Med. 57 (9), 992–1000.
Douglas-Lenders, R.C., Holland, P.J., Allen, B., 2017. Building a better workforce: A case study in management simulations and experiential learning in the construction industry. Education+ Training 59 (1), 2–14.
Ehmke, C., & Wilson, S. (2007). Identifying web usability problems from eyetracking data.
Eiris, R., & Gheisari, M. (2023). Applying 360-degree virtual reality for construction safety training. Handbook of Construction Safety, Health and Well-being in the Industry 4.0 Era.
Eiris, R., Gheisari, M., & Esmaeili, B. (2020-a). Desktop-based safety training using 360-degree panorama and static virtual reality techniques: A comparative experimental study. Automation in Construction, 109, 102969.
Eiris, R., Jain, A., Gheisari, M., & Wehle, A. (2020-b). Safety immersive storytelling using narrated 360-degree panoramas: a fall hazard training within the electrical trade context. Safety science, 127, 104703.
Eiris, R., John, B., Gheisari, M., Jain, E., Wehle, A., & Memarian, B. (2020-c). Hazard-recognition training using omnidirectional cinemagraphs: Comparison between virtual reality and lecture-based techniques. In Construction Research Congress 2020 (pp. 1117-1126). Reston, VA: American Society of Civil Engineers.
Eiris, R., Gheisari, M., 2017. Research trends of virtual human applications in architecture, engineering and construction. J. Inform. Technol. Constr. (ITcon) 22 (9), 168–184.
Eiris, R., Gheisari, M., Esmaeili, B., 2018. PARS: Using augmented 360-degree panoramas of reality for construction safety training. Int. J. Environ. Res. Public Health 15 (11), 2452.
Eiris, R., Wen, J., Gheisari, M., 2021. iVisit–Practicing problem-solving in 360-degree panoramic site visits led by virtual humans. Autom. Constr. 128, 103754.
Evanoff, B., Dale, A.M., Zeringue, A., Fuchs, M., Gaal, J., Lipscomb, H.J., Kaskutas, V., 2016. Results of a fall prevention educational intervention for residential construction. Saf. Sci. 89, 301–307.
Fredricks, J.A., McColskey, W., 2012. The measurement of student engagement: A comparative analysis of various methods and student self-report instruments. Handbk. Res. Student Engagement 763–782.
Garcia, P. (2018). "OSHA-30 Lab Topics Course on Construction Safety and Hazard Identification." Construction Management.
Guay, F., Vallerand, R.J., Blanchard, C., 2000. On the assessment of situational intrinsic and extrinsic motivation: The Situational Motivation Scale (SIMS). Motiv. Emot. 24 (3), 175–213.
Guo, H., Li, H., Chan, G., Skitmore, M., 2012. Using game technologies to improve the safety of construction plant operations. Accid. Anal. Prev. 48, 204–213.
Habibnezhad, M., Fardhosseini, S., Vahed, A. M., Esmaeili, B., & Dodd, M. D. (2016, January). The relationship between construction workers' risk perception and eye movement in hazard identification. In Construction research congress 2016 (pp. 2984-2994).
Halverson, L.R., Graham, C.R., 2019. Learner engagement in blended learning environments: A conceptual framework. Online Learning 23 (2), 145–178.
Harris, W., Yohannes, T., & Trueblood, A.B (2023). Fatal and Nonfatal Focus Four Injuries in Construction. Data Bulleting, March 2023, The Center for Construction Research and Training. Retrieved from: https://www.cpwr.com/wp-content/uploads/DataBulletin-March2023.pdf (Last Accessed on September 18th, 2023).
Hasanzadeh, S., Esmaeili, B., Dodd, M.D., 2018. Examining the relationship between construction workers' visual attention and situation awareness under fall and tripping hazard conditions: Using mobile eye tracking. J. Constr. Eng. Manag. 144 (7), 04018060.
Hasanzadeh, S., Esmaeili, B., & Dodd, M. D. (2017-a). Impact of construction workers' hazard identification skills on their visual attention. Journal of construction engineering and management, 143(10), 04017070.
Hasanzadeh, S., Esmaeili, B., & Dodd, M. D. (2017-b). Measuring the impacts of safety knowledge on construction workers' attentional allocation and hazard detection using remote eye-tracking technology. Journal of management in engineering, 33 (5), 04017024.
Henrie, C.R., Halverson, L.R., Graham, C.R., 2015. Measuring student engagement in technology-mediated learning: A review. Comput. Educ. 90, 36–53.
Holmqvist, K., Nyström, M., Andersson, R., Dewhurst, R., Jarodzka, H., & Van de Weijer, J. (2011). Eye tracking: A comprehensive guide to methods and measures. OUP Oxford.
Hu, K., Rahmandad, H., Smith, T., Winchester, W., 2011. Factors influencing the risk of falls in the construction industry: A review of the evidence. Constr. Manage. Econ. 29 (4).
Huang, Y., Shakya, S., Odeleye, T., 2019. Comparing the functionality between virtual reality and mixed reality for architecture and construction uses. J. Civ. Eng. Archit. 13 (1), 409–414.
Hung, Y.H., Winchester III, W.W., Smith-Jackson, T.L., Kleiner, B.M., Babski-Reeves, K. L., Mills III, T.H., 2013. Identifying fall-protection training needs for residential roofing subcontractors. Appl. Ergon. 44 (3), 372–380.
Hussain, R., Sabir, A., Lee, D.Y., Zaidi, S.F.A., Pedro, A., Abbas, M.S., Park, C., 2024. Conversational AI-based VR system to improve construction safety training of migrant workers. Autom. Constr. 160, 105315.
Isingizwe, J., Eiris, R., & Al-Bayati, A. (2023). Safety Immersive Storytelling Videos Using Virtual Humans and 360-Degree Panoramas: A Pilot Study of Fall Hazard Training with Residential Construction Professionals. In Computing in Civil Engineering 2023 (pp. 366-374).
Isingizwe, J., Eiris, R., & Jalil Al-Bayati, A. (2024-a) Immersive Storytelling Safety Training to Enhance Trainee Engagement: Pilot Study for Fall Hazards in the Residential Construction Sector. In Construction Research Congress 2024 (pp. 455-465).
Isingizwe, J., Eiris, R., & Gheisari, M. (2024-b). Exploring Intersectionality of Gender and Race: Immersive Storytelling Videos and Perceived Expertise among Diverse Construction Professionals. In Construction Research Congress 2024 (pp. 70-79).
Janicak, C.A., 1998. Fall-related deaths in the construction industry. J. Saf. Res. 29, 35–42.
Jantakoon, T., Wannapiroon, P., Nilsook, P., 2019. Virtual immersive learning environments (VILEs) based on digital storytelling to enhance deeper learning for undergraduate students. High. Educ. Stud. 9 (1), 144–150.
Jeelani, I., Han, K., & Albert, A. (2017-a). Development of immersive personalized training environment for construction workers. In *Computing in civil engineering 2017* (pp. 407-415).
Jeelani, I., Albert, A., & Gambatese, J. A. (2017-b). Why do construction hazards remain unrecognized at the work interface? Journal of construction engineering and management, 143(5), 04016128.
Johnson, H.M., Singh, A., Young, R.H.F., 1998. Fall protection analysis for workers on residential roofs. J. Constr. Eng. Manag. 124 (5), 418–428.
Just, M.A., Carpenter, P.A., 1980. A theory of reading: from eye fixations to comprehension. Psychol. Rev. 87 (4), 329.
Kang, Y., 2018. Use of fall protection in the U.S. construction industry. J. Manage. Eng. 27 (4), 04021036.
Karpman, S., 1968. Fairy tales and script drama analysis. Trans. Anal. Bull. 7 (26), 39–43.
Kaskutas, V., Dale, A.M., Lipscomb, H., Evanoff, B., 2013. Fall prevention and safety communication training for foremen: Report of a pilot project designed to improve residential construction safety. J. Saf. Res. 44, 111–118.
Kim, N., Kim, J., Ahn, C.R., 2021. Predicting workers' inattentiveness to struck-by hazards by monitoring biosignals during a construction task: A virtual reality experiment. Adv. Eng. Inf. 49, 101359.
Kruskal, W.H., Wallis, W.A., 1952. Use of ranks in one-criterion variance analysis. J. Am. Stat. Assoc. 47 (260), 583–621.
Le, Q. T., Pedro, A. K. E. E. M., Lim, C. R., Park, H. T., Park, C. S., & Kim, H. K. (2015-a). A framework for using mobile based virtual reality and augmented reality for experiential construction safety education. International Journal of Eng. Education, 31(3), 713-725.
Le, Q. T., Pedro, A., & Park, C. S. (2015-b). A social virtual reality-based construction safety education system for experiential learning. *Journal of Intelligent & Robotic Systems*, *79*, 487-506.
Lee, K., Hasanzadeh, S., & Esmaeili, B. (2022-a). Assessing Hazard Anticipation in Dynamic Construction Environments Using Multimodal 360-Degree Panorama Videos. Journal of Management in Engineering, 38(5), 04022039.
Lee, K., Shinde, Y., Hasanzadeh, S., & Esmaeili, B. (2022-b). Toward Personalized Safety Training: Automating the Classification of Construction Workers' Cognitive Failures. In ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction; Waterloo (Vol. 39).
Lee, K., Hasanzadeh, S., & Esmaeili, B. (2022-c). Spatial Exposure to Dynamic Safety Hazards in Construction Sites through 360-Degree Augmented Panoramas: Ecological Validity in Safety Research. In Construction Research Congress 2022 (pp. 715-725).
Lester, D. (2013). A review of the student engagement literature. Focus on colleges, universities & schools, 7(1).
Li, W., Qian, L., Feng, Q., Luo, H., 2023. Panoramic video in education: A systematic literature review from 2011 to 2021. J. Comput. Assist. Learn. 39 (1), 1–19.
Li, X., Yi, W., Chi, H.L., Wang, X., Chan, A.P., 2018. A critical review of virtual and augmented reality (VR/AR) applications in construction safety. Autom. Constr. 86, 150–162.
Liko, G., Esmaeili, B., Hasanzadeh, S., Dodd, M. D., & Brock, R. (2020, March). Working-memory load as a factor determining the safety performance of construction workers. In Construction Research Congress 2020 (pp. 499-508). Reston, VA: American Society of Civil Engineers.

Liu, R., Xu, X., Yang, H., Li, Z., Huang, G., 2022. Impacts of cues on learning and attention in immersive 360-degree video: An eye-tracking study. Front. Psychol. 12, 792069.

Loup-Escande, E., Frenoy, R., Poplimont, G., Thouvenin, I., Gapenne, O., Megalakaki, O., 2017. Contributions of mixed reality in a calligraphy learning task: Effects of supplementary visual feedback and expertise on cognitive load, user experience and gestural performance. Comput. Hum. Behav. 75, 42–49.

Man, S.S., Chan, A.H., Wong, H.M., 2017. Risk-taking behaviors of Hong Kong construction workers–A thematic study. Saf. Sci. 98, 25–36.

Man, S.S., Wen, H., So, B.C.L., 2023. Are virtual reality applications effective for construction safety training and education? A systematic review and meta-analysis. J. Saf. Res.

McDowell, K., 2021. Storytelling wisdom: Story, information, and DIKW. J. Assoc. Inf. Sci. Technol. 72 (10), 1223–1233.

Moore, H. F., Eiris, R., Gheisari, M., & Esmaeili, B. (2019, June). Hazard identification training using 360-degree panorama vs. virtual reality techniques: A pilot study. In *ASCE International Conference on Computing in Civil Engineering 2019* (pp. 55-62). Reston, VA: American Society of Civil Engineers.

Nadhim, E.A., Hon, C., Xia, B., Stewart, I., Fang, D., 2016. Falls from height in the construction industry: A critical review of scientific literature. Int. J. Environ. Res. Public Health 13 (7), 638.

Namian, M., Albert, A., Zuluaga, C.M., Behm, M., 2016. Role of safety training: Impact on hazard recognition and safety risk perception. J. Constr. Eng. Manag. 142 (12), 04016073.

Namian, M., Tafazzoli, M., Kermanshachi, S., & Huang, Y. (2022). Do OSHA 10/30-hours training programs revamp the safety attitudes of construction workers? In *Construction Research Congress 2022* (pp. 679-687).

Nwobi, F.N., Akanno, F.C., 2021. Power comparison of ANOVA and Kruskal-Wallis tests when error assumptions are violated. Metodoloski Zvezki 18 (2), 53–71.

Ogunseiju, O., Gonsalves, N. J., Akanmu, A. A., & Bairaktarova, D. (2024). Towards Personalized Mixed Reality-Based Learning Experience in Construction Education. In Digitalization in Construction (pp. 20-38). Routledge.

Olson, R., Varga, A., Cannon, A., Jones, J., Gilbert-Jones, I., Zoller, E., 2016. Toolbox talks to prevent construction fatalities: Empirical development and evaluation. Saf. Sci. 86, 122–131.

Peters, E.M., Burraston, B., Mertz, C.K., 2004. An emotion-based model of risk perception and stigma susceptibility: Cognitive appraisals of emotion, affective reactivity, worldviews, and risk perceptions in the generation of technological stigma. Risk Anal.: Int. J. 24 (5), 1349–1367.

Pham, H.C., Dao, N., Pedro, A., Le, Q.T., Hussain, R., Cho, S., Park, C.S.I.K., 2018. Virtual field trip for mobile construction safety education using 360-degree panoramic virtual reality. Int. J. Eng. Educ. 34 (4), 1174–1191.

Razali, N.M., Wah, Y.B., 2011. Power comparisons of shapiro-wilk, kolmogorov-smirnov, lilliefors and anderson-darling tests. J. Stat. Model. Analyt. 2 (1), 21–33.

Rokooei, S., Shojaei, A., Alvanchi, A., Azad, R., Didehvar, N., 2023. Virtual reality application for construction safety training. Saf. Sci. 157, 105925.

Sacks, R., Perlman, A., Barak, R., 2013. Construction safety training using immersive virtual reality. Constr. Manag. Econ. 31 (9), 1005–1017.

Saculinggan, M., & Balase, E. A. (2013, April). Empirical power comparison of goodness of fit tests for normality in the presence of outliers. In Journal of Physics: Conference Series (Vol. 435, No. 1, p. 012041). IOP Publishing.

Salvucci, D. D., & Goldberg, J. H. (2000, November). Identifying fixations and saccades in eye-tracking protocols. In Proceedings of the 2000 symposium on Eye tracking research & applications (pp. 71-78).

Seo, H.J., Park, G.M., Son, M., Hong, A.J., 2021. Establishment of virtual-reality-based safety education and training system for safety engagement. Educ. Sci. 11 (12), 786.

Shadiev, R., Li, D., 2023. A review study on eye-tracking technology usage in immersive virtual reality learning environments. Comput. Educ. 196, 104681.

Shinde, Y., Lee, K., Kiper, B., Hasanzadeh, S., 2023. A systematic literature review on 360° panoramic applications in architecture, engineering, and construction (AEC) industry. J. Inform. Technol. Constr. (ITcon) 28 (21), 405–437.

Skinner, E.A., Kindermann, T.A., Connell, J.P., Wellborn, J.G., 2009. Engagement and disaffection as organizational constructs in the dynamics of motivational development. Handbk. Motivation School 223, 245.

Slater, M., 2003. A note on presence terminology. Presence Connect 3 (3), 1–5.

Slovic, P., Finucane, M. L., Peters, E., & MacGregor, D. G. (2013). Risk as analysis and risk as feelings: Some thoughts about affect, reason, risk and rationality. In *The feeling of risk* (pp. 21-36). Routledge.

Suh, A., Prophet, J., 2018. The state of immersive technology research: A literature analysis. Comput. Hum. Behav. 86, 77–90.

Szabó, B. K., & Gilányi, A. (2020, September). The notion of immersion in virtual reality literature and related sources. In 2020 11th IEEE International Conference on Cognitive Infocommunications (CogInfoCom) (pp. 000371-000378). IEEE.

Taheri, S.M., Hesamian, G., 2013. A generalization of the Wilcoxon signed-rank test and its applications. Stat. Pap. 54, 457–470.

Underwood, G., Crundall, D., Chapman, P., 2011. Driving simulator validation with hazard perception. Transport. Res. F: Traffic Psychol. Behav. 14 (6), 435–446.

van Doorn, J., Ly, A., Marsman, M., Wagenmakers, E.J., 2020. Bayesian rank-based hypothesis testing for the rank sum test, the signed rank test, and Spearman's ρ. J. Appl. Stat. 47 (16), 2984–3006.

Wang, P., Wu, P., Wang, J., Chi, H.L., Wang, X., 2018. A critical review of the use of virtual reality in construction engineering education and training. Int. J. Environ. Res. Public Health 15 (6), 1204.

Wei, Y., Wang, J., Yang, H., Wang, X., & Cheng, J. (2019, July). An Investigation of Academic Self-Efficacy, Intrinsic Motivation and Connected Classroom Climate on College Students' Engagement in Blended Learning. In 2019 International Symposium on Educational Technology (ISET) (pp. 160-164). IEEE.

Wilkins, J.R., 2011. Construction workers' perceptions of health and safety training programmes. Constr. Manag. Econ. 29 (10), 1017–1026.

Wong, T.K.M., Man, S.S., Chan, A.H.S., 2020. Critical factors for the use or non-use of personal protective equipment amongst construction workers. Saf. Sci. 126, 104663.

Wu, C.J., Liu, C.Y., 2022. Refined use of the eye-mind hypothesis for scientific argumentation using multiple representations. Instr. Sci. 50 (4), 551–569.

Xu, Q., Chong, H.Y., Liao, P.C., 2019. Exploring eye-tracking searching strategies for construction hazard recognition in a laboratory scene. Saf. Sci. 120, 824–832.

Yap, B.W., Sim, C.H., 2011. Comparisons of various types of normality tests. J. Stat. Comput. Simul. 81 (12), 2141–2155.

Yu, W.D., Wang, K.C., Wu, H.T., 2022. Empirical comparison of learning effectiveness of immersive virtual reality-based safety training for novice and experienced construction workers. J. Constr. Eng. Manag. 148 (9), 04022078.

Zhang, M., Shu, L., Luo, X., Yuan, M., Zheng, X., 2022. Virtual reality technology in construction safety training: Extended technology acceptance model. Autom. Constr. 135, 104113.

Zuluaga, C. M., Namian, M., & Albert, A. (2016). Impact of training methods on hazard recognition and risk perception in construction. In Construction Research Congress 2016 (pp. 2861-2871).