A SYSTEMATIC LITERATURE REVIEW ON 360° PANORAMIC APPLICATIONS IN ARCHITECTURE, ENGINEERING, AND CONSTRUCTION (AEC) INDUSTRY

SUBMITTED: January 2023
REVISED: August 2023
PUBLISHED: August 2023
EDITOR: Bimal Kumar
DOI: 10.36680/j.itcon.2023.021

Yugandhar Shinde, M.S. Student,
Lyles School of Civil Engineering, Purdue University
yshinde@purdue.edu

Kyeongsuk Lee, PhD Student,
Lyles School of Civil Engineering, Purdue University
lee2490@purdue.edu

Beyza Kiper, PhD Student,
Tandon School of Engineering, New York University
bkiper@nyu.edu

Makayla Simpson, Undergraduate research assistant,
Division of Construction Engineering and Management, Purdue University
simpso80@purdue.edu

Sogand Hasanzadeh, Assistant Professor (Corresponding author),
Lyles School of Civil Engineering, Purdue University
sogandm@purdue.edu

SUMMARY: *While the advancement of visualization technologies—virtual-reality, augmented-reality, mixed-reality, and extended reality—has long produced opportunities to create more realistic simulated environments to provoke and study natural human behavior, recent interest in applying 360° panoramic visualizations has been increasing across several disciplines due to these technologies' lower costs, higher presence, and greater immersive-ness. However, the variety of applications of 360° panoramas (both images and videos) is limited in the architecture, engineering, and construction (AEC) domain compared to other domains. This paper systematically presents an in-depth understanding of 360° panorama research trends and reveals the challenges and opportunities for future research in the AEC area. In particular, this systematic review analyzed eighty studies across two decades (2000-2022) to consider 360° panoramas' application areas, methodologies, potential benefits, challenges, best practices, and future research directions for both AEC and non-AEC domains. Several prevalent application domains in AEC—namely architectural studies, construction education and training, construction visualization and progress monitoring, and cognitive analysis and human behavior in the construction industry—were identified. This paper indicates that 360° panoramas provide a higher sense of presence than conventional simulation methods (e.g., virtual reality). Moreover, pairing 360° panorama technologies with a head-mounted display significantly increases immersion when compared with other display options. Lastly, limitations of 360° panoramas, such as cybersickness and technical properties, are discussed. This paper is expected to shed light on the potential of these state-of-the-art technologies in the AEC domain, which can serve both academia and industry.*

KEYWORDS: *Settings, 360° Panoramic visualizations, Systematic review, Construction industry, Sense of presence, Omnidirectional photography*

REFERENCE: *Yugandhar Shinde, Kyeongsuk Lee, Beyza Kiper, Makayla Simpson, Sogand Hasanzadeh (2023). A Systematic Literature Review on 360° Panoramic Applications in Architecture, Engineering, and Construction (AEC) Industry. Journal of Information Technology in Construction (ITcon), Vol. 28, pg. 405-437, DOI: 10.36680/j.itcon.2023.021*

1. INTRODUCTION

Over the past decades, visualizations have helped scientists and researchers across many fields produce and explore different scenarios in multisensory three-dimensional (3D) environments to immerse and study users. The benefits of these visualizations lie in their ability of providing realistic visuals to increase in fidelity, users' involvement, and reducing the gap between virtual environments and reality (Jung and Lindeman 2021), which combine to raise a breadth of opportunities for simulating situations that are often either dangerous or too expensive to conduct in the real world (Getuli et al. 2020; Pooladvand et al. 2021). Among these visual simulation methods, Virtual Reality (VR) involves a high human-computer interface with computer-generated graphics; its essential characteristics entail immersion, interactivity, and visualization (Wang 2012). Alternatively, Augmented Reality (AR) superimposes computer-generated information on top of content to enhance user understanding (e.g., digital reverse car parking system) (Furht 2006). Mixed Reality (MR) is a live direct or indirect view of a physical and real-world environment whose elements are augmented by computer-generated sensory input (Salhi et al. 2019). Extended Reality (XR), an emerging umbrella term for multiple simulation methodologies, combines two or more reality technologies generated via a computer to enrich simulation experiences (Çöltekin et al. 2020; Gong et al. 2021). Lastly, 360° simulation technologies—or 360° panoramas—have been gaining popularity among researchers for their ability to deliver a higher sense of presence than any other simulation tool, allowing for greater immersion and visualization. Since a sense of "presence" can be defined as a psychological condition of experiencing a simulated environment as if consciously be present within it (Aitamurto et al. 2018; Herbelin et al. 2003), this dimension of users' realistic engagement provides a powerful opportunity for researchers seeking to understand true-to-life outcomes within a simulated space.

An immersive panoramic environment consists of 360° videos or images captured in the real world. Thus, this omnidirectional capturing method allows for an unbroken view of an environment (Bourke 2014) akin to humans' visual experience. The 360° images/videos are often captured from a fixed point and presented in a spherical way to display all details of the environment. Previous studies indicated that users can have an authentic, real-world experience via adopting 360° videos for such purposes as therapy, visualization, safety training, and education. For example, Reeves et al. (2021) used 360° videos to provide a realistic audience environment for reducing public speaking anxiety. Similarly, Eiris et al. (2020c), Chien Pham et al. (2018), and Mander et al. (2022) used 360° panoramas to achieve a high-quality simulation experience for virtual student field trips to construction sites. Such studies highlight opportunities for applying these visualization technologies across various domains and industries, though to-date, no comprehensive review paper covers the applications, advantages, limitations, and best practices of harnessing these technologies in Architecture, Engineering, and Construction (AEC) and related areas.

The successful delivery of high-quality visuals in each visualization technology is contingent upon the utilization of diverse tools including both hardware and software components, with their effective synchronization playing a pivotal role in achieving desired outcomes (Pooladvand et al. 2021). The tools employed in this context can be classified into two distinct categories based on their respective applications: development and presentation. The development of visualization environment (VE) encompasses a series of intricate stages involving the design of VEs, augmentation, animation, and other related processes, necessitating substantial computational power for efficient processing and rendering of visual elements. Likewise, an array of presentation devices is capable to showcase these VEs, exhibiting variations in characteristics such as display dimension (e.g., 2D options such as monitors and TVs, 3D alternatives like Head Mounted Displays and Cave Automated Virtual Environments), and posture options (e.g., handheld devices such as mobile phones and tablets, mounted devices like standalone headsets and VR glasses). Although the specifications of required component may vary among visualization technology (e.g., 360° - High resolution camera, VR – Powerful graphic memory), the capability and quality of these component affects the quality of virtual environment (Kavanagh et al. 2016; Eiris et al. 2020b). Multiple studies have thoroughly investigated the impact of each medium on participants' perception and their behavior in VE using subjective and objective methods (Ha et al. 2019; Martínez-Navarro et al. 2019; Nason et al. 2020). A detailed review of these studies will assist to comprehend the influence of these tools on participants' reaction to VE, and aid future studies to determine the effective combination of tools based on their research-needs.

The objective of this paper is to systematically obtain an in-depth understanding of 360° panorama visualization research trends as well as reveal these technologies' challenges and opportunities for future research in the AEC area. This literature review paper particularly answers the following questions: *(1) What are the current applications of 360° panoramas within AEC and other fields or industries? (2) Which advantages and limitations* *does the literature list regarding using 360° panoramas? (3) Which research methodologies were used in 360°-related papers? (4) What are the advantages of using a 360° panorama over a virtual reality environment? (5) What are the gaps in 360° technology-related research in AEC that need further investigations?*

This review provides a summary of important applications, advantages, and challenges affecting 360° technologies in the AEC industry and presents opportunities for improving the quality and usage of the 360° simulation method for different purposes. As application areas become more prominent, the construction industry and other sectors will benefit from the findings of this literature review paper.

2. RESEARCH METHODOLOGY

This paper followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method – Figure 1. During the primary exploration, the research team identified publication sources within AEC as well as other industries. This search examined ELSEVIER's *Automation in Construction*; *IEEE Transactions on Image Processing*; Emerald's *Engineering, Construction, Architectural Management*; ELSEVIER's *Safety Science*; and ASCE's *Journal of Computing in Civil Engineering*. Publications from other domains were also searched to understand different concepts and applications of 360° simulation. For a more detailed search, article search engines (e.g., Scopus and Google Scholar) were used with varying combinations of keywords to collect all relevant papers. The queries involved: "360° video," "360° image," "360° panorama," AND "construction," "360° virtual reality," "360° augmented reality," "360° mixed reality," "Panorama," "360-degree," "Panoramic reality," and "Spherical image." Interestingly, in the pool of collected literature, many studies used the same technologies yet named them differently. For example, most of the studies used the word "360-degree" or the symbol "360°" but followed the terms with "video" (Aitamurto et al. 2018; Mouratidis and Hassan 2020; Reeves et al. 2021; Wehking et al. 2019), "panoramas" (Eiris et al. 2020b; Lee et al. 2022b; Shih et al. 2001) or "immersive" (Argyriou et al., 2020; Felli et al., 2018; Shojaei et al., 2020). For the sake of this paper's review, we treated such phrasing as synonymous.

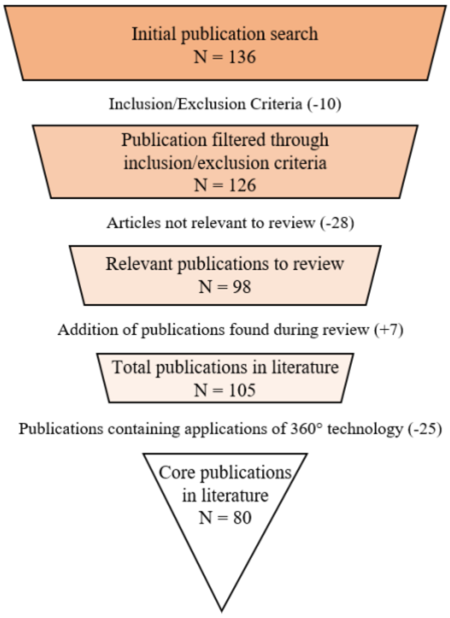

Figure 1. *Screening process for this systematic review*

Many researchers are working on understanding different applications of 360° technologies in various sectors to provide a better simulation experience. While the search only included published research or studies, some studies are still under development and were therefore outside the scope of this paper's consideration. In total, 136 publications were identified as containing one or more keywords mentioned in the search strategy.

After identifying the initial pool of potential studies for review, a screening strategy distilled the pool to papers relevant to this study's research questions. This screening process first filtered the 136 publications via a defined inclusion and exclusion criteria, namely: (1) the full paper was available and written in English; (2) the paper was published in peer-reviewed journals or conference proceedings; (3) the paper was published between 2000 and 2022; and (4) the paper utilized at least one format of 360° panoramas. Based on the eligibility criteria, ten publications were removed from the literature review, narrowing the literature down to 126 publications. Then, the researchers scanned the title and abstract of all identified articles, and 16 studies were removed from the pool to refine the literature more. The third screening included removing studies that were irrelevant to the review (i.e., duplicating the findings of another publication or not including any application of 360° technologies); as a result, Papers that duplicated information (e.g., papers expanding conference proceedings) were excluded. Since only a few publications explained cybersickness—an issue affecting 360° application spaces—additional publications were also studied to better understand concepts like cybersickness or motion sickness. Reviewing these additional publications helped the research team comprehend and discuss these concepts further.

A total of 105 papers were used for this systematic review, out of which 80 publications focused on the application of 360° directly. The whole searching and screening processes were conducted by four researchers who each independently examined all identified papers based on the inclusion criteria, discussed their perspectives on each paper, and reached a consensus.

2.1 Keyword Mining

To generate a bibliographical map highlighting trends and associations of keywords relevant to the study (Sinha and Modak 2021), data-driven keyword mining was conducted, which is illustrated in Figure 2. To drive the systematic review in this paper, keywords were extracted from a corpus of 80 publications. The selection criteria for such keywords were a minimum occurrence of five uses in the title and abstract fields. VOSviewer computed the frequency of keywords occurrence and co-occurrence with other keywords**.** The size of the circle of a keyword and the distance between two circles represent occurrence frequency and co-occurrence of keywords in the same document (i.e., close distance between circles indicates a higher co-occurrence of those in the same document more often), respectively.

Figure 2 shows the results of the keyword mining, with 39 keywords in 4 different clusters connecting 492 links; the clusters were defined by comparing the associated strength. Also, higher links between different keywords in different sections show that despite the differences in objectives across domains, the studies had common keywords within their findings. Since the number of publications was higher for the AEC domain, two clusters concentrate on publications in AEC.

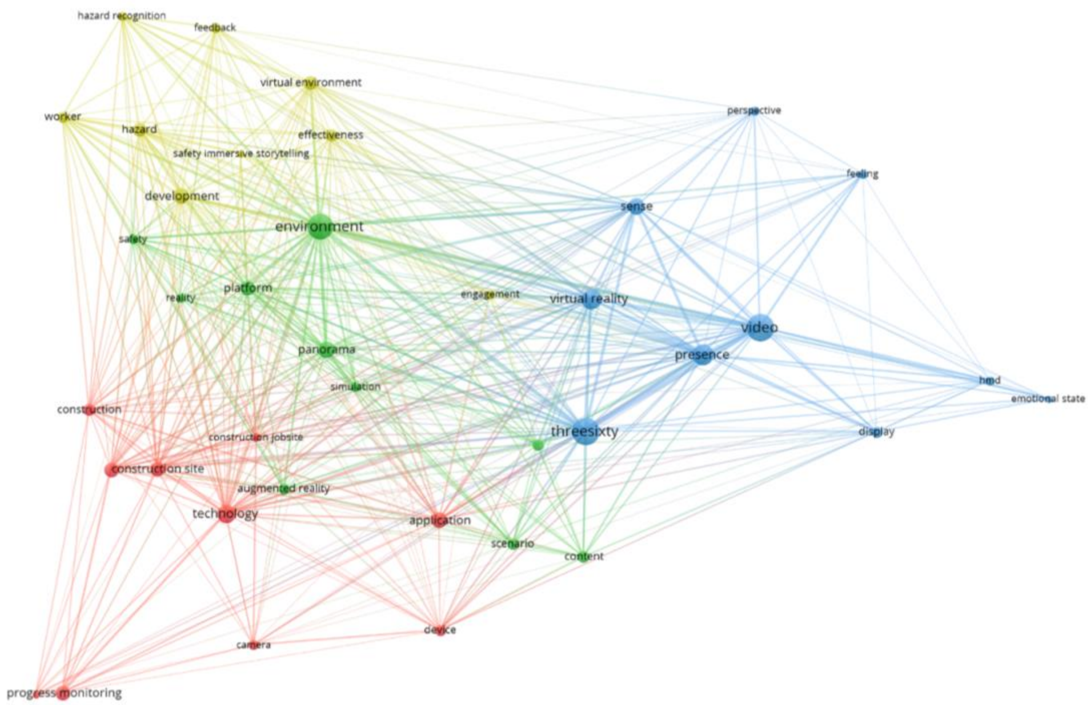

Figure 2*. Results of keyword mining of reviewed AEC-related papers*

Keywords in the red cluster focus on capturing 360° panorama for construction scenarios. The keywords in this cluster highlight the tool and the connection links between these keyword shows their association with application of 360° panorama such as ‘progress monitoring’. The yellow cluster highlights keywords related to virtual construction safety-training platforms—notably, a large proportion of literature in the AEC domain talks about the development and evaluation of different construction safety training platforms based on different simulation technologies. The blue cluster represents keywords related to different evaluation metrics for the ecological validity of simulations, especially for 360° panoramas and factors affecting the quality of a simulation studied in different domains. In addition, the links denoted the association of tools such as ‘hmd’, ‘threesixty’, ‘virtual reality’ with these evaluation metric highlighting their direct association (impact) with ecological validity. The green cluster includes keywords related to a simulation's technical characteristics—various studies aimed to assess and improve the quality of simulations based on these characteristics; this green cluster is at the center of keyword mining because the keywords in the green cluster have associations with most keywords in different clusters. These associations illustrate that regardless of the publications’ domain, many studies focused on specific technical characteristics within simulations. Per expectations, the keyword mining results helped identify the trend and keyword patterns in the literature and were helpful in categorizing these publications and performing an in-depth review.

3. FINDINGS

The histogram in Figure 3 shows the distribution of publications involving 360° panorama technologies over the years. Considering there were only two publications from 2000-2010, 52 from 2010-2020, and 26 from 2021-2022, the research domain is growing rapidly. This rapid increase in the number of publications in both AEC and other sectors since 2016 shows the interest in using 360° panorama technologies more widely. Figure 4 illustrates the geographical distribution of these publications and research studies worldwide. Specifically, the US was found dominant for 360°-related research, with 32 publications, followed by the United Kingdom (5 out of 80) and China (5 out of 80).

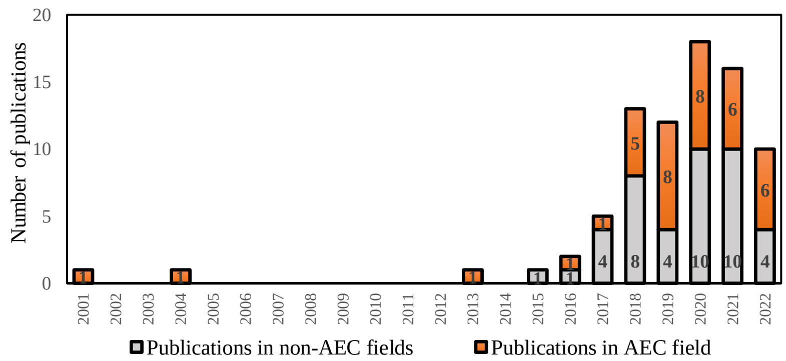

***Figure 3**. Publication distribution across years*

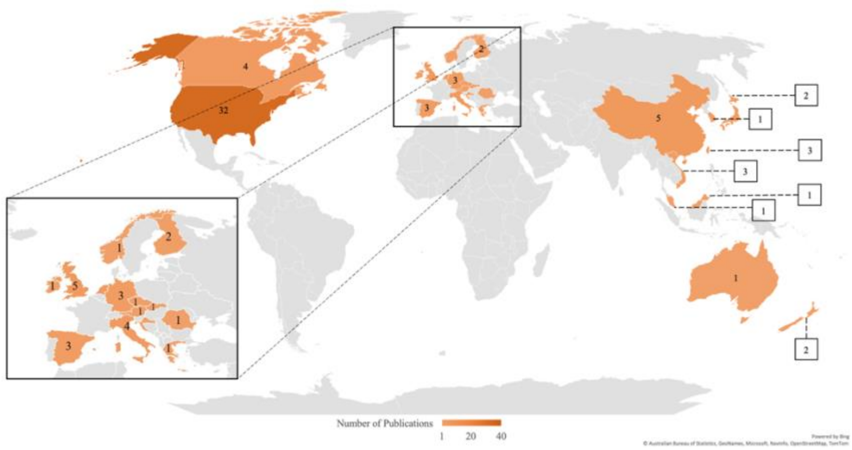

***Figure 4.** Geographical distribution of the reviewed 360° panorama publications*

Thirty-nine of the reviewed studies focused on using 360° panorama technologies in non-AEC sectors and were classified into seven application areas: education, cultural heritage, medical, hospitality, retail, driving safety and automation, emergency planning and safety, and psychology (Figure 5). Most of these non-AEC reviewed papers related to the psychology domain (9 out of 39), followed by medical-related applications (5 out of 39). The AEC-relevant publications were classified into five application areas: architecture, construction education and training, construction monitoring, construction visualization, and cognitive analysis and human behavior in construction, with most of the reviewed papers related to the education and training category (21 out of 41), followed by construction monitoring.

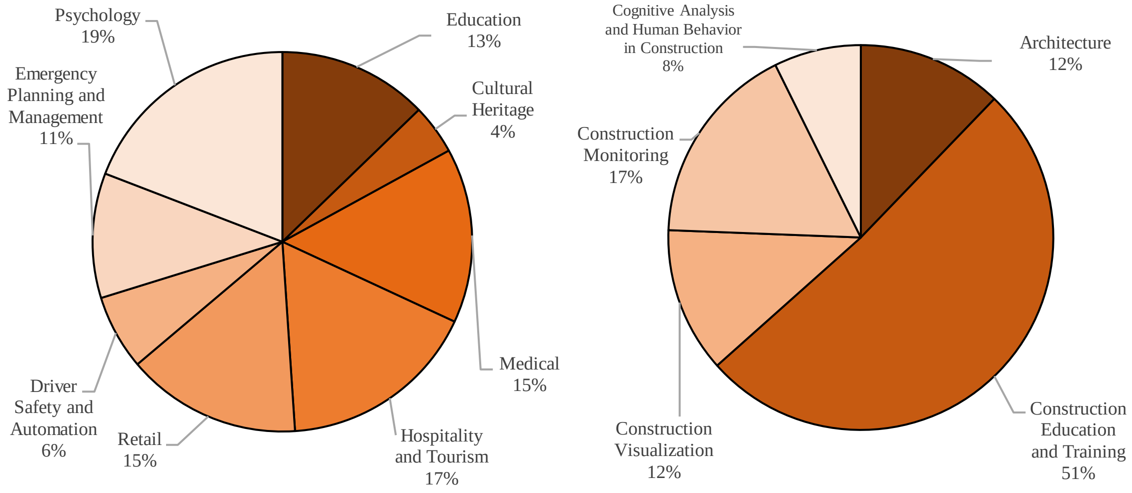

***Figure 5**. Publication distribution in (a) non-AEC (39 papers) and (b) AEC (41 papers)*

3.1 Methodology Used in 360° Research

Table 1 provides an overview of the methodologies utilized in the 80 reviewed studies. The studies were classified into five categories namely – action research, content analysis, survey with demonstration, scenario analysis and mixed methods. An action research methodology can be defined as a study where 360° technology has been utilized to develop an application or product (E.g., safety training, virtual tour, online-class) and the publication only elaborates the development process.

***Table 1.** Summaries of research methodologies used in the 80 reviewed papers*

Methodology	**No. of Studies (%)**	**Presence of empirical data: No. of Studies (%)**
Action research	12 (15%)	0%
Content analysis	18 (22%)	8 (47%)
Scenario analysis	4 (5%)	0%
Survey with demonstration	35 (44%)	0%
Mixed methods	11 (14%)	11 (100%)

Note: Action research: Developed the base study with no participant data collection. Content Analysis: Analysis of application performance data with no participant data collection. Scenario analysis: Limited number of participants for the study but no data/feedback collected via surveys or interviews. Survey with a demonstration: Data collected by conducting pre/post study survey or interview of participants. Mixed methods: Data collected via more than one method—e.g., survey, interview, experimental data.

When a study has finished the development and tested the application or product, and the publications include data related to performance or related characteristics of the application, it is categorized as content analysis. Furthermore, if the publication includes human participation in an experiment related to the application and product, but they did not provide data related to participant such as feedback, response, metrics etc., such studies are included in scenario analysis. The studies which included the data about participants of the experiment such as participant feedback and performance during or after experiencing the application or product are classified as survey with demonstration. Finally, if a study has used more than one approach of aforementioned methodologies, it is categorized as mixed method.

As shown, 'Survey with demonstration (44%)' is the most common type of methodology, followed by 'Content analysis (22%),' 'Mixed methods (14%),' 'Action research (15%),' and 'Scenario analysis (5%).' Only five studies used objective data—eye tracking metrics, EEG (Electroencephalography), HR (Heart Rate), and EDA (Electrodermal activity)—to capture user's performance or feedback when interacting with the 360° panorama technologies. Since 360° visualization is a relatively new technique, the majority of studies preferred a survey with a demonstration, since this methodology allowed researchers to analyze participants' experiences in a 360° virtual environment and then to consider the effectiveness of using 360° visualization in their respective application areas.

3.2 360° Application Areas Outside AEC Industry

While the slim majority of studied papers emphasized 360° technologies in AEC, this review paper also included current research and applications of 360° panorama technologies in other domains to foster innovative research ideas in AEC. Many sectors have been using 360° panorama technologies to explore the characteristics, practicality, effectiveness, and limitations of these technologies, which all contribute important considerations to AEC discussions. Table 2 provides a detailed overview of application areas and technologies used in non-AEC areas, and the following sub-sections further discuss best practices and research gaps.

Table 2. *A detailed overview of reviewed papers applying 360° panoramas in the non-AEC domains*

Sectors/ Industries	Application/Objective Description	Media and Delivery Formats	Specified Equipment	Paper
Education	To develop a virtual teaching tool for primary school.	360° Video with HMD	Not mentioned	Arvaniti and Fokides (2020)
	To develop an educational 360° video to discuss experienced challenges and future work.	360° Video with HMD	Ricoh Theta S 360 Cam, Samsung Gear HMD	Kavanagh et al. (2016)
	To use the recorded 360° video of teachers for post-teaching self-reflection.	360° Video with HMD	VR Shinecon	Walshe and Driver (2019)
	To use 360° video via HMD for content delivery in a business classroom.	360° Video with HMD, 360° Video Flat Screen	Google Cardboard VR	Lee et al. (2017)
	To develop 360° videos to enhance the learning of undergraduate chemistry laboratory content.	360° Video	Ricoh Theta S	Ardisara and Fung (2018)
	To develop 360° video to conduct peer assessment sessions in an English-speaking class.	360° Video with Handheld Device	Not mentioned	Chien et al. (2020)
Cultural Heritage	To develop cultural heritage virtual reality application with interactive digital storytelling	360° Video with HMD	HTC Vive HMD	Škola et al. (2020)
		360° Video with HMD	Oculus Rift VR HMD, Ricoh Theta S Camera	Argyriou et al. (2020)
Medical	To develop C-section tutorials for medical students.	360° Video with HMD	Not mentioned	Arents et al. (2021)
	To remotely teach emergency medicine to students.	360° Video	GoPro Max 360 camera	Petrica et al. (2021)
	To develop virtual reality training for computed tomography angiography for patients, radiographers, and radiography students.	360° Images with HMD	Not mentioned	Paalimäki-Paakki et al. (2021)

Sectors/ Industries	Application/Objective Description	Media and Delivery Formats	Specified Equipment	Paper
	To develop 360° video-based training to educate nursing students about childbirth.	360° Video with HMD	THETAS software, Google Cardboard	Chang et al. (2019)
	To develop an immersive surgery training application using 360° video and VR.	360° Video with HMD	GoPro Hero 360-degree setup, Oculus Rift Headset	Pulijala et al. (2017)
	To develop 360° videos to evaluate attentiveness, information retention, and appraisal compared to 2D display.	360° Video with HMD, 360° Video Flat Screen	GoPro Omni, Samsung Gear VR	Harrington et al. (2018)
	To deliver meditation instructions virtually.	360° Video with HMD, 360° Video Flat Screen	GoPro Fusion 360° camera, Samsung Gear headset	Waller et al. (2021)
Hospitality and Tourism	To investigate the impact of content and device type on virtual tours of hotel rooms	360° Video with HMD, 360° Video with Handheld Device	Not mentioned	Orús et al. (2021)
	To study parameters affecting the experience of viewing a 360° tourism video.	360° Video with HMD, 360° Video with Handheld Device	Samsung VR Gear headset	Kelling et al. (2017)
	To investigate the impact of 360° virtual mountain walking tour to motivate actual mountain walking.	360° Video with HMD	Insta360 OneX camera, Xiaomi all-in-one VR headset	Wu and Lai (2022)
	To identify the factors affecting the sense of presence and destination in a 360° virtual tour.	360° Video with HMD	Xiaomi all-in-one VR headset	Wu and Lai (2021)
	To compare 360° tourism video and actual visit experience in terms of presence and engagement.	360° Video with HMD	GoPro Omni 6 360 video rig, Oculus Rift VR headset	Wagler and Hanus (2018)
	To analyze the influence of 360° video on emotional responses and decision-making in the tourism context.	360° Video with HMD, 360° Video with Flat screen	Samsung Gear VR headset	Beck and Egger (2018)
Retail	To analyze the effectiveness of VR content formats and devices in physical store response.	360° Image with HMD, 360° Images with Flat Screen	HTC Vive VR headset,	Martínez-Navarro et al. (2019)
	To provide a virtual shopping experience of a boutique.	360° Video with HMD	Ricoh Theta V 360 camera	Jin et al. (2021)
	To develop a 360° video virtual tour of small independent stores.	360° Video with HMD	Ricoh Theta V 360 camera	Kim et al. (2022)
Driving Safety and Automation	To examine the relationship between attitudes toward traffic rules, impulsiveness, and behavioral intentions at crossings.	360° Video with HMD (VR Glasses)	Not mentioned	Barić et al. (2020)
	To detect and track moving objects at a road intersection.	360° Images	Ricoh THETA 360 camera	Premachandra et al. (2019, 2020)
Emergency Planning and Management	To understand the pedestrian exit choice behavior in an evacuation situation.	360° Video with HMD	Nikon KeyMission 360 Camera, Kodak Pixpro SP360 4 K Camera, VR Pro Virtual Reality Glasses	Feng et al. (2021)
	To examine an emergency escape drill system.	360° Video	Unity Game Engine	Peng et al. (2020)

Sectors/ Industries	Application/Objective Description	Media and Delivery Formats	Specified Equipment	Paper
	To capture 360° video of the post-disaster scenes.	360° Video	GoPro Hero Camera setup	Ferworn et al. (2015)
	To develop interactive training for evacuation drills in a nuclear reactor building.	360° Images with HMD	Nikon KeyMission 360 Camera, Pano2VR software	Xue et al. (2018)
	To evaluate rapid and effective workflow for reconstructing 3D indoor environments for earthquake simulation.	360° Video with HMD	Nikon KeyMission 360 Camera, Oculus Rift Headset	Feng et al. (2018)
Psychology (Personal Behavior Studies/ Cognitive Studies)	To offer 360° video VRET (Virtual Reality Exposure Therapy) to treat public speaking anxiety.	360° Video with HMD	Samsung Gear VR headset powered by Oculus, Samsung Gear 360° Camera	Reeves et al. (2021)
	To compare VRET offered via 360° video and VR environment in treating veteran social anxiety disorder.	360° Video with HMD, VR with HMD	Oculus Rift VR HMD	Nason et al. (2020)
	To evaluate the effect of 360° video environments on reducing public speaking anxiety.	360° Video with HMD	GoPro camera	Stupar-Rutenfrans et al. (2017)
	To compare 360° video and VR regarding sense of presence, anxiety, and positive emotions.	360° Video with HMD, VR with HMD	Kodak PixPro SP360 4K Camera, VR i7 head-mounted display	Brivio et al. (2021)
	To study the effect of a 360° video-based VR experience on males' empathy toward a female victim of sexual harassment	360° Video with HMD	LG360-105 camera, VR Glass	Ventura et al. (2021)
	To evaluate the impact of watching 360° virtual tours on reducing psychological stress caused by COVID-19.	360° Video with HMD	Not mentioned	Yang et al. (2021)
	To study emotional states induced by 360° videos via VR and computer screen.	360° Video with HMD, 360° Video with Flat Screen	Oculus Quest VR Headset, MSI Gaming Laptop (44cm)	Voigt-Antons et al. (2020)
	To study sense of presence, attitude change, perspective-taking, and usability in first-person split-sphere 360° video.	360° Video with HMD	Custom-designed two-camera modified GoPro rig, Samsung Gear VR	Aitamurto et al. (2018)
	To understand the effects of 360° immersive nature videos on enhancing feelings of commitment to the environmental protection.	360° Video with HMD, 2D Video with Flat Screen	Oculus Go HMD, Flat Computer Screen (32.5cm)	Breves and Heber (2020)

- ***Education***

Education is one sector that adopts the latest technologies much quicker than other sectors to enhance the learning environment. However, conventional teaching methods for classroom or laboratory experiments with insufficient visualization techniques can jeopardize student learning and understanding (Bolkas et al. 2020; Chien et al. 2020). To overcome these limitations, one of the contemporary teaching methods adopted is the use of simulation technologies, where educational resources such as interactive videos and live demos are presented virtually to students via computer graphics and different types of displays.

Currently, such visualization technologies as VR and AR are primarily being used as educational tools. VR is an effective technology that provides students with a realistic learning experience. Previous studies show the feasibility of using 360° panoramas as successful alternatives to virtual reality due to their simplicity and cost-saving. 360° panoramas can help instructors easily explain difficult concepts with high-quality visualized examples (Kavanagh et al. 2016). The results of a study comparing traditional and contemporary learning platforms illustrated that students showed better learning outcomes (e.g., interest in the topic, enhanced awareness regarding environmental issues) and reported experience of higher immersion in a 360° environment (Arvaniti and Fokides 2020). Apart from the standard teaching-learning application space, visualization tools can also help with evaluation (e.g., peer review and self-evaluation) and training novice teachers or professors at schools and universities (Walshe and Driver 2019). Chien et al. (2020). Existing studies showed that using 360° videos as a self-reflection tool can help teachers develop a subtler comprehension of their microteaching and support their self-efficacy (Walshe and Driver 2019; Chien et al. 2020)

Based on the findings of these studies, further research of similar objective can be conducted in AEC domain. The academic learning sessions in AEC require a factor of imagination of concepts for better understanding (e.g., stress in reinforcement, concrete behavior, equipment operation etc.) While providing students a hands-on experience of these concept may be unsafe, virtual environment can be a modern solution which can explain such concepts better with visualization. The results of these studies highlight 360° technologies' excellence in improving learning, which supports the practical implications of applying these technologies within the AEC industry for workforce training and enhanced educational materials.

- ***Cultural Heritage***

Historical places play a crucial role in delivering information and evidence of human evolution to future generations, but not all historic places can be easily visited. For example, some historical sites have unsafe structures, while some are now submerged under the sea. Thus, the cultural heritage sector needs visualization tools to deliver information about these places to people in a safer environment. Recent studies divulged that digital storytelling is a propitious tool for experiencing cultural heritage (Škola et al. 2020b) while providing users with an outstanding immersive experience with a higher sense of presence (Argyriou et al. 2020). In their study, Argyriou et al. (2020) discussed creating a 360° immersive video application and game to allow users to have a highly immersive and engaging experience during a virtual tour of the historic Rethymno city (Argyriou et al. 2020). Similarly, Škola et al. (2020) used 360° videos along with interactive storytelling to develop archaeological VR applications to visit (currently underwater) cultural heritage site (Villa con ingresso a protiro, Park of Baiae, Naples, Italy).

Studies in cultural heritage provide an illustrative example of virtual environment of a site or location. Projects in AEC have many stakeholders who are unable to visit the actual jobsite. Such projects can implement the reality-capturing technology implemented in these studies to create a virtual environment where stakeholders can visit the jobsite from anywhere in the world. While some of the publications in AEC investigate the impact of storytelling, future studies can be performed to design and examine more applications based on storytelling of various tasks in AEC profession. The cultural heritage domain demonstrated the effectiveness of combining 360° technologies with storytelling, a combination that can be used in the AEC industry, for example, in safety training for students and construction workers.

- ***Medical Sector***

While video-based learning (YouTube educational channels) has been practiced broadly in the medical education field, active participative learning (simulation-based learning) has better learning outcomes than passive observative learning (e.g., classroom learning, laboratory tutorials, 2D educational videos) (Arents et al. 2021; Harrington et al. 2018). Furthermore, since the Covid-19 pandemic, virtual communication has become necessary, especially in the medical sector, where professionals need to broadcast their recent findings, results, and related procedures to save many patients across the globe. Among the most pressing application spaces for visualization technologies, operating on a patient or conducting a surgical procedure necessitates precise visual data. Medical students can achieve this precision by learning and observing the correct procedure using realistic simulations (Harrington et al. 2018; Pulijala et al. 2017). For instance, 360° panorama technologies can realistically present some of the most complicated medical activities and prepare students to perform procedures when practicing medicine in the future. Even though studies have implied the importance of digital medicine, especially during disaster situations (Lurie and Carr 2018), such approaches to healthcare are underutilized. In such conditions, 360° video technology can be a viable medium of digital health—or telehealth—for hybrid teaching (Petrica et al. 2021), remote monitoring, and live-video teleconferencing.

Additionally, these studies confirmed that 360° technologies are an effective solution for e-learning methods, which provides an immersive, in-depth, and informative learning experience so critical in the medical and healthcare sectors. Such learning better prepares students for real-world and time-critical challenges. Many situations on a construction site require similar undivided attention, adaptive critical thinking, and time-sensitive responses to tasks happening in the surroundings. Students and professionals in AEC can be trained for such situations using 360° panorama virtual environment. Future studies can develop such VE based on the studies in medical sector, that will deliver similar experience to a hands-on training. Therefore, building out of the success of the medical sector, construction training using 360° technologies can become an accurate and reliable method for enhancing worker skills.

- ***Hospitality and Tourism***

The hospitality industry has such attributes as heterogeneity and intangibility, which makes optimal customer experience crucial. In order to offer superior added-value propositions, hotel and restaurant operators need to find appropriate tools to help the consumers decide (booking a room/restaurant or upgrading the reservation) (Orús et al. 2021). Many of the recent studies in the hospitality sector focused on investigating the impact of content (e.g., 360° panorama, VR, AR) on users' telepresence, response, and use of the correct device for simulating that content (e.g., HMD, Smartphone, Digital screens) for mitigating the challenges (e.g., lack of customer engagement, failure to induce purchase intentions) in current marketing strategies (e.g., website and traditional advertising, 2D videos) and effectively promoting tourism in a more immersive way. Further, A study investigating participants feedback to 360° video of KMI airport, suggested that these types of 360° depictions had an application in buying/renting houses and previewing travel destinations where physical travel is a major constraint (Kelling et al. 2017). Orús' study which showed participants a hotel room via different combinations of multimedia and display choice (360° vs. VR, Smartphone vs. HMD), noted that the 360° video successfully produced a greater sense of presence, ease of imagination, and visual appeal of the simulation, culminating in a higher interest in booking the hotel room (Orús et al. 2021). The results of these investigative studies argued that 360° panoramas positively impacted a sense of presence/spatial presence, immersion, emotional reaction, decision-making, and intention to book/visit (Beck and Egger 2018; Kelling et al. 2017; Orús et al. 2021; Wagler and Hanus 2018; Wu and Lai 2021, 2022). In addition, one of the studies used physiological responses (Heart rate and Electrodermal Activity (EDA)) to cross-examine the self-reported answers about users' 360° experience in an HMD and desktop-PC questionnaire (Beck and Egger 2018). The results of the study showed that physiological responses confirm more significant emotional reactions with HMD than with a desktop.

Purchases in the AEC sector (e.g., renting/buying apartments, land, pre-owned buildings) carry a considerable price tag, so consumers often expect a comprehensive and detailed view of the product they invest in. A 360° simulation can effectively deliver on these expectations by providing simple, low-cost, highly immersive virtual tours. Researchers in AEC can work towards developing a powerful tool in-house (internally) for construction companies to visualize the construction site without physical presence. Similar to the studies in hospitality and tourism, researchers in AEC can develop a tool with inexpensive HMDs and 360° cameras that will enable construction companies, architects, interior designers, and other professionals to develop a 360° walk-through internally.

- ***Retail Shopping***

Retailers spend vast sums to make stores attractive, provide a great shopping experience, and incentivize consumers to make purchases. To improve the shopping platform and its experience, retailers are now investing in developing virtual stores for consumers (Kim et al. 2022). Since 360° videos and images can provide an excellent virtual environment for stores, many retailers have already made these types of 360° virtual stores available online (Dior - smartphone, laptop/PC based) and in-store (Tommy Hilfiger, Coach - VR headset based) (Sina and Wu 2022). Research studies in the retail sector are advancing further by analyzing the effects of these virtual platforms on users' sense of presence, shopping enjoyment, pleasure, and purchase intentions. In a study, Martínez-Navarro and colleagues aimed to test different hypotheses to identify the correlation between human psychological parameters—such as affect, cognition—and their preferences related to retail shopping; their results showed that 360° store navigation had higher or similar interest and emotion (presence, dominance, and arousal) to visiting a physical store (Martínez-Navarro et al. 2019), effectively spiking participants' intention to visit the store.

The studies in retail shopping emphasize the impact of visualization on characteristics such as purchase intention. This application utilized by the retail shopping industry can also be effective for vendors and resellers in AEC profession. Numerous construction products (e.g., flooring, roof, plumbing, wood etc.) related to interior of a house or office requires inspection before purchase. This tool can be effective to provide a demo of construction-related products to buyers at different locations and countries. Such technology can be further combined with augmented reality, which can enable users to place the product using live camera feed. Future researchers can develop such mixed reality tool that will ease the sale of construction materials.

- ***Driving Safety and Automation***

Researchers in the transportation industry allocate a lot of effort to developing advanced Intelligent Transportation System (ITS) to minimize traffic congestion and accidents. Such advanced transportation systems need state-of-the-art real-world capturing technologies for different purposes, including clash detection, surrounding monitoring, and autonomous driving. For autonomous driving, researchers aim to optimize the currently available object detection and classification algorithms to avoid crashes or accidents and enhance the reliability of autonomous driving and the safety of passengers. Considering how important the quality and scope of these images are in the performance of these algorithms, 360°'s omnidirectional photography offers a promising option for detecting objects and effectively alerting the system or driver Premachandra et al. (2019, 2020). Interestingly, 360° panorama technologies were also commonly used to train drivers on road safety. For example, in a study by Barić et al. (2020), 360° video was used to examine the effects of 360° video-based educational intervention on driver learning and safety behavior (i.e., reduce their tendency to adopt risky driving behavior).

Vehicle driving and working on construction sites share characteristics, especially those related to the dynamic nature of the environments. Both tasks require high situational awareness and immediate response. Following the interventions used by studies in the automotive safety domain, the construction industry can utilize similar image processing algorithms coupled with a 360° camera to effectively monitor the surroundings at a construction site to ensure the safety of workers and the quality of work. Incorporating such an advanced application can assist to monitor unsafe behavior at construction jobsite, which is difficult with manual supervision. In addition to this application, researchers in AEC can further investigate about the algorithm (background-subtraction) developed in these studies, which can be effective to track the progress of construction activities. Furthermore, other studies validate the effectiveness of a safety training developed using 360° videos, which impacted the drivers' behavior. Researchers should develop a safety-training based on 360° videos of construction jobsite and evaluate if a similar effect is observed on construction workers.

- ***Emergency Planning and Management***

In emergency situations, identifying the best exit path considerably affects survival rate, and the information provided in the building influences how pedestrians choose to exit. Peng et al. (2020) proposed the use of 360° videos for simulating emergency drills to avoid building a time-consuming and expensive VR environment, using an application that has interactable information hotspots which provide details about firefighting equipment. A similar field experiment was conducted to study pedestrians' exit choice behavior during evacuations using smartphone-based HMD and 360° video. The outcomes of their study highlighted the ecological validity of the developed 360° immersive environment presented in HMD as a valuable method for monitoring pedestrian exit choices during an evacuation Feng et al. (2021).

Besides emergency/disaster planning, 360° technologies can be very useful also in post-disaster situations, which are difficult and unsafe to access, so it can be very challenging to survey the damages due to disaster or to look for any possible survivors (Ferworn et al. 2015). These advance tools can be incorporated in infrastructure rebuilding, especially after a natural disaster. Infrastructure resilience is a critical issue in U.S. especially with an increase in natural disaster, 360° panorama-based monitoring system can assist to gauge the damages after a disaster. Further, in keeping with the interactive and realistic simulations used in emergency planning studies, the AEC industry can use 360° technologies to develop serious games for creating simulation environments of various hazardous situations at a construction site to train its workers and employees without incurring safety risks.

- ***Psychology (Behavior/Cognitive Studies)***

The Psychology domain widely incorporated 360° panoramas to develop realistic, immersive environments for studying naturalistic human behavior and responses under various conditions. The key objective of creating a realistic environment is to ensure that subjects of the study will experience the virtual environment as if the actual environment to manifest the emotions they would experience during physical presence. For example, a study conducted by Yang et al. (2021) indicated considerable effects of 360° virtual tours on reducing psychological stress caused by the COVID-19 pandemic and highlighted higher telepresence experience by users (sense of presence).

Virtual Reality Exposure Therapy (VRET) is a therapy technique where individuals are gradually exposed to simulated situations or thoughts and memories that are viewed as frightening or anxiety-provoking (e.g., various phobias, public speaking, driving, Post Traumatic Stress Disorder—known as PTSD) (Stupar-Rutenfrans et al. 2017; Nason et al. 2020). For such therapies, the simulation environment has to be realistic and immersive enough to induce a similar sense of fear, agitation, or disturbance. Hence, various studies incorporated 360° panoramas as the simulation platform for VRET and investigated the compatibility, advantages, and challenges of using 360° panoramas (Nason et al. 2020; Reeves et al. 2021; Stupar-Rutenfrans et al. 2017). Further, Brivio et al. (2021) and Nason et al. (2020) compared the effectiveness of different types of immersive environments on veterans with PTSD and social anxiety disorder (SAD); the studies' results showed that in both VR and 360° simulation environments, participants felt low-to-medium levels of anxiety, while participants reported that the realistic nature of content in the 360° simulation provoked more immersive-ness. The results also highlighted that 360° panoramas could achieve similar—if not better—results than computer-generated virtual reality, with significantly less development cost and computational and human resources. Additionally, 360° videos can be used to give a first-person view which may help the user to feel more embodiment towards the video, increasing the immersion of the content, further highlighting the compatibility and advantages of using 360° simulation for first-person view experiments (Ventura et al. 2021).

Overall, research studies in the psychological domain emphasized the impact of 360° panoramas on the sense of presence and the emotional states of participants, which combine to deliver realistic conditions that render subjects' natural responses during a simulation. The examined studies repeatedly emphasize 360° panoramas' advantages regarding the low cost of development, high sense of presence, and excellent visualization. When combined with other domains' applications of 360° panoramas, these outcomes show these technologies offer an effective, cost-saving option that invokes the most natural responses from users. Thus, the advantages are significant enough to recommend 360° panorama technologies as an alternative to traditional methods of visualization.

Based on the findings of various studies in this domain, future researchers can develop such intervention training application. 360° panorama can provide a realistic exposure therapy which has been utilized in psychology domain and has shown positive response from participants. Construction industry in the U.S. ranks second about workers suicide rate which is 4.25 times higher than the national average (Tijani et al. 2023). Researchers in AEC are working towards developing various suicide intervention trainings or applications that can prevent or reduce suicide rate in construction. Such application can be translated in AEC industry for betterment of construction workers mental health. Additionally, findings also highlighted the effectiveness of 360° panorama in first-person view. Future researchers use these features to develop virtual tours, where user can embody the presence in virtual environments.

3.3 360° Application Areas in AEC Industry

As Table 3 shows, there have been 41 peer-reviewed articles published in the AEC area that used 360° panorama technologies. The most common context in which 360° panoramas were researched and applied was 'construction education and training (51%),' followed by 'construction monitoring (17%),' 'construction visualization (12%)' and 'architecture (12%)' and 'cognitive analysis and human behavior in construction (8%).'

Table 3. *Descriptive statistics of 360° studies in the AEC industry*

AEC application area	Number of studies (out of 41)	Percentages in reviewed papers of AEC (%)
Architecture	5	12%
Construction education and training	21	51%
Construction visualization	5	12%
Construction monitoring	7	17%
Cognitive analysis and human behavior in construction	3	8%

A preliminary review showed that the primary 360° panoramas application area in construction education and training corresponds with safety training and immersive visualization. Table 4 provides comprehensive details of the reviewed papers within the AEC application areas.

Table 4. *A detailed overview of the reviewed papers applying 360° panorama technologies in the AEC domain*

AEC Application Area	Application/Objective Description	Media and Delivery Formats	Specified Equipment	Related Publication
Architecture	To conduct augmented diagnostic, assessment, and control over architectural heritage sites.	360° Images	Canon EOS M3, GoPro Camera, PTGui Pro	de Fino et al. (2018)
	To develop a methodological workflow for 3D model tools when sharing and elaborating on diagnostic data regarding architectural heritage conservation.	360° Images	Samsung Gear 360 C200 Camera	de Fino et al. (2019)
	To design a virtual tour of an architectural heritage site.	360° Images	Canon EOS M3 Camera	de Fino et al. (2020)
	To develop a methodological workflow for conducting virtual tours of historical-architectural heritage sites.	360° Images	Samsung Gear 360 C200 Camera	de Fino et al. (2022)
	To study differences between contemporary & traditional architecture.	360° Video with HMD	Ricoh Theta V, View-Master deluxe HMD	Mouratidis and Hassan (2020)
Construction Education and Training	To develop a virtual site visit platform for students.	360° Images with Flat Screen	Not mentioned	Dickinson et al. (2004)
	To develop virtual classes for surveying engineers.	360° Video with HMD	Garmin VIRB 360-degree camera, Oculus Rift	Bolkas et al. (2020)
	To develop an immersive storytelling experience about the electrical construction industry for students.	360° Video with Flat Screen	Not mentioned	Wen and Gheisari (2021)
	To develop a virtual field trip to analyze deictic gestures and its effect on students' quantitative learning outcomes.	360° Images with Flat Screen	Not mentioned	Wen et al. (2022)
	To develop a 360° panoramic photography platform for a virtual construction site visit.	360° Images with Handheld Device (iPad), 360° Images with HMD	Ricoh S 360 camera, Oculus Go HMD	Kim et al. (2019)
	To develop virtual field trips for mobile construction safety education.	360° Images with Handheld Device	Not mentioned	Chien Pham et al. (2018)
	To develop a virtual site visit platform.	360° Images with HMD	Insta360 One, Oculus Go HMD	Eiris et al. (2020c)
	To develop and test digital interactive virtual site visits.	360° Images with HMD	Insta360 One, Ricoh Theta V, NCTech Fusion, Oculus Quest HMD	Eiris et al. (2021, 2022)
	To investigate students' interest with virtual site visits.	360° Images with Flat Screens	Not mentioned	Mander et al. (2022)
	To provide guidelines to educational stakeholders for recording 360° video of the construction site visit.	360° Video with HMD	Insta360 ONEX, Oculus GO HMD,	Wehking et al. (2019)
	To develop an energy-efficient learning system for construction	360° Images with HMD	Samsung Gear VR	Pham et al. (2018)

AEC Application Area	Application/Objective Description	Media and Delivery Formats	Specified Equipment	Related Publication
	safety education to replace conventional VR systems.			
	To develop immersive 360° video content for teaching construction means and methods.	360° Video with HMD	GoPro fusion, Qoocam, GoPro Hero, Lenovo Mirage	Shojaei et al. (2020)
	To develop a construction hazard investigation system on an augmented photoreality platform.	360° Images with Flat Screen	Samsung Gear 360 Camera	Pham et al. (2019)
	To develop hazard identification training based on VR and 360° panoramas.	360° Images with Flat Screen, VR with Flat Screen	Samsung Gear360 Camera, Insta 360 One Camera	Eiris et al. (2020a)
	To improve hazard recognition and risk perception using immersive storytelling.	360° Images with HMD	Samsung Gear360 Camera, Google Cardboard HMD	Eiris et al.(2020b)
	To develop virtual reality and stereo-panoramic environments for construction safety training.	360° Video with HMD, VR with HMD	Not mentioned	Jeelani et al. (2020)
	To develop and conduct usability testing of a panoramic augmented reality environment for fall hazard safety training.	360° Images with Flat Screen, AR	NCTech iStar Fusion	Eiris et al. (2019)
	To develop and compare hazard identification training scenarios using 360° panorama and VR simulation.	360° Images with Flat Screen	NCTech iStar Fusion	Moore et al. (2019)
	To develop augmented 360° panoramas for construction safety training.	360° Images with Flat Screen	NCTech iStar Fusion	Eiris et al. (2018)
	To develop a VR safety training application and compare the effectiveness of 360° panoramas with 3D modeled VR application.	360° Images with HMD, VR with HMD	YI360 camera	Ritter and Chambers (2022)
Construction Visualization	To develop an immersive visualization mechanism to help post-construction sales.	360° Video with HMD	Not mentioned	Felli et al. (2018)
	To compare the effectiveness of different visualization tools with traditional building tours.	360° Images with Handheld Device (iPad), 360° Images with HMD, Virtual Reality	Oculus HMD	Ha et al. (2019)
	To develop a virtual representation of construction sites to learn more about the project and jobsite.	360° Video with Handheld Device (Tablet), 360° Images with Handheld Device (Tablet)	Ricoh Theta S	Eiris Pereira et al. (2017)
	To develop a semi-augmented reality experience to access building information such as plumbing and HVAC system.	360° Images in AR with Handheld Device (iPad)	Not mentioned	Gheisari et al. (2016)
	To develop live, high-accuracy, 360° augmented reality for construction visualization.	360° live Video stream with Flat Screen	Ladybug 3 panoramic camera, Lenovo W520 laptop	Côté et al. (2013)
Construction Monitoring	To conduct architecture-related supervision of interior renovation.	360° Video with Flat Screen	Hypercam camera	Shih et al. (2001)

AEC Application Area	Application/Objective Description	Media and Delivery Formats	Specified Equipment	Related Publication
	To compare surrounding scanning techniques to create point cloud data of a construction site.	360° Images and Laser Scanning	Insta 360 One camera	Subramanian and Gheisari (2019)
	To assess the impact of lighting conditions on the potential variability of 360° photogrammetry for construction monitoring on the actual site.	360° Images	Ricoh Theta Z1, Ricoh Thera V1	Funtik and Mayer (2021)
	To track the progress of a construction jobsite.	360° Images	viAct 360° camera	Ng et al. (2021)
	To develop and evaluate a four-legged robot for construction monitoring.	360° Images	Ricoh Theta V	Afsari et al. (2021)
	To use a robot to develop BIM-enabled automated reality capture for construction inspection.	360° Images with Flat Screen	Ricoh Theta V	Halder et al. (2021)
	Evaluate using a four-legged robot to automate construction progress monitoring.	360° Images	Ricoh Theta V	Afsari et al. (2022)
Cognitive Analysis and Human Behavior in Construction	To investigate the impact of hazard characteristics, attention, and workers' perception on hazard identification performance.	360° Videos with HMD	Insta360 OneX, HTC Vive pro Eye	Lee et al. (2022a)
	To identify the impact of hazardous stimuli format on workers' subjective and objective hazard identification and situation awareness.	360° Images with HMD, 360° Videos with HMD	Insta360 OneX, HTC Vive pro Eye	Lee et al. (2022b)
	To conduct an empirical examination of workers' visual search strategies and hazard identification performance.	360° Videos with HMD	Insta360 OneX, HTC Vive pro Eye	Lee et al. (2022c)

- ***Architecture***

Recent developments in digitalizing architectural heritage tours into virtual reality applications are providing better opportunities for tourists and researchers to remotely visit historical places. For such applications, it is necessary to capture the heritage sites in a realistic way so that users can have a natural visit experience. 360° panoramas offer a realistic and immersive method for capturing these buildings or historical heritage sites to achieve virtual representation. For example, de Fino et al. (2020) used 360° images of indoor and outdoor areas of Swabian Castle of Trani, Italy, to develop a WebGIS-based platform for a virtual tour of the castle. Further, they augmented this platform with information hotspots and highlights to make the tour navigable, immersive, and informative. Thanks to its realistic content, the use of 360° images in this platform helped deliver similar experiences to that of a physical visit. Furthermore, de Fino and his colleagues (2022) developed an additional methodological framework for creating three different thematic virtual tours for inclusive dissemination, technical assessment, and smart management of architectural heritage structures, all using 360° images in WebGIS-based applications. This study also highlighted that using 360° images offered various advantages, including low-cost tools and time-saving, realistic visual communication, easy integration with external documents and tools, and straightforward implementation and management for collaborative design processes (de Fino et al. 2022).

Beyond fabricating virtual tours, de Fino et al. (2018) adopted 360° panorama images to diagnose and analyze characteristics, pathologies, and degradation in an architectural heritage building (Masseria Don Cataldo, Adelfia, Italy). The researchers augmented the captured 360° images with analytical and experimental information to systematically collect, elaborate on, interpret, and manage architectural heritage structure diagnostic data. de Fino's study found that panoramic images are favorable for such usage as they provide faster and lighter navigation tools in a virtual tour compared to point clouds, which might need high computational power and response time.

These studies highlighted the effectiveness and suitability of 360° panoramas in different situations in the architectural domain.

- ***Construction Education and Training***

Recently, construction and architecture education has been vastly innovated using such new technologies as computer-aided designing tools, advanced project management software, and virtual simulation environments. Of these, 360° panorama technologies have been harnessed for various simulation environments, replacing conventional teaching approaches such as classroom lectures, PowerPoint presentations, and written tests, which often fail to promote participant engagement.

One of the most common application areas for 360° panoramas is to use these tools to conduct virtual site visits for students. According to Wehking et al.'s study, taking field trips for educational purposes is one of the key learning experiences for students (Wehking et al. 2019). However, field trips often show several limitations, such as expensive trip costs and inaccessible places due to safety issues (Eiris et al. 2020c, Chien Pham et al. 2018). Thus, 360° images and videos started to replace field trips as a more cost-effective way for students to gain extensive educational benefits without leaving the classroom.

As Table 4 describes numerous studies in construction education evaluated the feasibility, advantages, and challenges of these panoramic virtual site visits. For example, Kim et al.'s study (2019) incorporated 360° images of a construction site to create a virtual environment for students and displayed these images using both HMD and an iPad. The results showed 73% of the students reported that combining 360° images with HMD rendered a more realistic environment and mimicked the experience of an actual site visit (Kim et al. 2019). Similarly, Eiris et al. (2020c) designed an interactive virtual field trip platform (iVisit) using 360° panoramas and a virtual human storytelling feature for civil engineering students. Students described the iVisit 360° platform as a realistic and immersive experience and gave high ratings for usability. Further, Eiris and his colleagues performed a study to compare students' learning performance using the iVisit-based digital assessment tool versus a paper-based assessment; the study illustrated that iVisit was more effective in developing problem-solving skills since the learning was based on empirical observation of jobsite's properties.

While these studies support the effectiveness of using 360° panoramas as a simulation method for educating future workers (Eiris et al. 2021, 2022), such interactive 360° panoramas can similarly be employed to recruit students' to construction careers since interactive 360° panoramas provide virtual yet very realistic inductions and can attract students to the electric-construction industry, Wen and Gheisari (2021) used 360° videos for virtual storytelling about electrical construction within an active environment. The results of their study showed that virtual storytelling in the immersive virtual environment positively affected students' attitudes towards the electrical construction field.

Additionally, 360° panoramas can replicate complex on-site conditions as well as various concepts for students in a classroom setting. One example of this application is the study conducted by Bolkas et al. (2020), which created interactive 360° immersive educational videos related to land surveying in order to overcome visualization and equipment challenges in land surveying practicals. The immersive training using 360° videos successfully helped provide an interactive, immersive, and life-like education experience for students to understand land surveying better, leading to improved grades. Such outcomes confirm other sectors' educational applications by demonstrating 360° panoramas' effectiveness as an alternative to traditional teaching methods.

Due to the complex and dynamic nature of construction sites, construction safety remains a crucial educational challenge driving the development of safety training interventions. Safety training often aims to educate workers about hazards on a construction site, since successful hazard identification highly corresponds to workers' safety performance (Hasanzadeh et al. 2017). Choosing the correct virtual environment for such training becomes a crucial consideration, as the environment will affect workers' hazard identification abilities (Lee et al. 2022b; Liao et al. 2021). While many studies have used virtual reality as a promising safety training platform (e.g., Eiris et al. 2020a; Moore et al. 2019; Pooladvand et al. 2021), various limitations—such as high computational cost and extended development time—limit their application. Consequently, 360° panorama training resources are gaining attention since these tools require less time and lower costs than virtual reality (Eiris et al. 2018,2020a; Lee et al. 2022c; Moore et al. 2019). In one of the seminal studies, Eiris et al. (2018) developed the Panoramas of Reality for Safety training (PARS) platform to enhance the hazard-identification skills of trainees. In this Unity 3D desktop-based platform, four types of hazards were augmented on the 360° panoramas; participant's hazard identification skills were then assessed by monitoring their behavior within the panoramas, and feedback was provided based on the trainees' performance during the assessment session. Although participants reported a higher sense of presence and provided positive feedback about the realism of the 360° environment, the results showed that, on average, only 73.3% of the hazards were recognized by subjects, as compared to 86.9% of hazards identified in the VR platform (Eiris et al. 2020a). Such data present opportunities but raise questions about the comparative advantage of 360° panoramas for training purposes.

Another study developed an HMD-based platform that integrates immersive interactions within 360° panoramas (Eiris et al. 2020b) to investigate the cogency of the platform for hazard-recognition and risk-perception training and to compare the platform's training effectiveness with the OSHA 10- or 30-hour safety training. The outcomes highlighted participants in the non-OSHA-certified group successfully achieved similar hazard identification scores after 15 minutes of training to OSHA-certified participants spending 10 or 30 hours in OSHA training. In addition, Jeelani et al. (2020) developed safety training using 360° panoramic images and 360° walk-through videos captured on a construction site to simulate hazards and improve workers' safety performances. The study used the 360° visualizations to customize training by assessing hazard recognition performance and providing users with feedback regarding missed hazards (Jeelani et al. 2020). Recently, a study conducted by Lee and his colleagues proposed a personalized multi-modal safety assessment and training platform using 360° construction videos, eye-tracking, and physiological responses to address cognitive limitations that cause failures in hazard recognition, including attentional failure, inattentional blindness, and low perceived risk (Lee et al. 2022c).

Overall, all the studies reviewed reported positive feedback for greater immersion and realism within the 360° panorama environments. Since these features play a considerable role in developing a more effective learning environment, 360° panorama technologies offer the potential for developing effective construction-related educational materials and training.

- ***Construction Visualization***

A visual representation of a construction site helps users comprehend related information better. The scope of this representation may vary from a simple desktop walk-through video to an advanced interactive VR digital twin. However, a visualization tool must be highly immersive to provide a realistic representation of any construction site. Accordingly, in one seminal study, Gheisari et al. (2016) integrated building information modeling (BIM) and 360° panorama simulations to produce a semi-augmented visual experience to convey required building information in a virtual interactive environment. This simulation showed that participants responded positively to the platform's usability and productivity with augmented panorama. In another study, Eiris and his colleagues used 360° images and videos to develop a virtual representation of a construction site using an interactive panoramic scene displayed on an iPad; their goal was to provide a virtual tour of a complex project and use the visualization as a documentation and asset management tool for locating and visualizing building components, monitoring conditions, and documenting defective work (Eiris et al. 2017).

Additionally, immersive visualization methods can be employed to enhance post-construction sales (i.e., real-state). One study that designed 360° videos with VR glasses (HMD) to increase real estate sales carried out a field experiment (Felli et al. 2018). The results emphasized that customers were highly satisfied with the proposed application and their need for personal inspection could be minimized (Felli et al. 2018)—the adaptation of 360° panoramas worked as a replacement for on-site visits. In another study, Ha and his colleagues (2019) explored the implications of providing an immersive experience for future building occupants using visualization technologies (e.g., VR, AR, 360°). Results of this study showed that while participants reported the 2D images were insufficient visualization techniques due to the missed mark and failure to provide enough information regarding the building, the immersive environments were found to be more effective visualization tools for participants (VR was the most informative and immersive visualization tool compared to AR and 360°) (Ha et al. 2019).

These visualization studies demonstrate the benefits of using 360° panoramas as a proper visualization tool for various activities within construction. Currently, the use of 360° panoramas as a visualization and augmentation tool is limited. However, with its versatility, cost advantages, and successful implementation examples in other industries, 360° panorama technologies could foreseeably find further utilization and applications within construction visualization.

- ***Construction Monitoring***

One recent application area for 360° panorama technologies is construction monitoring and quality control. Construction progress monitoring keeps projects on track per schedule and budget (Halder et al. 2021). Usually, supervision and monitoring are performed via on-site human supervision and quality control checklists, but manual inspection can be time-consuming, lack consistency, be inaccurate, and is often highly dependent on the supervisor's work experience (Afsari et al. 2022). Alternatively, software applications including HoloBuilder, StructionSite, Reconstruct, VisualPlan, CUPIX, OneSpace, OnSiteIQ, and ContextVR provide 360° viewing and documentation solutions to capture more views using fewer images, enhance accuracy, and save time (Afsari et al. 2022).

In one of the early studies of 360° panorama, a panoramic supervision system was developed to closely monitor an interior renovation (Shih et al. 2001). This PC-based system used Hypercam 360° cameras, which were installed on the ceiling of the building, to record 360° videos. The application was compared to a standard checklist, a common manual supervision approach. The results showed a significant increase in the efficiency and effectiveness of the supervision when using the panoramic supervision system. Similarly, Ng et al. (2021) developed an AI-enabled viAct's 360° camera for construction progress tracking. The camera used a unique wall texture classification algorithm as well as image segmentation and experimental feature-extraction algorithms, which distinguished it from other technologies used for construction monitoring. The AI system of viAct's 360° camera made progress tracking faster, more accurate, and more reliable (Ng et al. 2021).

Automated construction progress monitoring is one of the most recent advancements in the construction industry using 360° panorama technologies. Due to their advanced capabilities and high accuracy, these automated inspection systems can overcome the limitations of traditional in-person project monitoring by improving the efficiency and quality of process monitoring on a construction site (Alizadehsalehi and Yitmen 2019). Recently, several studies used the 'SPOT' four-legged robot, which was developed by Boston Dynamics, along with a 360° camera and Holobuilder JobWalk application to capture images of a construction site to monitor the progress of the project (Afsari et al. 2021, 2022; Halder et al. 2021). This system obtained 360° monitoring information from fixed waypoints—locations within the construction site identified through the JobWalk application's 2D layout of the construction site. The effectiveness of this monitoring setup was later evaluated by Afsari et al. (2022), where the study used a series of evaluation criteria to compare human-driven image capturing to the robot-enabled automated construction progress–monitoring system. Apart from certain robotic and operational limitations, the robot-enabled automated progress–monitoring system was found to be very efficient (Afsari et al. 2022). Similarly, Halder et al. (2021) developed a BIM-led visualization to capture images of a construction jobsite. They used the BIM initially to create the virtual environment, which they spatially linked with waypoints, where SPOT captured the 360° images. This environment was then shared with supervisors and remote stakeholders and was linked with default BIM models for real-time progress monitoring (Halder et al. 2021).

Apart from progress monitoring, 360° panorama technologies have considerable application spaces regarding quality control on construction jobsites. In such cases, 360° reality capture can be beneficial for extracting spatial information such as the size, shape, and position of building components in its real or as-built state. This information can be used to construct 3D models for visualization in different environments (Subramanian and Gheisari 2019). Subramanian's study compared 360° panoramic photogrammetry to laser scanning in creating point cloud data for assessing a project's time, cost, and quality. This study showed that 360° panoramic photogrammetry is less time-consuming and less costly for generating data points; however, laser scanning provided higher capturing quality with less error rate (Subramanian and Gheisari 2019). Therefore, 360° panoramic photogrammetry can be a very effective tool where accuracy is not a key concern or where budget is a key concern.

Overall, the reviewed literature confirmed that using 360° panoramic technologies for progress monitoring and quality control can increase the realism of the content captured and, in combination with other technologies such as robotics, can enhance opportunities for remote or automated monitoring.

- ***Cognitive Analysis and Human-behavior in Construction***

Due to the dynamic nature of construction sites, workers are required to properly allocate their attention toward the surrounding environment to remain situationally aware. As situation awareness affects which information people attend to and which they ignore—cognitive processes—situation awareness informs humans' decision-making in response to a given event (Hasanzadeh et al. 2017). Thus, to study and understand workers' cognitive processing, researchers must capture workers' natural behaviors, a task that demands providing realistic and convincing immersive environments for experimental settings. In fact, some studies indicate that a disconnect between the testing environment and the real construction environment could cause an incorrect assessment of workers' capabilities, which would impede effective training (Jeelani et al. 2020).

Accordingly, in a cognitive behavior analysis study, Lee and his colleagues used 360° panoramic videos to empirically explore workers' hazard identification skills and corresponding attention and perception behavior (Lee et al. 2022a). In this study, Lee emphasized the importance of ecological validity and its impact on an individual's cognitive processes and naturalistic behavior, providing insight into the ecological validity of 360° videos for hazard identification performance assessment. Additionally, Lee et al. (2022b) provided evidence of the impact of the simulation environment on hazard identification performance (360° image vs. 360° video). The results highlighted that most workers could identify more hazards in the 360° videos than in 360° images. The empirical evidence provided by both studies highlights the effectiveness of using 360° panoramas in cognitive and human behavior analysis studies in construction.

In sum, these studies manifest the breadth of research potential in this domain, since 360° panoramas offer additional ecology, contributing towards a more naturalistic environment that provides beneficial alternatives to current simulation environments used for safety training, virtual education, field trips, and assessing construction workers' behavior. Further, the advanced high-end development of these applications for 360° panoramas can translate to new, versatile opportunities for immersive visualization approaches in the AEC industry.

4. DISCUSSION

4.1 Prevalent 360° Application Areas in AEC

The findings demonstrated that scholars employed 360° technologies in various domains. However, there are specific areas in the construction industry where the use of 360° panorama is prominent:

Safety training (24%): Regarding safety training development, information delivery, realism, and a sense of presence play a vital role in increasing workers' engagement. Researchers have identified that 360° panoramas can be an effective alternative to virtual reality, which is often too expensive and time-consuming to develop. Additionally, some studies explained that VR creates a simplified and clean environment, which contradicts the nature of construction sites and raises concerns about safety training, where ecological validity is fundamental to assessing workers' true abilities (Lee et al. 2022b). Notably, a few studies tried to compare safety training provided with different simulation techniques (Eiris et al. 2020a; Moore et al. 2019).

Virtual site visits (18%): Among various 360° panorama applications, construction education holds a lot of potential scope for future development. Currently, 360° panorama technologies have been used to conduct studies related to learning through construction labs and as a substitute for physical site visits, providing an excellent alternative to expensive and dangerous site visits. Due to the higher telepresence and realism of the contents, students perceived the experience as similar to an actual site visit. Moreover, tele-education can allow students to experience a more collaborative and inclusive learning environment.

Progress monitoring (18%): Due to the realistic content of 360° panoramas, progress monitoring is more accurate and takes less time than manual or in-person supervision and monitoring. Coupled with advanced robotic technology, many studies incorporated 360° panoramas to elevate the performance of existing progress monitoring tools. Researchers are currently working on AI-enabled image classification algorithms, which will automate the classification and analysis of these images for better progress monitoring. Further, this application can significantly affect the remote progress monitoring for large-scale projects, where stakeholders often cannot access construction sites.

Site visualization (13%): Visualization tools can reduce complications for pre- and post-construction quality checks and clash detection in construction areas. In addition, 360° videos and images can be an excellent tool for post-construction demonstration and sale purposes. Combining 360° panoramas with other simulations or technologies, such as VR and AR, can create better visualizations of a construction site. These visualization tools are crucial to new opportunities, such as remote monitoring and advanced sales marketing.

This review illustrates that 360° panorama technologies provide a much easier and cost-effective platform for AEC industry professionals as producers while offering more realism and a higher sense of user presence. While these technologies may be a game changer for many aspects of the AEC industry and have the potential to replace many existing technologies and methods (e.g., 2D images and videos, animation and virtual reality), the current status of applications is nascent. Additional research is indeed required to understand the suitability and impact of 360° panorama technologies in more diverse situations.

4.2 Comparison Between 360° Panoramas and Virtual Reality

Since different visualization methods have varied advantages and characteristics, it is crucial to properly understand the nature of each technology. Accordingly, previous studies have compared several parameters related to simulations, such as users' sense of presence, visual appeal, and ease of imagination (Eiris et al. 2020a; Orús et al. 2021). As Table 5 illustrates, among the eighty reviewed studies, eight include a comparison between two visualization technologies—360° panorama and virtual reality (Brivio et al. 2021; Eiris et al. 2020a; Ha et al. 2019; Martínez-Navarro et al. 2019; Moore et al. 2019; Nason et al. 2020; Orús et al. 2021; Ritter and Chambers 2022).

Table 5. *Comparison between 360° panoramas and virtual reality in reviewed studies*

Evaluation Parameters	Measurement Tool	360° panorama	VR	Publications
Presence, ease of imagination, visual appeal, intention to book	Questionnaire	Higher sense of presence	Less ease of imagination	(Orús et al. 2021)
Immersive-ness, anxiety, motion sickness	Questionnaire	More realistic, more anxiety	More control within virtual space	Nason et al. (2020)
Emotional experience, anxiety, feeling of presence	Questionnaire	Similar levels of sense of presence and emotional states (e.g., arousal, happiness, anxiety)	Similar levels of sense of presence and emotional states	Brivio et al. (2021)
Opinion formation scale (i.e., opinion about the building)	Questionnaire	No significant contribution towards forming opinions	More elaborated, greater visualization	Ha et al. (2019)
Sense of presence, emotions, discomfort, intention to purchase	Questionnaire	High sense of presence, more discomfort, higher purchase intention	Less discomfort	Martínez-Navarro et al. (2019)
Presence, comparative analysis (spatial understanding, distraction, comfort)	Questionnaire	Similar sense of presence, more spatial understanding	More comfort, less distraction	Ritter and Chambers (2022)
Hazard identification index (HII)	None	More realistic, chaotic, messy	Cleaner, easy to use, higher hazard identification index	Moore et al. (2019)
Sense of presence, hazard identification index (HII)	Questionnaire	Higher sense of presence	Higher hazard identification index	Eiris et al. (2020a)

These studies often assessed various factors depending on the purpose of the study and the objective of their experiment to establish the comparison. Commonly, for realism, the "sense of presence" parameter was the main parameter. As the sense of presence influences participants' arousal and immersion in a simulated environment, it plays a key role in the successful projection of any simulation. While five studies directly used the sense of presence as a parameter to compare 360° panorama and virtual reality (Brivio et al. 2021; Eiris et al. 2020a; Martínez-Navarro et al. 2019; Orús et al. 2021; Ritter and Chambers 2022), two papers utilized different scales and parameters obtained in the form of the post-trial questionnaire from participants (Ha et al. 2019; Nason et al. 2020). The reviewed studies generally indicated that a 360° environment could be very immersive and realistic, invoking a higher sense of presence. However, the higher immersion or sense of presence may not assure a higher perception of surroundings (Brivio et al. 2021; Eiris et al. 2020a; Moore et al. 2019); there may be additional factors that may influence visualization, depending on the studied conditions.

360° simulation platform is a more realistic and cost-friendly alternative to the VR platform, as VR often requires a longer development process and faces higher computational costs. The results illustrated that students found the

360° panoramas platform more realistic, while professionals observed no significant difference in both platforms. Some studies reported that participants were more comfortable using virtual reality environments than 360° environments (Ha et al. 2019; Martínez-Navarro et al. 2019; Nason et al. 2020).

In terms of hazard identification performance, VR simulations correlated with better hazard identification among users (Eiris et al. 2020a; Moore et al. 2019), though a critique suggested the VR environment was cleaner and less chaotic and therefore actually did not represent the actual jobsite (Eiris et al. 2020a). Therefore, selecting an appropriate hazard delivery format regarding construction safety training is crucial as it can affect workers' overall hazard identification ability (Lee et al. 2022b; Liao et al. 2021), and the simulated environment should be able to represent the dynamic and complex nature of the construction site. Even though VR creates a clean and simplified environment, it fails to mimic the dynamic and risky nature of a construction site. Thus, while scores for effectiveness may weigh in VR's favor, 360° technologies may be more effective in assessing natural hazard identification performance, providing a better and more accurate training strategy to construction workers.

4.3 Comparison Between Head-Mounted and Flat Screen/Handheld 360° Display Options

Virtual environments, or simulations, are designed to mimic real-world experience as closely as possible, but how they are displayed significantly affect the entire illusion. Virtual environments can be displayed through various devices, including CAVEs (Cave automatic virtual environment), head-mounted displays (VR headset), flat-screen computers or laptops, and handheld displays (cellphones or tablets). Such displays play a significant role in achieving the immersion required for a better user experience because displays facilitate human interactions with the process, simulation, and data presented; furthermore, displays provide feedback to the users that personify the exchange between the person and the simulation, completing an essential human-system-human loop (Sadagic 2016). Various complex and multidimensional links between perception, cognition, physical body, and actions in an environment are unified in a single phenomenon called embodiment. Consequently, it is essential to investigate the interdependence and correlation among these links, embodiment, and choice of display, to create a perfectly immersive and compelling simulation environment that can provide the highest feeling of telepresence to its user.

Thus, some studies in the literature compared the type of display used to deliver the visualization to understand the influence of display selection on factors such as sense of presence, visual appeal, and arousal level. As shown in Table 6, seven of the eighty publications studied compared the effects of display on participants' perception of the environment (Breves and Heber 2020; Kelling et al. 2017; Kim et al. 2019; Martínez-Navarro et al. 2019; Orús et al. 2021; Voigt-Antons et al. 2020; Waller et al. 2021). All seven studies that compared the display methods on multiple parameters showed that participants reported a higher level of spatial presence when they watched the 360° scenarios using an HMD rather than using a regular screen or handheld device. However, laptops and handheld devices were found to be handier, easier to operate, and less expensive than HMD, though these devices did not deliver the same experience. Previous studies also showed that participants had a lower engagement in the scenario when it was delivered with a handheld device. While Waller et al. (2021) did not measure the sense of presence directly with a scale or a tool, the comments from the participants stressed that they felt more 'present' while viewing a pre-recorded 360° video on HMD than on a flat-screen. Two other studies (Orús et al. 2021; Voigt-Antons et al. 2020) used presence as a measure to evaluate immersive-ness; Orús' study utilized a handheld device (smartphone), whereas Voigt-Antos used a computer screen as a comparison display. Both studies showed that participants had a higher sense of presence when the content was delivered in an HMD than on a smartphone or computer flat screen. Based on these findings, the current research team concluded that the type of display affects participants' sense of presence in a 360° environment and HMD serves as the best display tool to boost the feeling of presence and enhance the experiment's realism.

Table 6. *Comparison between the effectiveness of display options for 360° panoramas in reviewed studies*

Evaluation Parameters	Measurement Tool	Head-Mounted Display[1]	Flat Screen/Hand-Held Display	Publications
Positive/negative emotions, satisfaction, and credibility	Questionnaire	Higher relaxation, more attention	Less sense of presence	Waller et al. (2021)
Presence, ease of imagination, visual appeal, and intention to make reservation	Questionnaire	Higher sense of presence	Less sense of presence, less visualization	Orús et al. (2021)

Evaluation Parameters	Measurement Tool	Head-Mounted Display[1]	Flat Screen/Hand-Held Display	Publications
Spatial presence, involvement, experienced realism, and general presence	Interview and questionnaire	More spatial presence, more realism	Lower involvement	Kelling et al. (2017)
Presence, valence, and arousal	Questionnaire	Higher sense of presence	Lower arousal level, similar level of valence	Voigt-Antons et al. (2020)
Perception in terms of ability to interact with the environment, telepresence	Questionnaire	Better perception	Less interactive, similar telepresence	Kim et al. (2019)
Sense of presence, emotions, affective appraisal, discomfort, Intention to purchase	Questionnaire	Similar sense of presence, more discomfort, similar purchase intention	Less discomfort	Martínez-Navarro et al. (2019)
Spatial presence, commitment to environment	Questionnaire	Higher sense of presence	Low impact to improve commitment to environments	Breves and Heber (2020)

[1] *HMDs can either be standalone devices or a smartphone-mounting device. Compared to standalone HMD devices, smartphone HMDs are less expensive and easier to operate. The comparison results showed significant differences between types of display in terms of resolution, refresh rate, the field of view, update rate, and other factors that determine the quality of visualization perceived by users.*

4.4 Advantages of 360° Panorama Technologies in AEC industry

Previous studies highlighted the advantages of 360° panorama technologies over other visualization technologies, as relevant to applications in the AEC industry.

Economical Choice: Many publications indicated that 360° panorama technologies are economical and time-saving choices (Kavanagh et al. 2016; Eiris et al. 2020a,b). These systems can replace the expensive and lengthy traditional experience of a complete VR environment. Thus, 360° panoramas can be used as an alternative simulation technology where the cost and time of development are a severe concern. Since construction projects often have these two constraints, 360° panorama acts as an ideal visualization tool, to capture, store and report the progress at construction jobsite. The affordability of this technology offers a great cost-effectiveness due to being inexpensive and having multi-disciplinary applications.

Ecological validity: Ecological validity can be defined as “the degree to which results obtained in controlled experimental conditions are related to those obtained in naturalistic environments” (Chaytor and Schmitter-Edgecombe 2003). Consequently, a visualization’s ability to simulate an environment that is highly similar to the real world fundamentally underpins a participant’s sense of presence and immersion. Indeed, the accuracy of participants’ behaviors, natural reactions, and subjective data all highly depend on whether the participants behaved/reacted as they would in the real world (Lee et al. 2022a; Deb et al. 2017). While past studies (e.g., Reggente et al. (2018)) have used a computer-generated VR for conducting studies related to ecological validity, a VR environment fundamentally struggles to provide a realistic simulation due to its animated characteristics. Furthermore, although animation versus photographic cameras certainly affect ecological validity, even the type of camera used in a 360° study may affect users’ experience: Lee’s study used 360° videos and images captured from jobsite and compared subjects’ cognitive ability under different information delivery methods (i.e., image-based versus video-based) (Lee et al. 2022b). The results indicated that using static images reduces the experiment's ecological validity due to information distortion and fails to stimulate participants’ naturalistic cognitive performance. In comparison, 360° videos of construction scenarios effectively simulate the dynamic nature of the jobsite and can serve as a better hazard identification assessment platform.

Sense of Presence: A fundamental strength of using 360° panoramas over computer-generated VR is users’ sense of reality, which, as discussed above, significantly impacts their sense of presence. Sense of presence is a complex mental mechanism that profoundly relates to human reasoning abilities (Herbelin et al. 2003), and it is one of the critical cognitive elements highly connected to the simulation environment. 360° panoramas’ strength for this consideration is important. The post-construction sale of properties can greatly benefit from such a realistic visualization tool. As highlighted by studies in AEC, virtual tour using 360° panorama eliminated the need of physical inspection or on-site visit. This feature allows professionals from AEC to advertise their product widely and expand the real-estate markets.

4.5 Applications of 360° Panorama Technologies with-in existing digital tools in AEC industry

Although 360° panorama can function as a standalone visualization tool that does not require additional technology for its application, various platforms have emerged that incorporate this visualization technology into their existing frameworks. Traditionally, virtual reality (CGI-based virtual environment) has been the preferred choice for researchers in diverse applications within domains such as Building Information Modeling (BIM), walk-through videos, and safety training. However, recent studies have started adopting 360° panorama as a new visualization technology within their platforms.

For instance, Côté et al. (2013) and Gheisari et al. (2016) introduced platforms that combined 360° panorama with augmented reality, allowing the projection of HVAC systems and associated layouts onto the panoramic view. Furthermore, 360° panoramas have been integrated into BIM platforms like Revit and WebGIS, enabling researchers to create panoramic walkthroughs of construction jobsites (Chien Pham et al. 2018; Halder et al. 2021). In the AEC domain, researchers have integrated 360° panorama with tools such as game engines and architecture/BIM software. It is worth noting that, currently no studies in the AEC field have explored the integration of 360° panorama within project management software or tools. However, certain commercially available software already offers the feature of incorporating 360° panorama into their platforms. Therefore, future researchers can potentially explore the application of 360° panorama within project management tools, leveraging the capabilities of these software solutions.

4.6 Limitations of 360° Panorama Technologies in AEC industry

As with any other simulation technology, 360° panoramas have a few limitations identified within the reviewed studies.

Cybersickness: Cybersickness (CS) is a type of motion sickness and discomfort that users in virtual environments commonly experience. CS symptoms include nausea, headaches, and dizziness. Many publications referred to CS as simulator sickness, a motion sickness syndrome often experienced during or after a session in a simulator or VR exposure (Dużmańska et al. 2018). According to Groth et al., (2021), sensory conflict theory, a conflict between different modalities, can be the most common cause of CS, since cybersickness can present as a conflict between the vision system and the vestibular system. Alternatively, optical flow, a critical component that affects CS, can be defined as a motion pattern created due to the relative motion of objects present in the visual scene compared to the camera/observer (Bala et al. 2020). Each of these factors may fundamentally affect users' experience of CS.

As immersive technologies become more prevalent and commercially available, researchers place a growing concern on CS. In the literature, only a few studies evaluated the impact of using a 360° environment on users' CS (Ardisara and Fung 2018; Arvaniti and Fokides 2020; Eiris et al. 2021; Feng et al. 2021; Kelling et al. 2017; Mouratidis and Hassan 2020; Nason et al. 2020; Škola et al. 2020; Ventura et al. 2021). Even though many studies (Arvaniti and Fokides 2020; Eiris et al. 2021; Feng et al. 2021) reported that it is less likely that participants undergo CS, a few publications (Mouratidis and Hassan 2020; Nason et al. 2020; Ventura et al. 2021) noted higher CS experienced by their participants. These studies also indicated that the causal factor for the higher CS may relate to the motion involved while capturing the 360° videos, i.e., participants observed videos that were in motion in a standstill position. These studies also suggested that static capturing, where the whole capturing or recording is done from a single point without any motion, may help reduce the CS (Ardisara and Fung 2018; Mouratidis and Hassan 2020).

The case of HMDs' effect on CS demonstrates that it is critical to use compatible visual environment applications (e.g., Game engines, WebGIS) to support the presentation of a virtual environment. For instance, Nason et al. (2020) reported that participants experienced more CS when the motion in the 360° panorama did not sync with the participant's motion (i.e., they experienced a lag when they rotated their head, such that the image would rotate after the head turned). Thus, developers should emphasize the selection of compatible technologies to avoid CS, and researchers should consider CS as part of their experimental protocol when using an immersive environment.

To mitigate CS with 360° videos, two approaches, such as gaze-contingent peripheral blurring and gaze-contingent peripheral occlusion, are suggested (Groth et al. 2021). While blurring reduces the resolution of the unfocused area, under the occlusion approach, the unfocused area is completely occluded or overshadowed. Previous studies showed that gaze-contingent peripheral opaque occlusion is more effective in mitigating cybersickness in 360° videos because of the considerably reduced optical flow (e.g., Groth et al. 2021). These past studies show CS is a limitation that can obstruct a user from having a flawless experience with 360° technologies. Researchers are well-advised to find an effective strategy to reduce CS in order to enhance the effects of presence in their immersive environments.

Since many applications of 360° panorama in AEC domain may expose this technology to novice or even first-time user (e.g., students taking lessons or attending VR tour, sales customers, project stakeholders etc.) mitigation of cybersickness is a crucial task. In addition, for applications such as safety training and progress monitoring which can occur repetitively and require undivided attention of the user, cybersickness presents a serious threat. In order to overcome this limitations, researchers and developers can employ the solutions suggested by these studies to eliminate cybersickness to an extent and improve their experience.

Technical Properties: Several studies reviewed in the literature reported multiple technical limitations due to 360° panorama technologies, such as low image quality (e.g., Kim et al. 2019; Eiris et al. 2020c; Kelling et al. 2017; Nason et al. 2020), the fixed vantage point (e.g., Feng et al. 2021; Ritter and Chambers 2022), stitching error artifacts (e.g., Eiris et al. 2020a; Nason et al. 2020; Ritter and Chambers 2022), and lack of mobility (e.g., Eiris et al. 2020a, 2022; Kim et al. 2019; Nason et al. 2020).

The image quality is a typical concern for 360° panoramas. Specifically, the cheaper, commercially available 360° cameras do not offer as high an image quality as traditional photography or videography. As the final image displayed in 360° panoramas is an amplified version of the overall image, the amplification process (increasing the size portions of the original image) causes lower image quality (Eiris et al. 2020b). More professional cameras provide higher image quality for 360° panoramas. However, these cameras need to sacrifice mobility and image-capturing speed.

In the dynamic environment of construction, these limitations are significant. High-speed image capturing is needed to obtain high-resolution data. In addition, a static vantage point constrains the field's spatial movement and users' exploration by limiting optical rotation only to captured view (e.g., Eiris et al. 2020a; Pereira and Gheisari 2019; Saarinen et al. 2017). In addition, some parallax issues (e.g., blurriness, discontinuities, illumination) may appear in 360° videos due to problems with stitching algorithms. These stitching error artifacts often occur close to the camera focal point and/or at positions where the stitching lines intersect and when there is a considerable difference in the light exposure between camera lenses (Eiris et al. 2020a; Saarinen et al. 2017).

Based on the observations and recommendations of the existing studies, the selection of technology is a critical decision for researchers or commercial developers. Some of the limitations related to technical properties, such as capturing resolution, lighting etc. can be overcome by using advanced cameras that are equipped with state-of-the-art features. Sales visualization and cognitive studies are the application that will specifically benefit from mitigating this error as users can experience a higher sense of presence because of maximized resolution and improved quality. As researchers of AEC domain increase the adoption of this technology in future, more limitations will surface. Future researchers can investigate additional measures to address the new as well as existing limitations of such technical limitations to improve the quality of this visualization technology.

Overall, the review of the studies presented in this paper demonstrate various technical challenges and limitations faced by researchers implementing 360° panorama technologies into their respective fields. Such limitations are good to consider to more efficiently design future experimental settings.

5. CONCLUSION

360° panorama technologies use omnidirectional photography to realistically record the entire surrounding of a camera. Recently, these image-capturing and simulation technologies received increasing attention for such characteristics as their realism, high-quality visualization, information delivery, ecological validity, ease of use, and affordability. To explore such considerations within research spaces, this review paper provided detailed applications of 360° technologies across different sectors, discussed potential future research avenues, and raised summaries of these technologies' limitations. This systematic literature review delivers thorough information about using 360° technologies in non-AEC domains—such as psychology, behavioral analysis, marketing, emergency planning, classroom and laboratory teaching sessions, and driving automation assistance—as well as within the AEC domains of architecture, construction education/training, construction visualization and monitoring, and worker-behavior studies. Overall, the results of the review provide future research ideas in the AEC domain.

After a rigorous review of studies in the AEC domain, it was observed that even though some researchers have conducted interesting studies into replacing traditional in-person tasks with 360° technologies, the AEC domain failed to adapt certain applications of 360° panorama that are prominent among non-AEC domains. Moreover, the methodology of application of 360° technology was versatile in non-AEC domains, compared to methodologies in AEC domain. Primarily, 360° panoramas (mainly images) were used for 'construction education and training,' followed by 'construction monitoring,' 'construction visualization,' 'architecture,' and 'cognitive analysis and human behavior.' Interestingly, previous studies reported that 360° simulations are more similar to an actual construction site, confirming a higher sense of presence. Overall, 360° in combination with HMD provoked a better sense of presence when compared with simple VR. Limitations identified in the reviewed paper are worth noting: cybersickness, stitching error effects, static vantage point, and resolution. If the experiment/platform is not appropriately designed, these limitations can significantly affect visualization quality concerning the sense of presence, immersion, and involvement. It must be noted that the findings of this study are limited to the inclusion and exclusion criteria discussed.

To summarize, this state-of-the-art systematic literature review addressed various research questions regarding the current status and potential application areas of 360° panorama technologies. This paper's findings have theoretical and practical implications. Theoretically, this paper systematically discussed the findings of all 360° related papers in the last decade to deepen the understanding of how this state-of-art technology can overcome other technologies' limitations/challenges and support future research ventures. Furthermore, by discussing the development process, limitations, and advantages of these technologies, this paper can serve as a guide for future researchers and practitioners seeking useful guidelines for designing and using 360° technologies more effectively in the AEC domain and beyond.

ACKNOWLEDGMENT

The National Science Foundation is thanked for partially supporting the research reported in this paper (2049711). Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

Afsari, K., S. Halder, M. Ensafi, S. DeVito, and J. Serdakowski. 2021. "Fundamentals and Prospects of Four-Legged Robot Application in Construction Progress Monitoring." 274–263.

Afsari, K., S. Halder, R. King, W. Thabet, J. Serdakowski, S. DeVito, M. Ensafi, and J. Lopez. 2022. "Identification of Indicators for Effectiveness Evaluation of Four-Legged Robots in Automated Construction Progress Monitoring." *Construction Research Congress 2022*, 610–620. Reston, VA: American Society of Civil Engineers.

Aitamurto, T., S. Zhou, S. Sakshuwong, J. Saldivar, Y. Sadeghi, and A. Tran. 2018. "Sense of Presence, Attitude Change, Perspective-Taking and Usability in First-Person Split-Sphere 360° Video." *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, 1–12. New York, NY, USA: ACM.

Alizadehsalehi, S., and I. Yitmen. 2019. "A Concept for Automated Construction Progress Monitoring: Technologies Adoption for Benchmarking Project Performance Control." *Arab J Sci Eng*, 44 (5): 4993–5008. Springer Berlin Heidelberg. https://doi.org/10.1007/s13369-018-3669-1.

Ardisara, A., and F. M. Fung. 2018. "Integrating 360° Videos in an Undergraduate Chemistry Laboratory Course." *J Chem Educ*, 95 (10): 1881–1884. https://doi.org/10.1021/acs.jchemed.8b00143.

Arents, V., P. C. M. de Groot, V. M. D. Struben, and K. J. van Stralen. 2021. "Use of 360° virtual reality video in medical obstetrical education: a quasi-experimental design." *BMC Med Educ*, 21 (1): 1–9. BMC Medical Education. https://doi.org/10.1186/s12909-021-02628-5.

Argyriou, L., D. Economou, and V. Bouki. 2020. "Design methodology for 360° immersive video applications: the case study of a cultural heritage virtual tour." *Pers Ubiquitous Comput*, 24 (6): 843–859. Personal and Ubiquitous Computing. https://doi.org/10.1007/s00779-020-01373-8.

Arvaniti, P. A., and E. Fokides. 2020. "Evaluating the effectiveness of 360 videos when teaching primary school subjects related to environmental education." *Journal of Pedagogical Research*, 4 (3): 203–222. https://doi.org/10.33902/JPR.2020063461.

Bala, P., I. Oakley, V. Nisi, and N. Nunes. 2020. "Staying on Track: A Comparative Study on the Use of Optical Flow in 360° Video to Mitigate VIMS." *IMX 2020 - Proceedings of the 2020 ACM International Conference on Interactive Media Experiences*, 82–93. https://doi.org/10.1145/3391614.3393658.

Barić, D., G. M. Havârneanu, and C. Măirean. 2020. "Attitudes of learner drivers toward safety at level crossings: Do they change after a 360° video-based educational intervention?" *Transp Res Part F Traffic Psychol Behav*, 69: 335–348. https://doi.org/10.1016/j.trf.2020.01.018.

Beck, J., and R. Egger. 2018. "Emotionalise Me: Self-reporting and Arousal Measurements in Virtual Tourism Environments." *Information and Communication Technologies in Tourism 2018*, 3–15. https://doi.org/10.1007/978-3-319-72923-7_1.

Bolkas, D., J. D. ; Chiampi, J. R. Kepner, L. J. Kepner, and D. Neilson. 2020. "Development and Integration of Immersive 360-Videos in Surveying Engineering Education Development and Integration of Immersive 360-Videos in Surveying Engineering Education."

Bourke, P. 2014. "The Panorama: Applications to Science and Heritage Visualization." *Lawrence Wilson Art Gallery, Web.< http://paulbourke. net/papers/lawrencewilson*.

Breves, P., and V. Heber. 2020. "Into the Wild: The Effects of 360° Immersive Nature Videos on Feelings of Commitment to the Environment." *Environ Commun*, 14 (3): 332–346. Taylor & Francis. https://doi.org/10.1080/17524032.2019.1665566.

Brivio, E., S. Serino, E. Negro Cousa, A. Zini, G. Riva, and G. de Leo. 2021. "Virtual reality and 360° panorama technology: a media comparison to study changes in sense of presence, anxiety, and positive emotions." *Virtual Real*, 25 (2): 303–311. Springer London. https://doi.org/10.1007/s10055-020-00453-7.

Chang, C.-Y., H.-Y. Sung, J.-L. Guo, B.-Y. Chang, and F.-R. Kuo. 2019. "Effects of spherical video-based virtual reality on nursing students' learning performance in childbirth education training." *Interactive Learning Environments*, 30 (3): 400–416. https://doi.org/10.1080/10494820.2019.1661854.

Chaytor, N., and M. Schmitter-Edgecombe. 2003. "The Ecological Validity of Neuropsychological Tests: A Review of the Literature on Everyday Cognitive Skills." *Neuropsychol Rev*, 13 (4): 181–197. https://doi.org/10.1023/B:NERV.0000009483.91468.fb.

Chien Pham, H., Q. Tuan Le, N. Dao, A. Pedro, Q. le Tuan, R. Hussain, S. Cho, and C. Park. 2018. "Virtual Field Trip for Mobile Construction Safety Education Using 360-Degree Panoramic Virtual Reality." *International Journal of Engineering Education*, (June): 1174–1191.

Chien, S. Y., G. J. Hwang, and M. S. Y. Jong. 2020. "Effects of peer assessment within the context of spherical video-based virtual reality on EFL students' English-Speaking performance and learning perceptions." *Comput Educ*, 146 (April 2019): 103751. Elsevier Ltd. https://doi.org/10.1016/j.compedu.2019.103751.

Çöltekin, A., I. Lochhead, M. Madden, S. Christophe, A. Devaux, C. Pettit, O. Lock, S. Shukla, L. Herman, Z. Stachoň, P. Kubíček, D. Snopková, S. Bernardes, and N. Hedley. 2020. "Extended reality in spatial sciences: A review of research challenges and future directions." *ISPRS Int J Geoinf*, 9 (7). https://doi.org/10.3390/ijgi9070439.

Côté, S., P. Trudel, M. Desbiens, M. Giguère, B. Systems, and R. Snyder. 2013. "Live Mobile Panoramic High Accuracy Augmented Reality for Engineering and Construction." *Proc. Int'l Conf. on Construction Applications of Virtual Reality (CONVR'13)*, (October): 30–31.

Deb, S., D. W. Carruth, R. Sween, L. Strawderman, and T. M. Garrison. 2017. “Efficacy of virtual reality in pedestrian safety research.” *Appl Ergon*, 65: 449–460. Elsevier Ltd. https://doi.org/10.1016/j.apergo.2017.03.007.

Dickinson, I., R. C. T. Ellis, A. Riley, and J. Tenant. 2004. “VIRTUAL SITE : PHOTO-REALISM IN THE CLASSROOM.”

Dużmańska, N., P. Strojny, and A. Strojny. 2018. “Can Simulator Sickness Be Avoided? A Review on Temporal Aspects of Simulator Sickness.” *Front Psychol*, 9 (NOV). https://doi.org/10.3389/fpsyg.2018.02132.

Eiris Pereira, R., H. F. Moore, M. Gheisari, and B. Esmaeili. 2019. “Development and Usability Testing of a Panoramic Augmented Reality Environment for Fall Hazard Safety Training.” *Advances in Informatics and Computing in Civil and Construction Engineering*, 271–279. Cham: Springer International Publishing.

Eiris Pereira, R., H. I. Moud, and M. Gheisari. 2017. “Using 360-Degree Interactive Panoramas to Develop Virtual Representation of Construction Sites.” *Lean and Computing in Construction Congress - Volume 1: Proceedings of the Joint Conference on Computing in Construction*, 775–782. Edinburgh: Heriot-Watt University.

Eiris, R., M. Gheisari, and B. Esmaeili. 2018. “Pars: Using augmented 360-degree panoramas of reality for construction safety training.” *Int J Environ Res Public Health*, 15 (11). https://doi.org/10.3390/ijerph15112452.

Eiris, R., M. Gheisari, and B. Esmaeili. 2020a. “Desktop-based safety training using 360-degree panorama and static virtual reality techniques: A comparative experimental study.” *Autom Constr*, 109 (September 2019): 102969. Elsevier. https://doi.org/10.1016/j.autcon.2019.102969.

Eiris, R., A. Jain, M. Gheisari, and A. Wehle. 2020b. “Safety immersive storytelling using narrated 360-degree panoramas: A fall hazard training within the electrical trade context.” *Saf Sci*, 127 (September 2019): 104703. Elsevier. https://doi.org/10.1016/j.ssci.2020.104703.

Eiris, R., J. Wen, and M. Gheisari. 2020c. “iVisit: Digital Interactive Construction Site Visits Using 360-Degree Panoramas and Virtual Humans.” *Construction Research Congress 2020*, 1106–1116. Reston, VA: American Society of Civil Engineers.

Eiris, R., J. Wen, and M. Gheisari. 2021. “iVisit – Practicing problem-solving in 360-degree panoramic site visits led by virtual humans.” *Autom Constr*, 128 (May): 103754. Elsevier B.V. https://doi.org/10.1016/j.autcon.2021.103754.

Eiris, R., J. Wen, and M. Gheisari. 2022. “iVisit-Collaborate: Collaborative problem-solving in multiuser 360-degree panoramic site visits.” *Comput Educ*, 177 (April 2021): 104365. Elsevier Ltd. https://doi.org/10.1016/j.compedu.2021.104365.

Felli, F., C. Liu, F. Ullah, and S. M. E. Sepasgozar. 2018. “Implementation of 360 videos and mobile laser measurement technologies for immersive visualisation of real estate & properties.” *Education Building Professionals for the Future in the Globalised World*, 2 (November): 294–305.

Feng, Y., D. C. Duives, and S. P. Hoogendoorn. 2021. “Using virtual reality to study pedestrian exit choice behaviour during evacuations.” *Saf Sci*, 137 (August 2020): 105158. Elsevier Ltd. https://doi.org/10.1016/j.ssci.2021.105158.

Feng, Z., V. A. González, L. Ma, M. M. A. Al-Adhami, and C. Mourgues. 2018. “Rapid 3D Reconstruction of Indoor Environments to Generate Virtual Reality Serious Games Scenarios.” (2011): 185–195. https://doi.org/arXiv.1812.01706.

Ferworn, A., B. Waismark, and M. Scanlan. 2015. “CAT 360 — Canine augmented technology 360-degree video system.” *2015 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*, 1–4. IEEE.

de Fino, M., S. Bruno, and F. Fatiguso. 2022. “Dissemination, Assessment and Management of Historic Buildings By Thematic Virtual Tours and 3D Models.” *Virtual Archaeology Review*, 13 (26): 88–102. https://doi.org/10.4995/VAR.2022.15426.

de Fino, M., C. Ceppi, and F. Fatiguso. 2020. “VIRTUAL TOURS AND INFORMATIONAL MODELS FOR IMPROVING TERRITORIAL ATTRACTIVENESS AND THE SMART MANAGEMENT OF ARCHITECTURAL HERITAGE: THE 3D-IMP-ACT PROJECT.” *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLIV-M-1–2 (M–1): 473–480. https://doi.org/10.5194/isprs-archives-XLIV-M-1-2020-473-2020.

Fino, M. de, R. A. Galantucci, and F. Fatiguso. 2019. “Remote diagnosis and control of heritage architecture by photorealistic digital environments and models.” *Scires-It*, 9 (2): 1–16. https://doi.org/http://dx.doi.org/10.2423/i22394303v9n2p1.

de Fino, M., A. Scioti, R. Rubino, A. Pierucci, and F. Fatiguso. 2018. “‘Augmented diagnostics’ for the architectural heritage.” *International Journal of Heritage Architecture: Studies, Repairs and Maintence*, 2 (2): 248–260. https://doi.org/10.2495/HA-V2-N2-248-260.

Funtik, T., and P. Mayer. 2021. “Assessing the Influence of on-Site Lighting Conditions To the Potential Variability of the 360 ° Photogrammetry Usability.” *Czech Journal of Civil Engineering*, 6 (2): 41–50. https://doi.org/10.51704/cjce.2020.vol6.iss2.pp41-50.

Furht. 2006. *Encyclopedia of Multimedia*. (B. Furht, ed.). New York: Springer-Verlag.

Getuli, V., P. Capone, A. Bruttini, and S. Isaac. 2020. “BIM-based immersive Virtual Reality for construction workspace planning: A safety-oriented approach.” *Autom Constr*, 114 (March): 103160. Elsevier. https://doi.org/10.1016/j.autcon.2020.103160.

Gheisari, M., M. Foroughi Sabzevar, P. Chen, and J. Irizzary. 2016. “Integrating BIM and Panorama to Create a Semi-Augmented-Reality Experience of a Construction Site.” *Int J Constr Educ Res*, 12 (4): 303–316. Routledge. https://doi.org/10.1080/15578771.2016.1240117.

Gong, L., Å. Fast-Berglund, and B. Johansson. 2021. “A Framework for Extended Reality System Development in Manufacturing.” *IEEE Access*, 9: 24796–24813. https://doi.org/10.1109/ACCESS.2021.3056752.

Groth, C., J. P. Tauscher, N. Heesen, S. Grogorick, S. Castillo, and M. Magnor. 2021. “Mitigation of cybersickness in immersive 360°videos.” *Proceedings - 2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops, VRW 2021*, (March): 169–177. https://doi.org/10.1109/VRW52623.2021.00039.

Halder, S., K. Afsari, J. Serdakowski, and S. DeVito. 2021. “A Methodology for BIM-enabled Automated Reality Capture in Construction Inspection with Quadruped Robots.” *Proceedings of the 38th International Symposium on Automation and Robotics in Construction (ISARC)*.

Harrington, C. M., D. O. Kavanagh, G. Wright Ballester, A. Wright Ballester, P. Dicker, O. Traynor, A. Hill, and S. Tierney. 2018. “360° Operative Videos: A Randomised Cross-Over Study Evaluating Attentiveness and Information Retention.” *J Surg Educ*, 75 (4): 993–1000. Elsevier. https://doi.org/10.1016/j.jsurg.2017.10.010.

Hasanzadeh, S., B. Esmaeili, and M. D. Dodd. 2017. “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. https://doi.org/10.1061/(asce)me.1943-5479.0000526.

Ha, S., N. Mohammadi, L. Sena Soysal, J. E. Taylor, A. Francisco, S. Flanagan, and S. Ç. Yapıcı. 2019. “Exploring Future Stakeholder Feedback on Performance-Based Design Across the Virtuality Continuum.” *Advances in Informatics and Computing in Civil and Construction Engineering*, I. Mutis and T. Hartmann, eds., 423–429. Cham: Springer International Publishing.

Herbelin, B., F. Vexo, and D. Thalmann. 2003. “Sense of Presence in Virtual Reality Exposures Therapy.” *First international workshop on virtual reality rehabilitation, VRMHR*, (June 2014).

Jeelani, I., K. Han, and A. Albert. 2020. “Development of virtual reality and stereo-panoramic environments for construction safety training.” *Engineering, Construction and Architectural Management*, 27 (8): 1853–1876. https://doi.org/10.1108/ECAM-07-2019-0391.

Jin, B., G. Kim, M. Moore, and L. Rothenberg. 2021. "Consumer store experience through virtual reality: its effect on emotional states and perceived store attractiveness." *Fashion and Textiles*, 8 (1). Springer Singapore. https://doi.org/10.1186/s40691-021-00256-7.

Jung, S., and Robert. W. Lindeman. 2021. "Perspective: Does Realism Improve Presence in VR? Suggesting a Model and Metric for VR Experience Evaluation." *Front Virtual Real*, 2. https://doi.org/10.3389/frvir.2021.693327.

Kavanagh, S., A. Luxton-Reilly, B. Wüensche, and B. Plimmer. 2016. "Creating 360° educational video: A case study." *Proceedings of the 28th Australian Computer-Human Interaction Conference, OzCHI 2016*, (November): 34–39. https://doi.org/10.1145/3010915.3011001.

Kelling, C., H. Väätäjä, and O. Kauhanen. 2017. "Impact of device, context of use, and content on viewing experience of 360-degree tourism video." *ACM International Conference Proceeding Series*, 211–222. https://doi.org/10.1145/3152832.3152872.

Kim, G., B. Jin, and D. C. Shin. 2022. "Virtual reality as a promotion tool for small independent stores." *Journal of Retailing and Consumer Services*, 64: 102822. https://doi.org/10.1016/j.jretconser.2021.102822.

Kim, J. S., T. Leathem, and J. Liu. 2019. "Comparing Virtual Reality Modalities and 360 Photography in a Construction Management Classroom." *55th ASC Annual International Conference Proceedings*, (February 2020): 221–228.

Lee, K., S. M., S. Hasanzadeh, A. M., B. Esmaeili, and A. M.. 2022a. "Assessing Hazard Anticipation in Dynamic Construction Environments Using Multimodal 360-Degree Panorama Videos." 38 (5): 1–16. https://doi.org/10.1061/(ASCE)ME.1943-5479.0001069.

Lee, K., S. Hasanzadeh, and B. Esmaeili. 2022b. "Spatial Exposure to Dynamic Safety Hazards in Construction Sites through 360-Degree Augmented Panoramas: Ecological Validity in Safety Research." *Construction Research Congress 2022*, 715–725. Reston, VA: American Society of Civil Engineers.

Lee, K., Y. Shinde, S. Hasanzadeh, and B. Esmaeili. 2022c. "Toward Personalized Safety Training: Automating the Classification of Construction Workers' Cognitive Failures."

Lee, S. H. (Mark), K. Sergueeva, M. Catangui, and M. Kandaurova. 2017. "Assessing Google Cardboard virtual reality as a content delivery system in business classrooms." *Journal of Education for Business*, 92 (4): 153–160. Taylor & Francis. https://doi.org/10.1080/08832323.2017.1308308.

Liao, P. C., X. Sun, and D. Zhang. 2021. "A multimodal study to measure the cognitive demands of hazard recognition in construction workplaces." *Saf Sci*, 133 (August 2019): 105010. Elsevier Ltd. https://doi.org/10.1016/j.ssci.2020.105010.

Lurie, N., and B. G. Carr. 2018. "The Role of Telehealth in the Medical Response to Disasters." *JAMA Intern Med*, 178 (6): 745. American Medical Association. https://doi.org/10.1001/jamainternmed.2018.1314.

Mander, S., V. Vishnupriya, and R. Lovreglio. 2022. *Using 360-Degree Virtual Tours to Teach Construction Students*.

Martínez-Navarro, J., E. Bigné, J. Guixeres, M. Alcañiz, and C. Torrecilla. 2019. "The influence of virtual reality in e-commerce." *J Bus Res*, 100 (October 2018): 475–482. https://doi.org/10.1016/j.jbusres.2018.10.054.

Moore, H. F., R. Eiris, M. Gheisari, and B. Esmaeili. 2019. "Hazard Identification Training Using 360-Degree Panorama vs. Virtual Reality Techniques: A Pilot Study." *Computing in Civil Engineering 2019*, 55–62. Reston, VA: American Society of Civil Engineers.

Mouratidis, K., and R. Hassan. 2020. "Contemporary versus traditional styles in architecture and public space: A virtual reality study with 360-degree videos." *Cities*, 97 (September 2019): 102499. Elsevier. https://doi.org/10.1016/j.cities.2019.102499.

Nason, E. E., M. Trahan, S. Smith, V. Metsis, and K. Selber. 2020. "Virtual treatment for veteran social anxiety disorder: A comparison of 360° video and 3D virtual reality." *J Technol Hum Serv*, 38 (3): 288–308. Routledge. https://doi.org/10.1080/15228835.2019.1692760.

Ng, G., H. Cheuk, L. C. Chun, S. Singh, and B. Sharma. 2021. "Advanced Construction Progress Tracking with viAct ' s 360 ° Camera : Advanced Construction Progress Tracking with viAct ' s 360 ° Camera : Implementation Methodology , Working & Advantages." (December). https://doi.org/10.35629/5252-03126669.

Ojha, A., J. Seagers, S. Shayesteh, and M. Habibnezhad. 2020. "Construction Safety Training Methods and their Evaluation Approaches: A Systematic Literature Review Computer Vision-based Approach to Automatically Processing Histology Images View project Assessing Construction Workers' Physical and Mental Status Using ." (December).

Orús, C., S. Ibáñez-Sánchez, and C. Flavián. 2021. "Enhancing the customer experience with virtual and augmented reality: The impact of content and device type." *Int J Hosp Manag*, 98 (May). https://doi.org/10.1016/j.ijhm.2021.103019.

Paalimäki-Paakki, K., M. Virtanen, A. Henner, M. T. Nieminen, and M. Kääriäinen. 2021. "Patients', radiographers' and radiography students' experiences of 360° virtual counselling environment for the coronary computed tomography angiography: A qualitative study." *Radiography*, 27 (2): 381–388. https://doi.org/10.1016/j.radi.2020.09.019.

Park, S., C. Park, C. Lee, S. Han, S. Yun, and D. Lee. 2022. "Exploring inattentional blindness in failure of safety risk perception: Focusing on safety knowledge in construction industry." *Safety Science*, 145: 105518. https://doi.org/10.1016/j.ssci.2021.105518

Peng, X., W. Xiu, and B. Zhang. 2020. "Research on Application of Key Technologies of Public Security Virtual Reality Based on Panoramic Video." *2020 International Conference on Computer Engineering and Application (ICCEA)*, 830–834. IEEE.

Pereira, R. E., and M. Gheisari. 2019. "360-Degree Panoramas as a Reality Capturing Technique in Construction Domain : Applications and Limitations." *ASC Annual International Conference Proceedings*, (April): 435–442.

Pereira, R. E., M. Gheisari, and B. Esmaeili. 2018. "Using panoramic augmented reality to develop a virtual safety training environment." *Construction Research Congress 2018: Safety and Disaster Management - Selected Papers from the Construction Research Congress 2018*, 2018-April (April): 29–39. https://doi.org/10.1061/9780784481288.004.

Petrica, A., D. Lungeanu, A. Ciuta, A. M. Marza, M. O. Botea, and O. A. Mederle. 2021. "Using 360-degree video for teaching emergency medicine during and beyond the COVID-19 pandemic." *Ann Med*, 53 (1): 1520–1530. Taylor & Francis. https://doi.org/10.1080/07853890.2021.1970219.

Pham, H. C., N. N. Dao, S. Cho, P. T. Nguyen, and A. T. Pham-Hang. 2019. "Construction hazard investigation leveraging object anatomization on an augmented photoreality platform." *Applied Sciences (Switzerland)*, 9 (21): 1–14. https://doi.org/10.3390/app9214477.

Pham, H. C., N. N. Dao, J. U. Kim, S. Cho, and C. S. Park. 2018. "Energy-efficient learning system using Web-based panoramic virtual photoreality for interactive construction safety education." *Sustainability (Switzerland)*, 10 (7): 1–17. https://doi.org/10.3390/su10072262.

Pooladvand, S., H. Taghaddos, A. Eslami, A. Nekouvaght Tak, and U. (Rick) Hermann. 2021. "Evaluating Mobile Crane Lift Operations Using an Interactive Virtual Reality System." *J Constr Eng Manag*, 147 (11): 04021154. https://doi.org/10.1061/(asce)co.1943-7862.0002177.

Premachandra, C., S. Ueda, and Y. Suzuki. 2019. "Road intersection moving object detection by 360-degree view camera." *Proceedings of the 2019 IEEE 16th International Conference on Networking, Sensing and Control, ICNSC 2019*, (June): 369–372. IEEE. https://doi.org/10.1109/ICNSC.2019.8743319.

Premachandra, C., S. Ueda, and Y. Suzuki. 2020. "Detection and Tracking of Moving Objects at Road Intersections Using a 360-Degree Camera for Driver Assistance and Automated Driving." *IEEE Access*, 8: 135652–135660. https://doi.org/10.1109/ACCESS.2020.3011430.

Pulijala, Y., M. Ma, and A. Ayoub. 2017. “VR Surgery: Interactive Virtual Reality Application for Training Oral and Maxillofacial Surgeons using Oculus Rift and Leap Motion.” *Serious Games and Edutainment Applications*, M. Ma and A. Oikonomou, eds., 187–202. Cham: Springer International Publishing.

Reeves, R., A. Elliott, D. Curran, K. Dyer, and D. Hanna. 2021. “360° Video virtual reality exposure therapy for public speaking anxiety: A randomized controlled trial.” *J Anxiety Disord*, 83 (July). https://doi.org/10.1016/j.janxdis.2021.102451.

Reggente, N., J. K. Y. Essoe, Z. M. Aghajan, A. v. Tavakoli, J. F. McGuire, N. A. Suthana, and J. Rissman. 2018. “Enhancing the ecological validity of fMRI memory research using virtual reality.” *Front Neurosci*. Frontiers Media S.A.

Ritter, K. A., and T. L. Chambers. 2022. “Three-dimensional modeled environments versus 360 degree panoramas for mobile virtual reality training.” *Virtual Real*, 26 (2): 571–581. Springer London. https://doi.org/10.1007/s10055-021-00502-9.

Saarinen, S., V. Mäkelä, P. Kallioniemi, J. Hakulinen, and M. Turunen. 2017. “Guidelines for designing interactive omnidirectional video applications.” *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 10516 LNCS: 263–272. https://doi.org/10.1007/978-3-319-68059-0_17.

Sadagic, A. 2016. “Design and Choice of Visual Display Solutions in the Training Domain.” *IEEE Comput Graph Appl*, 36: 18–25. https://doi.org/10.1109/MCG.2016.112.

Salhi, I., M. Poreba, E. Piriou, V. Gouet-Brunet, and M. Ojail. 2019. “Multimodal Localization for Embedded Systems: A Survey.” *Multimodal Scene Understanding*, 199–278. Elsevier.

Shih, N. J., Y. L. Tsai, D. Lai, and H. Y. Chang. 2001. “A preliminary application of panoramic supervision system in construction site.” *Proceedings of the International Conference on Information Visualisation*, 2001-Janua: 103–108. https://doi.org/10.1109/IV.2001.942045.

Shojaei, A., S. Rokooei, L. Carson, G. Ford, and A. Mahdavian. 2020. “Immersive Video Capture Technology for Construction Management Education.” *20th International Conference on Construction Applications of Virtual Reality (CONVR 2020)*, (September): 163–172.

Sina, A. S., and J. Wu. 2022. “The effects of retail environmental design elements in virtual reality (VR) fashion stores.” *International Review of Retail, Distribution and Consumer Research*, 00 (00): 1–22. Routledge. https://doi.org/10.1080/09593969.2022.2049852.

Sinha, S., and N. M. Modak. 2021. “A systematic review in recycling/reusing/re-manufacturing supply chain research: a tertiary study.” *International Journal of Sustainable Engineering*, 14 (6): 1411–1432. Taylor and Francis Ltd. https://doi.org/10.1080/19397038.2021.1986594.

Škola, F., S. Rizvić, M. Cozza, L. Barbieri, F. Bruno, D. Skarlatos, and F. Liarokapis. 2020. “Virtual reality with 360-video storytelling in cultural heritage: Study of presence, engagement, and immersion.” *Sensors (Switzerland)*, 20 (20): 1–17. https://doi.org/10.3390/s20205851.

Stupar-Rutenfrans, S., L. E. H. Ketelaars, and M. S. van Gisbergen. 2017. “Beat the Fear of Public Speaking: Mobile 360° Video Virtual Reality Exposure Training in Home Environment Reduces Public Speaking Anxiety.” *Cyberpsychol Behav Soc Netw*, 20 (10): 624–633. https://doi.org/10.1089/cyber.2017.0174.

Subramanian, P., and M. Gheisari. 2019. *Using 360-Degree Panoramic Photogrammetry and Laser Scanning Techniques to Create Point Cloud Data: A Comparative Pilot Study Unmanned Aerial Systems (UAS) for Construction Safety Applications View project 360-Degree VR for Construction Safety View projec*.

Tijani, B., J. Falana, X. Jin, and R. Osei-Kyei. 2023. “Suicide in the construction industry: literature review.” *International Journal of Construction Management*, 23 (10):1684-1693. https://doi.org/10.1080/15623599.2021.2005897

Ventura, S., G. Cardenas, M. Miragall, G. Riva, and R. Baños. 2021. “How Does It Feel to Be a Woman Victim of Sexual Harassment? The Effect of 360°-Video-Based Virtual Reality on Empathy and Related Variables.” *Cyberpsychol Behav Soc Netw*, 24 (4): 258–266.

Voigt-Antons, J. N., E. Lehtonen, A. P. Palacios, D. Ali, T. Kojic, and S. Moller. 2020. "Comparing Emotional States Induced by 360° Videos Via Head-Mounted Display and Computer Screen." *2020 12th International Conference on Quality of Multimedia Experience, QoMEX 2020*, 0–5. https://doi.org/10.1109/QoMEX48832.2020.9123125.

Wagler, A., and M. D. Hanus. 2018. "Comparing Virtual Reality Tourism to Real-Life Experience: Effects of Presence and Engagement on Attitude and Enjoyment." *Communication Research Reports*, 35 (5): 456–464. Routledge. https://doi.org/10.1080/08824096.2018.1525350.

Waller, M., D. Mistry, R. Jetly, and P. Frewen. 2021. "Meditating in Virtual Reality 3: 360° Video of Perceptual Presence of Instructor." *Mindfulness (N Y)*, 12 (6): 1424–1437. Mindfulness. https://doi.org/10.1007/s12671-021-01612-w.

Walshe, N., and P. Driver. 2019. "Developing reflective trainee teacher practice with 360-degree video." *Teach Teach Educ*, 78: 97–105. Elsevier Ltd. https://doi.org/10.1016/j.tate.2018.11.009.

Wang, J. 2012. "Research on application of virtual reality technology in competitive sports." *Procedia Eng*, 3659–3662.

Wehking, F., M. Wolf, H. Söbke, and J. Londong. 2019. "How to Record 360-degree Videos of Field Trips for Education in Civil Engineering." *Proceedings of DELFI Workshops 2019 Berlin, Germany, September 16, 2019*, 177–188. https://doi.org/10.18420/delfi2019-ws-120.

Wen, J., and M. Gheisari. 2021. "VR-Electricians: Immersive storytelling for attracting students to the electrical construction industry." *Advanced Engineering Informatics*, 50 (August): 101411. Elsevier Ltd. https://doi.org/10.1016/j.aei.2021.101411.

Wen, J., S. Zalake, and M. Gheisari. 2022. "Influence of Pedagogical Agent Deictic Gestures on Construction Management Students Learning within a 360-Degree Virtual Field Trip." 715–707.

Wu, X., and I. K. W. Lai. 2021. "Identifying the response factors in the formation of a sense of presence and a destination image from a 360-degree virtual tour." *Journal of Destination Marketing and Management*, 21 (July): 100640. Elsevier Ltd. https://doi.org/10.1016/j.jdmm.2021.100640.

Wu, X., and I. K. W. Lai. 2022. "The use of 360-degree virtual tours to promote mountain walking tourism: stimulus–organism–response model." *Information Technology and Tourism*, 24 (1): 85–107. Springer Berlin Heidelberg. https://doi.org/10.1007/s40558-021-00218-1.

Xue, F., B. Zhao, W. L. Zhou, L. Y. Chen, and H. K. Wong. 2018. "Computational egress simulation and analysis for nuclear reactor building." *ACM International Conference Proceeding Series*, 1–6. https://doi.org/10.1145/3207677.3278104.

Yang, T., I. K. W. Lai, Z. bin Fan, and Q. M. Mo. 2021. "The impact of a 360° virtual tour on the reduction of psychological stress caused by COVID-19." *Technol Soc*, 64: 101514. https://doi.org/10.1016/j.techsoc.2020.101514.