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Bringing reality to virtual reality: the role of environmental richness in improving construction practitioners' VR experience

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Abstract

Purpose – This study aims to investigate how environmental richness in virtual construction environments influences construction practitioners' behavior and presence. It aims to identify elements within these environments that significantly contribute to an enhanced sense of presence, addressing the gap in understanding the relationship between environmental richness and ecological validity in virtual safety training.

Design/methodology/approach – A mixed-methods study involving 28 full-time construction practitioners was conducted. Participants navigated two virtual environments – a "rich" version with nonhazardous, realistic details and a "bare" version with minimal environmental richness. Data were collected through eye-tracking, positional analysis, presence questionnaires and semistructured interviews. The study used exploratory, confirmatory and explanatory analyses to evaluate behavioral impacts, statistical differences in presence scores and thematic insights into participants' experiences.

Findings – Environmental richness significantly impacted participants' sense of presence, with the rich version producing higher presence scores ($p = 0.018$). Qualitative data highlighted that nonhazardous elements, such as terrain details, climatic conditions and virtual co-workers, enhanced realism and immersion. Heatmaps revealed wider visual attention and movement patterns in the rich environment, indicating greater engagement.

Practical implications – The findings suggest that investing in nonhazardous elements, often overlooked in virtual reality (VR) development due to resource constraints, can enhance presence and realism in virtual construction environments. This can lead to more ecologically valid training experiences that better replicate real-world scenarios, ultimately improving hazard recognition and decision-making skills.

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Originality/value – Prior VR-based safety training has often lacked ecological validity, i.e. missing realistic site context or social dynamics, which may limit behavioral realism. This study addresses that gap by comparing a richly detailed virtual construction site against a bare version, to examine how added realism impacts users' sense of presence and safety behaviors. By providing empirical evidence on the role of environmental richness in virtual construction environments, it emphasizes the importance of nonhazardous elements in enhancing presence, offering actionable insights for designing more effective VR-based safety training solutions.

Keywords Innovation, Construction management, Digitalization, Construction technology, Health and safety, IT/CAD/VR, Building services

Paper type Research paper

1. Introduction

Construction environments include safety hazards that, on average, lead to over 1,000 deaths and hundreds of thousands of injuries annually (BLS, 2021). The need to provide workers with effective safety training to mitigate and avoid hazards has been explored by researchers in various capacities, ranging from the implementation of adult learning strategies to the introduction of psychological antecedents (Albert *et al.*, 2020; Albert and Hallowell, 2013; Bhandari and Hallowell, 2017; Jeelani *et al.*, 2017b). In recent years, the use of virtual construction training environments has been especially popular because these environments can provide realistic experiences involving safety hazards without inflicting physical harm. Virtual environments (VEs) have been used to challenge users to identify hazards and illustrate consequences of poor safety decisions in a manner that would be ethically impossible to do onsite (Hasanzadeh *et al.*, 2017; Jeelani *et al.*, 2017a, 2018, 2020). The purpose behind such training interventions has been to not only improve learning outcomes among workers but also introduce changes in risk-taking behaviors (Bhandari and Hallowell, 2022; Hasanzadeh *et al.*, 2020; Tixier *et al.*, 2014). While these virtual environments can be expensive to create, their potential to save lives and reduce injuries provides ample justification for most studies.

By contrast, conventional classroom lectures and video-based toolbox talks present hazards as static, two-dimensional (2D) images that learners passively observe from a single viewpoint. Virtual reality (VR) environments may offer significant advantages compared to such traditional training modalities, particularly in the construction sector, where safety training is critical. Unlike static classroom settings, which may lack the realistic representation of physical context and embodied experiences inherent to actual construction sites, VR immerses users in highly interactive, three-dimensional (3D) simulations that closely mimic real-world dangers and scenarios. As highlighted by Alzarrad *et al.*, traditional visualization methods provide a basic understanding but cannot replicate the multisensory engagement that VR offers, making it more effective for skill acquisition and hazard recognition (Alzarrad *et al.*, 2024). Moreover, classroom and video training formats often suffer from limited sensory cues, which can undermine trainees' situational awareness and cognitive processing needed to respond effectively in emergencies (Alzarrad *et al.*, 2024). Conversely, VR environments can present realistic cues that engage users through sight, sound and movement, fostering a strong sense of presence, a key factor for successful learning outcomes in safety contexts (Alzarrad *et al.*, 2024). While traditional methods emphasize cognitive knowledge transfer, VR training allows practitioners to physically practice responding to hazards within realistic simulations, creating an embodied understanding that is harder to achieve via other media (Zhou *et al.*, 2025). This not only enhances engagement but also promotes retention and the application of learned skills in real-life situations, which contrasts with the often passive nature of videos or lectures, leading to reduced knowledge retention and lower incident preparedness (Lindner *et al.*, 2025).

Most research on virtual safety training environments has devoted development resources to accurately modeling typical site conditions and common construction tasks related to hazards. However, it remains unclear how these learnings in virtual simulations translate into real-world impacts. In reality, workers are performing a multitude of tasks, and real construction environments contain not only hazardous situations but also other nonhazardous points of interest that may distract workers. Too many distractions can overload their cognition and impair their situational awareness (Sweller, 2011). This mix of hazardous and nonhazardous stimuli may affect their behavior and make it more challenging for individuals to identify and mitigate hazards in practice. From a training standpoint, this illustrates the need for safety researchers to learn the ways in which virtual environments should be developed that create hyper-realistic environments to not only study behaviors in VEs that align with behaviors expected onsite but also improve the ecological validity of such learning modalities.

The need for alignment between observations from research environments and their real counterparts has been thoroughly explored by researchers outside of the construction safety domain. Researchers often aim to create controlled, but "ecologically valid," environments that maintain the integrity of the real-life situations to ensure that results in research settings reliably predict results that would be present in real environments (Schmuckler, 2001; Bronfenbrenner, 1977, 1979). As it relates to construction safety research, this concept of ecological validity is especially critical because results derived from VEs that do not elicit the kinds of behaviors expected onsite may lead to unrealistic conclusions that do not meaningfully impact the construction industry's persistent injury and fatality records. As previously indicated, it is often ethically or practically impossible to directly compare virtual behaviors involving safety incidents to identical situations in reality. Previous studies have shown that the realism of a user's behavior is directly impacted by the level of presence that a virtual simulation can facilitate (Freeman *et al.*, 2000; Skarbez *et al.*, 2017). Therefore, researchers may need to explore various aspects of a VR construction environment that affect how behaviors in VR match (or differ from) those in practice.

For this study, the authors explore how the design of a VE influences the sense of "presence." Presence is defined as the subjective experience of being in one environment (virtual), even when one is physically situated in another (real-world) (Witmer and Singer, 1998). Elevated levels of presence have been suggested to relate to the degree to which behaviors in a VE align with behaviors in real environments (Busch et al., 2014; Freeman *et al.*, 2000; Meehan *et al.*, 2002). For example, Freeman et al. (2000) found that the postural responses, or the way people move their body, in reaction to the presentation of a video sequence filmed from the hood of a car, were more realistic for content presented with higher immersion and presence. Therefore, presence is especially well-suited to defining development strategies because it does not require direct comparison of virtual behaviors to physical behaviors, which is often impossible to study in the domain of construction safety.

This research strategically explores two different virtual construction environments that are based on the same site and the same safety hazards, but purposefully incorporates differing levels of additional nonhazardous site elements. These added elements provide greater environmental richness, which enables the researchers to determine if, and how, reports of presence in these environments differ statistically. The rationale behind testing the efficacy of environmental richness is to confirm, from a practical standpoint, whether organizations should make additional investments to improve the realism of virtual safety training environments by including aspects that may not be directly related to the hazards in focus. Environmental richness refers to the inclusion of nonessential but realistic elements, such as detailed terrain, vegetation or social interactions, that enhance the fidelity of a VE.

And while the concept of environmental richness has been extensively explored in various domains (Paes *et al.*, 2021), little has been done to understand its impact on construction practitioners. Given the importance of realism in virtual training, this study investigates whether environmental richness – characterized by realistic but nonessential details – influences the sense of presence construction workers feel in VR environments. Therefore, this study explores the impact of environmental richness on presence within VR and identifies the aspects of the VE that affect the users' behaviors and sense of presence. The paper explores the following research questions:

RQ1. How does environmental richness of a virtual construction environment affect construction practitioners' behavior in VR?

RQ2. Is the presence score for the rich version higher than that of the bare version?

RQ3. What aspects of a virtual construction environment do practitioners pay attention to in VR?

This work empirically identifies aspects of a virtual construction environment that lead to increased presence among construction practitioners. This can directly contribute to construction safety literature by informing the development of VR environments that evoke a higher sense of presence that more effectively enable workers to experience and react to potential hazards without the risk of physical harm. This realistic, immersive training experience can potentially lead to better hazard recognition and decision-making skills among workers because the VR experience can more closely align with the experience of the real environment, where decisions made impact actual safety outcomes.

Our study aims to investigate the impact of environmental richness on the sense of presence experienced by construction practitioners in VR environments. We do not claim that higher presence and richness always lead to better task performance or knowledge acquisition and retention. Instead, we focus on identifying the aspects of the VE that are relevant to construction practitioners and help resemble real-world situations and responses. By understanding the relationship between environmental richness and presence, we hope to inform the development of ecologically valid and reliable virtual construction environments for safety training. This will directly support industry and academia in providing support for digitalization efforts surrounding VR aimed at improving resilience related to safety training.

3. Background

3.1 Lack of ecological validity in construction safety research

Traditionally, researchers have used photographs (Uddin *et al.*, 2020; Zuluaga *et al.*, 2016) and 2D videos (Eiris *et al.*, 2021) to measure and teach safety skills (e.g. hazard recognition, risk assessment, etc.). However, the need for more realistic presentation of stimuli for construction safety research is evident in the methodological limitations of previous studies in which researchers used pictures and videos of construction sites to assess hazard recognition performance of construction workers (Albert *et al.*, 2020; Albert and Hallowell, 2013; Bhandari *et al.*, 2016; Hasanzadeh *et al.*, 2016; Tixier *et al.*, 2018). While these studies have undoubtedly contributed to developing training programs, they are limited in predicting performance effects that can be expected on real construction sites due to the simplicity of the assessment environment.

Similarly, pictures have also been used to observe construction workers' eye-movements, cognitive load (Bhoir *et al.*, 2015; Dao *et al.*, 2018; Dzeng *et al.*, 2016) and effects of distraction on certain tasks (Namian *et al.*, 2018a, 2018b). These studies have significantly added to the body of knowledge in understanding construction worker behavior. However, based on existing literature on visual perception and cognitive processes, it can be concluded that eye-movements would significantly vary between looking at planar stimuli as opposed to 3D stimuli like those on a real construction site (Gibson, 2014; Reichelt *et al.*, 2010; Todd, 2004). Some researchers have used alternative strategies to address this limitation by conducting observations on real construction sites (Hasanzadeh *et al.*, 2016) or recreating the dynamics of a construction site in laboratories (Liao *et al.*, 2021; Sun and Liao, 2019). Although more effective, the logistical and safety concerns implicit in taking test subjects in a hazardous environment or arranging resources to replicate the construction environment in a laboratory call for a cost-effective solution in ecologically valid VEs.

3.2 Virtual reality as a solution

The introduction of VR as a research tool in various domains has brought promise to overcoming the limitations of traditional methodologies (Jeelani *et al.*, 2017b, 2020). For construction safety studies, VR offers the potential of exposing subjects to realistic VEs that can closely mirror real-life scenarios without risking their safety (Jeelani et al., 2020). In spite of its potential, the adoption of VR in construction safety research has been limited (Teizer and Cheng, 2015). The reasons for this are multifaceted and primarily revolve around issues of cost, the required technical expertise to develop VEs and the general lack of evidence on how best to create and use such environments in research. Additionally, there exists a challenge in striking a balance between creating environments that are engaging and captivating enough to induce a sense of presence for the user while ensuring that the additional elements do not distract from the research objectives (Loomis *et al.*, 1992).

3.3 Cognitive load in virtual environments

Cognitive load theory (CLT) posits that both learning and performance depend on how limited working-memory resources are allocated (Sweller, 2011). It distinguishes between three types of cognitive load: intrinsic load, which refers to the inherent complexity of the task itself, such as identifying hazards on a construction site; extraneous load, which represents the mental effort consumed by how information is presented, including interface navigation, visual clutter or system latency; and germane load, which involves productive effort dedicated to building and refining mental models (schemas) essential for transferring learning to new contexts.

Early e-learning studies framed immersive media as a risk for overload, citing increased sensory input and interface novelty (Parong and Mayer, 2018; Chandler and Sweller, 1992). Recent VR work paints a more nuanced picture. In a chemistry-lab simulation, Makransky and Lilleholt (2018) found that higher extraneous load outweighed presence gains for novices, depressing quiz scores. Conversely, Klingenberg *et al.* (2020) showed that when environmental cues directly supported procedural reasoning, overall cognitive load dropped relative to 2D video even though visual complexity rose. These findings underline CLT's central claim that it is the balance of extraneous and germane load, not stimulus fidelity *per se*, that determines outcomes (Paas *et al.*, 1994; Sweller *et al.*, 1998). In construction safety, intrinsic load is fixed by the hazard-spotting task, so the key question is whether extra detail acts as distracting noise or meaningful cues that enrich site schemas. VR affords precise control over this trade-off: developers can dial richness up or down, isolate individual assets (e.g. weather effects and co-workers) and benchmark system performance to keep frame-rate-related extraneous load constant (Makransky *et al.*, 2021).

Situating the present study within CLT, therefore, sharpens its contribution. The following sections examine how environmental richness was operationalized

(Section 3.4) and how its cognitive-load profile manifested in user experience and presence (Sections 6 and 7).

3.4 Environmental richness

Environmental richness indicates the degree to which an environment is populated by aspects that may be unrelated to the targeted process but incorporated to enhance its attractiveness and realism (Chen and Teh, 2013; Mikropoulos and Strouboulis, 2004). A study that compared varying levels of visual fidelity found increased presence in the higher-fidelity version of the VE (Mizuho *et al.*, 2023). In a construction context, the degree of environmental richness implies the inclusion (rich) or exclusion (bare) of aspects of the construction site based on their relevance to the objective of the VR experience. For example, in the case of a hazard-recognition task, a "rich" version of the virtual environment would include aspects that are seemingly unrelated to the hazards on the virtual site, such as virtual coworkers, visual cues of the climatic conditions, social interactions, detailed vegetation and sophisticated terrain details. On the other hand, the "Bare" version would include only aspects related to the hazards and processes around the hazards that are targeted in the task at hand. Most safety research environments have used bare VEs, which makes sense due to the lack of evidence to spend development resources on including irrelevant details to the simulation (Albert *et al.*, 2014a; Bhandari *et al.*, 2019). However, to create VEs with higher presence, it is necessary to understand how environmental richness affects construction practitioners and which aspects of the environment are relevant to the targeted users.

Although there has been long-standing research indicating that environmental richness could provide situational context and increase the effectiveness of a simulation (Chen, 2010; Mikropoulos and Strouboulis, 2004; Witmer and Singer, 1998), there are also reports suggesting that richness may not have a statistically significant effect on learning outcomes or, worse, potentially interfere with the targeted outcomes in some contexts (Jones and Dumais, 1986; Ragan *et al.*, 2012; Wilson and Soranzo, 2015). In addition, development efforts are associated with additional resource requirements, which can be financially and logistically prohibitive, leading developers and researchers to make conscious decisions to limit the environmental richness of the VE. Finally, environmental richness also faces the problem of having a seemingly unlimited amount of detail that can be considered to add richness to a virtual model (*example illustrated in* Figure 1). There is no validated objective scale that bifurcates a rich environment from a nonrich environment, which makes creating an objectively rich version of a virtual model practically impossible. Instead, the work on the aspectual nature of representations (the virtual construction site being a representation of the real environment) in cognitive science indicates the aspects that are relevant to the user are what make a good representation (Sperber and Wilson, 1986; Vervaeke *et al.*, 2012, 2013).

We acknowledge that the level of pictorial realism and vividness in virtual environments (VEs) is application-dependent (Bozgeyikli *et al.*, 2021). In some cases, low-fidelity simulations might be sufficient for achieving the desired realism and presence levels, depending on the specific task or activity being performed (Paes *et al.*, 2021). However, our study focuses on construction safety training, where realistic experiences involving safety hazards without inflicting physical harm are essential. Therefore, understanding the impact of environmental richness on presence can help guide the development of ecologically valid and reliable safety research in this context. One aspect of construction safety training that can be enhanced using VR is the development of visual search skills. Visual search refers to the process of actively scanning and analyzing visual stimuli in the environment, which is crucial for hazard recognition and risk assessment in construction sites (Wolfe, 1994). It was

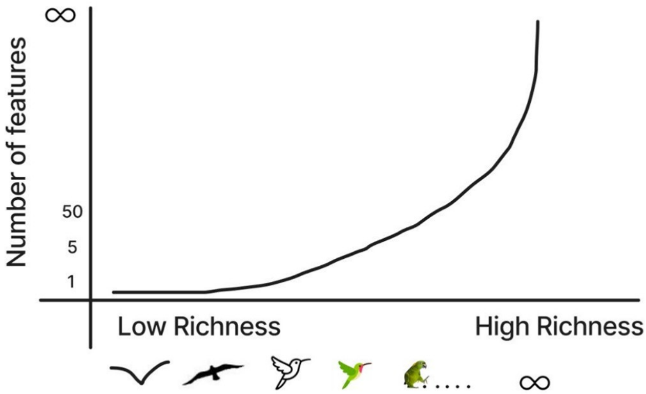

Figure 1. Depiction of the problem with unlimited potential for model richness
Source: Authors' own work

found that the visual search without training is highly inefficient for hazard recognition in the chaotic environment of the construction site (Albert *et al.*, 2014b; Cheng *et al.*, 2021). Additionally, a systematic review of eye-tracking studies of construction safety found that visual search patterns are predictive of hazard recognition performance of construction workers (Cheng *et al.*, 2022). By creating ecologically valid VEs that closely resemble real-world construction sites, VR can help improve construction practitioners' visual search skills and, consequently, their ability to identify and mitigate hazards in practice. Therefore, knowing what is relevant to construction practitioners in a virtual construction environment is crucial for design decisions in developing a virtual construction site. This knowledge gap hinders the development of ecologically valid VEs for construction applications.

3.5 Knowledge gap

To attain ecological validity, researchers aim to mimic the experimental conditions as closely as possible such that observations made can realistically be applied to the real environment. As it relates to hazard recognition training, it is not possible to conduct training or experiments in the real environment since it would entail putting participants in actual danger. Because of practical and ethical factors, it is not always possible to test hypotheses in actual construction environments. Therefore, construction research often requires experiments and simulations in VEs. In such studies, ecological validity is required to ensure that results obtained in VEs are generalizable to the real world. The potential for such validity in VR can be achieved by creating immersive environments that induce a high level of presence. However, the high resource demand for developing these and their unknown impact on presence has led to a tendency for construction VR environments to be low in their environmental richness. Studying the effects of environmental richness on construction workers and identifying relevant richness for construction VR can guide developers to create ecologically valid and reliable safety research.

4. Methods

4.1 Overview

The mixed-methods approach was selected following Creswell's (2018) convergent design to capture both behavioral manifestations (quantitative) and experiential insights (qualitative) of presence. Two similar virtual sites were developed with differing levels of environmental richness. Participants completed pre- and post-activity surveys that indicated the level of presence that participants experienced. Furthermore, during the experience, participants described their experience through a think-aloud protocol. After exiting the VE, participants were asked interview questions to understand how various aspects of the VEs affected their sense of presence. Semistructured interviews were chosen over structured surveys to allow practitioners to articulate unanticipated aspects of their site experience that rigid questionnaires might miss (Magaldi and Berler, 2018). This data, and the recordings of participants navigating the virtual environments, were used to address the targeted research questions. These methodological steps are detailed in the subsequent paragraphs.

The VEs were developed in Unity game development engine with the support of other resources like SketchUp and Blender for developing 3D models and Rokoko studio and Maximo online library for realistic motion capture animations. The system did not include facial/eye tracking or lip-sync and thus, high-fidelity nonverbal expressivity (gestures and micro-expressions) was not modeled. The VR headset used for the activity was the HTC Vive Pro-Eye. This particular model of the HTC Vive was used due to its capability to track eye-movements during the VR experience. To ensure that environmental richness was the primary variable under investigation, efforts were made to maintain comparable technical performance between the "rich" and "bare" virtual environments. Interaction capabilities and hardware were identical across conditions, isolating environmental richness as the manipulated factor. While a formal prevalidation of frame rates and loading times was not conducted, both environments were developed using the same software and hardware configurations, and visual fidelity settings were optimized to prevent significant performance disparities that could introduce confounding variables. In addition, the Cognitive3D platform was used to record and analyze the eye-tracking data that was collected for each participant.

The protocol required two versions of the virtual construction site, namely a "rich" and a "bare" version. Both versions were identical in the construction processes being depicted, but varied in the level of environmental richness that was developed. While the rich version was high in its environmental richness, the bare version was low. Guided by CLT, we expected richness to raise extraneous load but raise germane load even more, producing a net gain in presence (*H1*). Table 1 lists some aspects that were different between the rich and bare versions with scene-specific examples, and Figure 2 depicts a screenshot from each version.

4.2 Environmental richness operationalization

The distinction between "rich" and "bare" environments was based on identifying elements that appear on real construction sites but are not directly related to hazards or primary

Table 1. Differences in the Rich and Bare versions of the virtual environment

Differences	Bare	Rich
Communication with RA	Talk-out-loud	Speak into the in-game radio
Hazard documentation	Notify the researcher	Document using an in-game tablet
Report hazards	Talk-out-loud	Hand tablet to supervisor avatar
Climatic conditions	Nothing developed	Dust, heat-distortion and sun-glare visuals
Terrain	Generic	Detailed terrain details (rocks and dirt)
3D models	Generic	Visual effects like wear and tear
Social presence	Nothing developed	Virtual workers chatting on the side during a break

Source(s): Authors' own work

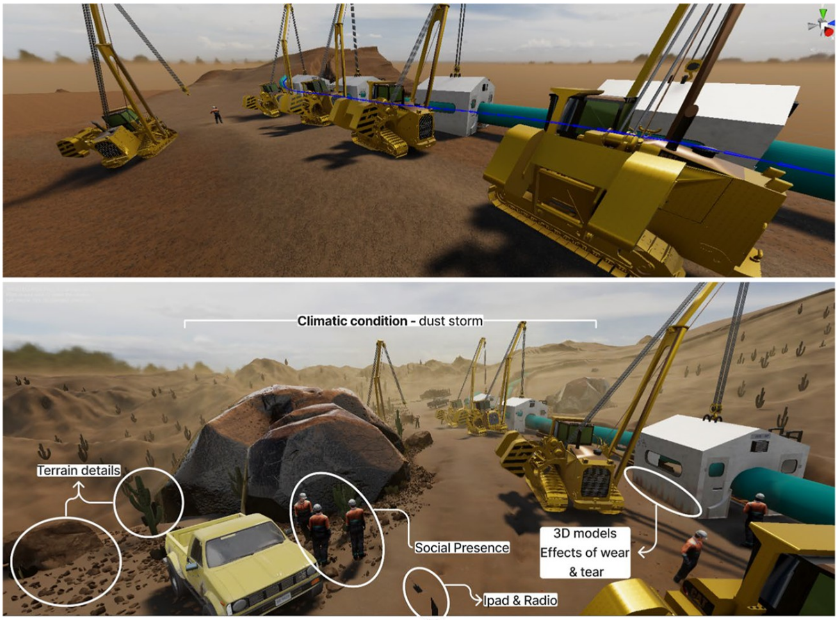

Figure 2. Screenshot depicting the difference in the Bare (top) and Rich (bottom) versions of the virtual environment
Source: Authors' own work

construction tasks. As noted earlier in Section 3.4, there is no validated objective scale for environmental richness. Therefore, we operationalized richness through the inclusion (rich) or exclusion (bare) of contextual elements commonly found on construction sites but typically omitted from VR safety training: social interactions, climatic conditions, terrain details and environmental wear patterns. These elements were selected based on pilot tests with construction professionals during the design phase of the construction environment and literature suggesting their potential impact on presence. This approach aligns with presence scholarship that distinguishes plausibility/authenticity from raw fidelity (Hameed and Perkis, 2024) and with mixed-methods guidance permitting expert operationalization in the absence of standardized instruments (Messick, 1995; Lawshe, 1975; Stanick *et al.*, 2018), as reflected in recent VR studies that define "rich" vs "bare" environments via literature-grounded parameters (Saha *et al.*, 2024).

4.3 Research protocol

The research protocol and sequence of data collection steps are illustrated in Figure 3. A purposeful or purposive sampling was conducted where practitioner participants were recruited from construction companies (Creswell and Poth, 2016). This was done to leverage their level of familiarity with real construction environments, considering the role relevance plays in how humans perceive their environment. Furthermore, the researchers only included participants who reported spending time onsite regularly, which ensured some level of site familiarity and, equally importantly, avoided recruiting participants who might work for construction companies but only work in an offsite capacity.

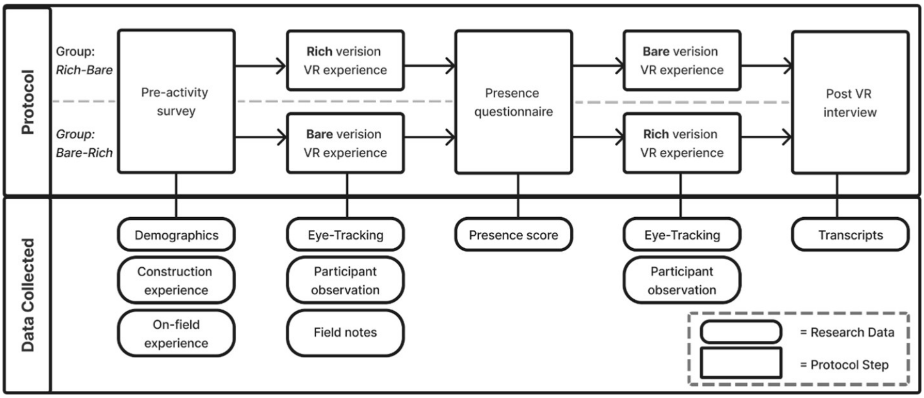

Figure 3. Research protocol and data collected during the VR activity
Source: Authors' own work

4.3.1 Pre-activity survey. The participants from both groups completed a pre-activity survey where they provided informed consent and provided the following demographic information:

- Experience in the construction industry;
- Estimated percent of a typical workday spent on the field; and
- Familiarity with VR.

4.3.2 Virtual reality introduction. Following the pre-activity survey, the participants were given a brief description of the VR experience and what they would be doing in the VR session. This included an introduction to the pipeline construction project context modeled in VR and the job walk that participants would perform to identify any safety hazards. Along with this, instructions to use the VR headset and its controllers to navigate inside the simulation were also provided, accompanied by a short training session in a nonconstruction environment to ensure that lack of performance or impact on perception would be less likely to be related to confusion with using the VR equipment. The simulation does not reproduce the full nonverbal communication bandwidth common on construction sites (e.g. standardized hand signals, gaze and facial cues). While this was outside the present scope, future work that targets communication training could incorporate tracked hand/facial rigs and evaluate their effects.

Before entering the VR environment, participants were instructed to navigate the virtual construction site to identify any hazards they may find. Participants were also informed that the researcher would be in communication with them during their VR experience, playing the role of a colleague back in the office to whom they would describe any hazards they identify. This was done to keep the participants immersed in the VE and ensure that the data collected was ecologically valid, as it mimicked the conditions and behaviors that would occur on a real construction site for the task explored.

4.3.3 First virtual reality session. Participants of both groups entered the version of the simulation assigned to their group (Rich or Bare). During their time in the VE, participants' eye-movements and position inside the VE were recorded and associated with a unique anonymous participant unique identification (ID) to associate the data with each participant. This step ended when participants mentioned they had completed the job walk and identified all the hazards they found.

4.3.4 Presence questionnaire. Participants were assisted in removing the VR headset and asked to provide feedback related to the level of presence they experienced in the virtual simulation. A self-reporting questionnaire was used to evaluate the impact of environmental richness on presence, which is a predominant mode of measuring presence by researchers (Skarbez *et al.*, 2017). The Slater–Usoh–Steed (SUS) by Usoh *et al.* (2000) was selected, which was identified by Rosakranse and Oh (2014) as a dominant questionnaire to measure the fidelity of presence facilitated by VEs in leading journals (Skarbez *et al.*, 2017) (presence questionnaire is attached in Appendix). Internal consistency for the SUS in this sample was good with the calculated Cronbach's alpha α of 0.84 ($n = 28$). This feedback was recorded via an online survey tool and was associated with the unique participant ID for each participant. This approach provided the researchers with timely reports of the presence of participants in both the Rich and Bare environments for subsequent analysis.

4.3.5 Second virtual reality session. After completing the presence questionnaire, participants explored the alternate version of the VR environment. This provided participants with a point of reference between the two versions of the environments, allowing them to compare and contrast their experiences in responding to the post-VR interview. During this second session, participants did not try to identify hazards, as the hazards were identical between both versions of the environment. The second VR session was recorded using eye-tracking and positional data, similar to the first VR session, to ensure that data was collected consistently across both sessions.

4.3.6 Postvirtual reality interview. In the final step of the activity, a semistructured interview was conducted with participants from both groups to allow for the construction of rich, contextualized data (Creswell, 2007; Magaldi and Berler, 2020) from the participants' experience of having experienced the virtual construction site and their evaluation of its realism based on their experience of the actual construction site environment. These questions were aimed to provide a variance explanation for the results of the presence questionnaire presented to participants during the activity. The following are some questions that were used to guide the semistructured interview:

- To what extent did you feel present on the virtual construction site, as if you were really there?
- Did you notice any differences in the two scenes? What were they and what effect (if any) did they have on your experience?
- Which aspects of the VR experiences helped in recreating the feeling of being on a construction site?
- Which aspects of the VR experiences broke the illusion of being on a construction site?

Finally, in addition to the data that was collected at various stages of the protocol, the researcher overseeing implementation of the protocol also took field notes to support data interpretation during analysis of all the qualitative data being collected.

4.4 Data validation and quality assurance

To ensure the robustness and credibility of the findings, multiple validation procedures were used across quantitative and qualitative data sources. These steps focused on establishing the reliability of measurement instruments, the accuracy of eye-tracking data collection and the trustworthiness of qualitative coding.

Presence questionnaire reliability: The SUS questionnaire demonstrated strong internal consistency with a Cronbach's alpha of 0.844, exceeding the recommended threshold of 0.7 for research instruments (Nunnally, 1978). This confirms the reliability of our presence measurement across the six questionnaire items.

Eye-tracking calibration: Each participant underwent a nine-point calibration procedure with the HTC Vive Pro-Eye, achieving <1° visual angle accuracy. Fixations with confidence scores below 0.6 were excluded from analysis, following Cognitive3D's recommended thresholds.

Inter-rater reliability: For thematic analysis, two researchers independently coded 35% of interview transcripts. Discrepancies were resolved through consensus discussion, and the refined codebook was applied to the remaining transcripts.

5. Data analysis

Once the data was collected, it was analyzed in three distinct stages, which were exploration, confirmation and explanation. These stages correspond to the three research questions targeted. This approach is illustrated in Figure 4 and explained in the following sections:

In the first exploratory stage of data analysis, the data collected during the VR activity for both the rich and bare versions were compared qualitatively to identify whether there was a difference in participants' behavior. Therefore, observational data of the participants' fixations and their position in the VE during the activity were used. A comparison of the fixations during the two versions provided observations on whether there was an impact on the participants' visual attention during their VR experience. Similarly, the position data was another source of observational data to compare whether the two versions impacted participant behavior based on their movement inside the VE. Cognitive3D, a Web-based platform, was used to process and create heatmaps of the spread of fixations and positions across the VE.

In the second stage, to quantitatively confirm if the varying levels of environmental richness affected the user's presence score, a hypothesis test was conducted on the presence scores reported for each version. Since the presence scores were not normally distributed, the Mann–Whitney U-test, which is a nonparametric one-tailed test, was used to test the hypothesis that the presence felt by participants in the rich version was lower than or equal to the presence felt by participants in the bare version. The following hypotheses were tested:

H0. Presence score for the rich version has a smaller or equal value than the bare version.

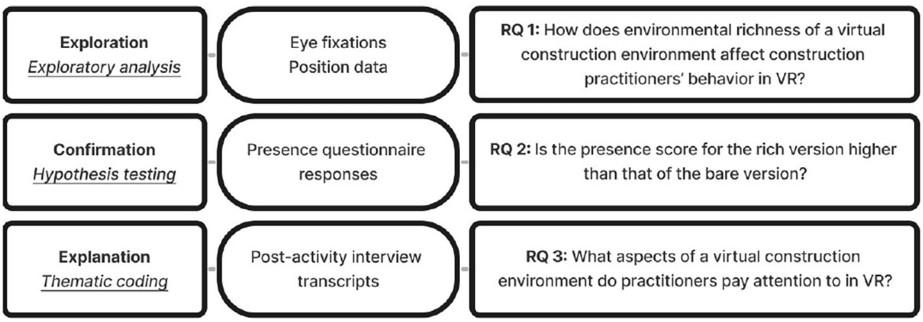

Figure 4. Stages of data analysis
Source: Authors' own work

Finally, in the explanatory stage of data analysis, postactivity interviews were qualitatively analyzed to identify aspects of the VE that impacted the difference, or lack of difference, between the two versions of the VE. The transcripts of the interviews were analyzed at a semantic level using thematic analysis, where the themes, or aspects of the VE in this case, were identified within the explicit meanings of the data as recommended by Creswell (2007, 2018). The data analysis process was similar to other interview analysis protocols conducted in previously published qualitative research (Boyatzis, 1998; Braun and Clarke, 2006). An inductive approach was used to code the transcripts based on the research question of identifying aspects of the VE that the participants found interesting and considered to be impactful on the presence they felt. To ensure the dependability and credibility of the analysis, a rigorous, multi-stage process was used. The analysis followed the six phases outlined by Braun and Clarke (2006): familiarization, coding, theme generation, theme review, theme definition and naming and write-up. To minimize individual researcher bias and ensure a consistent interpretation of the data, a process of consensus coding was used. The research team first collaboratively developed a preliminary codebook with clear definitions and examples based on an initial reading of five transcripts. Subsequently, a subset of the data (an additional five transcripts) was coded independently by two researchers. The researchers then convened to compare their application of the codes, discuss any discrepancies and collaboratively refine the code definitions to resolve ambiguities. This iterative process was repeated until a stable and shared understanding of the codebook was achieved. This systematic procedure ensures that the emergent themes presented in Table 3 are a trustworthy and grounded representation of the participants' collective experience.

6. Results

The SUS questionnaire demonstrated a strong internal consistency (Cronbach's α of 0.844), confirming the reliability of the presence measurements. A total of 28 full-time employees in the construction industry participated in this study. Every participant was able to complete the research protocol completely. All 28 participants had at least heard of VR, and 21 had previously used a head-mounted display. Among those with prior exposure, self-reported comfort spanned the full scale but was skewed toward the upper end (very uncomfortable 14.3%, somewhat uncomfortable 9.5%, undecided 4.8%, somewhat comfortable 38.1% and very comfortable 33.3%). These figures suggest our sample leaned toward moderate-to-high VR familiarity.

Of the 28 participants, each was randomly assigned to either the Rich–Bare or Bare–Rich groups. The Rich–Bare group had 15 participants, whereas the Bare–Rich group had 13 participants. Participants for both groups had on average more than 12 years of industry experience and spent on average more than 40% of their workday on the construction site. Every participant reported previous awareness of VR and around 75% of them had also used VR in the past at least once.

6.1 Exploratory results: How does environmental richness of a virtual construction environment affect construction practitioners' behavior in virtual reality?

Heatmaps for the spread of fixations and participant position across the virtual environment were developed for both versions of the VE, as shown in Figures 5 and 6, respectively. The comparison of these figures reveals the impact that the varying levels of environmental richness had on the participants' visual attention and their movement patterns in the VE. For example, the rich version of the virtual environment led to participants directing their visual attention over a larger portion of the construction site and exploring a larger footprint of the VE. While the intention of this stage of data analysis is not to make empirical conclusions

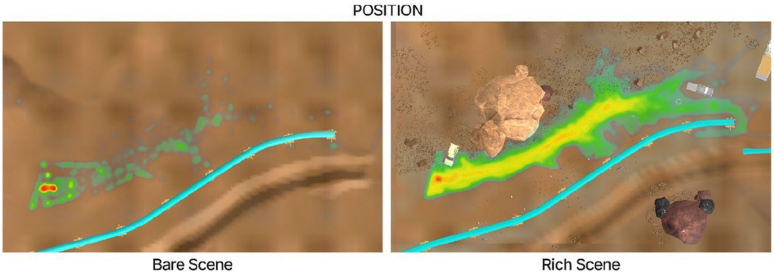

Figure 5. Comparison of the spread of fixations between the Bare and Rich versions of the virtual environment
Source: Authors' own work

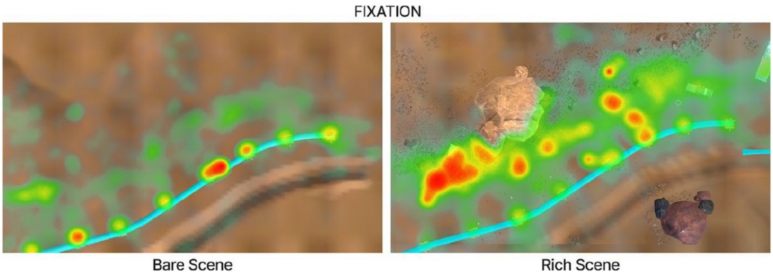

Figure 6. Comparison of the spread of participant's positions between the Bare and Rich versions of the virtual environment
Source: Authors' own work

about the differences in these environments, it indicates that there was some effect that the differences in environmental richness had on participants' behavior in analyzing the construction environment. Based on these initial observations, hypothesis testing was conducted to test whether the differences in presence felt by participants in the VE were statistically significant.

6.2 Confirmatory analysis: Does environmental richness affect presence for construction practitioners?

The SUS questionnaire demonstrated strong internal consistency (Cronbach's α = 0.844), confirming the reliability of presence measurements. The null hypothesis that the presence score for the "Rich" VE was smaller or equal to the presence score for the "Bare" version was tested using a one-tailed Mann–Whitney U-Test. The result was statistically significant at the 95% confidence level ($p = 0.018$), and thus the null hypothesis is rejected. To quantify the magnitude of this difference, the rank-biserial correlation (r) was calculated from the obtained Z-score using the formula $r = Z$, where n is the total sample size. With $Z = -2.1$ and $n = 28$, the calculation yielded r = −0.40. This effect size represents a medium-to-large effect, indicating that the observed difference in presence scores between the "Rich" and "Bare" environments is not only statistically significant but also practically meaningful. Furthermore, a post hoc power analysis conducted using G*Power (using the *t*-test for independent means as an analogue) revealed that the study achieved a statistical power (1-β)

of approximately 0.78 for detecting an effect of this magnitude. This robust effect, detectable even with a modest sample size, strengthens our confidence in the finding that environmental richness significantly enhances presence for construction practitioners. Presence differences also suggest that the net cognitive-load balance favored the rich scene, consistent with CLT predictions.

However, with only 28 full-time construction employees participating in the study, the power to detect significant differences or trends is limited. Although the results showed a statistically significant increase in presence scores for the “Rich” version of the VE, it is important to approach these findings with caution. The small sample size impacts the statistical power of the study, reducing the confidence in the results and potentially inflating the Type II error. Therefore, while the statistical significance and effect size support the meaningfulness of the observed differences, it should be noted that a larger sample might offer a more robust validation of these findings.

6.3 Explanatory analysis: What aspects of a virtual construction environment do practitioners pay attention to in virtual reality?

Based on the memos written during the VR activity and transcripts of the postactivity interview, the data were coded to highlight participant responses where they referred to aspects of the VE that they found interesting or that affected the presence they felt during the VR experience. The higher-order themes that emerged from the data were a natural result of the interviews, representing the essence of the differences in development of the VE. Table 3 presents the results organized according to the themes that naturally emerged from the interviews. The table includes quotes from the transcripts and descriptions of the themes, to provide a clear and usable representation of the findings for future researchers who are interested in developing realistic construction VEs. It is worth noting that while differences in specific details of the virtual environments presented in Table 1, such as the iPad or radio, may have influenced the participants’ experiences, the themes that emerged from the interviews provide a deeper insight into the essence of the differences in the two versions of the VE. These themes suggest candidate items for a presence/realism scale tailored to construction VR.

7. Discussion

Across data sources, the rich scene produced broader fixation spread and larger movement footprints (exploratory), a statistically and practically meaningful increase in SUS presence (confirmatory) and interview accounts emphasizing plausibility cues (explanatory). Under CLT, these cues appear to convert added stimulus complexity into germane processing, enabling more realistic worksite schemas rather than mere distraction. This aligns the behavioral heatmaps with the SUS difference. From a CLT perspective, the richer environment appears to have shifted the balance between extraneous and germane cognitive load in a way that favored deeper processing and, ultimately, a stronger sense of presence (Sweller, 2011). These findings illustrate the difference in behavior impacted by the amount of environmental detail incorporated in the VE, which can be expected in comparison to the real construction site. While these findings suggest that environmental richness within VR has an impact on the manner in which practitioners behave on the virtual construction site, the confirmatory hypothesis test results presented in Table 2 confirm the higher presence scores reported for the rich version of the VE. These findings collectively demonstrate that by adding nonhazardous elements to enhance the environment, future researchers can increase the sense of presence for construction practitioners in VR, providing valuable empirical insights. This is particularly noteworthy because previous studies have shown that

Table 2. Statistics for Mann–Whitney U-Test

Test statistics	Values
Mann–Whitney U	52
Z	−2.1
Asymptotic significance (one-tailed)	0.018
Exact significance (one-tailed)	0.018
Rank-biserial correlation	−0.40

Source(s): Authors' own work

the realism of a user's behavior is directly impacted by the level of presence that a virtual simulation can facilitate (Freeman *et al.*, 2000; Skarbez *et al.*, 2017).

The interview findings from the explanatory analysis indicate aspects of the environment that impacted the difference in presence that were reported by construction practitioners. Among these, it is noteworthy to mention that while visual fidelity was a highly referenced theme that emerged, most references were to realism of the terrain and vegetation models as opposed to the models directly related to the construction processes depicted in the scene (e.g. equipment, pipe sections and vehicles). Based on literature on how visual attention may be subjective to the observer's salience landscape, these findings provide specific insight into how construction practitioners perceive a virtual construction environment. Furthermore, participants referenced social presence (nearby workers and side-talk), climatic/terrain realism (dust, heat shimmer, uneven ground and wear) and immersive audio as markers of "a real site," consistent with presence theory that separates plausibility/authenticity from raw fidelity. By contrast, UI/process elements (tablet/radio) and general busyness contribute secondarily, which supports plausibility when aligned with site practices, but risk adding friction or clutter if over-specified. We therefore infer a ranked portfolio of cues, with social/climatic/terrain/audio > process/UI > generic busyness for presence in this context. These highlight the importance of considering aspects of the VE which may not be directly related to the construction process but still have a significant impact on the user's (construction practitioner) sense of presence. This may be an area that is often overlooked or minimally developed in the creation of virtual construction environments.

Apart from the visual fidelity of nonconstruction items, the social element of the virtual construction site and the climatic conditions were other aspects identified by the participants as important. The social element referred to the presence and interaction of virtual co-workers on the construction site, which could create a sense of realism and immersion for the participants. And the aspect of climatic conditions referred to the simulation of weather factors such as temperature, wind, dust, heatwaves and modeling erosion and dirt on construction equipment. Both aspects highlight the importance of developing the VE to target the user's day-to-day experience in the real environment. While all nonhazardous elements contributed to the presence, our data suggests a hierarchy of impact. Social presence elements (virtual co-workers) appear particularly critical, as participants explicitly noted the unrealistic nature of scenes without "people milling about." This finding challenges the conventional resource allocation in VR safety training, which typically prioritizes hazard modeling over social dynamics. The 0.40 effect size suggests these "background" elements may contribute as much to ecological validity as the primary hazard content itself.

These hierarchical findings about specific environmental elements align with broader VR research. Similar to previous studies in the field of VR. Similar to previous studies, our results indicate that immersive VR experiences can lead to more realistic experiences for users. Additionally, our study found a positive correlation between perceived thermal comfort and presence, which aligns with the broader understanding that environmental factors can influence the sense of presence in VR environments.

Interestingly, a study by Higuera–Trujillo *et al.* compared psychological, physiological and presence responses among different display formats, including photographs, 360-degree panoramas and a VE. Their results indicated that VR offers the closest-to-reality experience with respect to the user's physiological responses, and that physiological and psychological responses correlate with the sense of presence. This corroborates our findings and provides a robust scientific foundation for the importance of environmental richness in VR experiences, particularly for construction practitioners.

7.1 Implications

Under a CLT lens, our findings imply that VR designers should intentionally add contextual detail that stimulates germane load without overwhelming working memory. It also implies that observations made in VEs are more likely to mirror real-world scenarios when the presence of workers is enhanced. This implies that making an investment to increase the environmental richness in virtual construction environments could lead to more realistic observations. This, in turn, addresses a previous limitation in construction safety research, where ecological validity was often compromised.

Furthermore, the study findings underscore the significance of elements in the VE that might initially appear unrelated. Factors such as the inclusion of virtual co-workers and the simulation of climatic conditions emerged as having a considerable impact on the reported presence of construction practitioners. This has far-reaching implications for studies aiming to achieve ecological validity in safety research involving hazards, a goal that can often prove complex and challenging. In such instances, presence can serve as a valuable proxy measurement to predict the realism of construction practitioners' behavior in the VE. These findings challenge the parsimony principle often applied in VR training design. Rather than viewing non-task-essential elements as wasteful, our results suggest they serve a critical scaffolding function for presence. This aligns with ecological psychology's emphasis on environmental affordances? But contradicts efficiency-focused instructional design paradigms. The implication is that VR training effectiveness may require reconceptualizing "relevance" to include elements that support psychological presence even when they do not directly support task completion.

Finally, an important caveat that emerges from our study is that the list of nonhazardous site elements modeled for the investigation, while logical, was not comprehensive. Our findings provide evidence of how certain non-hazardous elements can influence presence. However, it remains unclear how specific modeling decisions impacted the outcomes. For instance, it is unclear how changes in the details developed for specific aspects may impact the users. Thus, while our study illuminates the potential impact of nonhazardous elements on presence in virtual construction environments, it does not offer a comprehensive guide to modeling a site for increased presence.

It should be noted that although our study investigates the potential benefits of using VR for construction safety training, we acknowledge that the effectiveness of VR in this context may depend on various factors, such as the specific tasks being performed, the level of detail required and the emotional arousal induced by the VE. While our study emphasizes the correlation between environmental richness and presence, it is crucial to understand that the desired level of realism in VEs can be contingent on the specific task at hand. For instance, tasks that rely heavily on intricate visual details might benefit from richer environments, whereas others might achieve optimal performance with lower-fidelity simulations. By understanding the factors that contribute to the effectiveness of VR in construction safety training, we can better inform the development of ecologically valid and reliable virtual construction environments that cater to the specific needs and requirements of construction practitioners. Therefore, as researchers continue to investigate this domain, they should be mindful of the complexities involved and approach modeling with an open-ended perspective, ready to explore and incorporate a diverse range of elements that can contribute to an enhanced sense of presence.

7.2 Interpreting the findings through the lens of cognitive load theory

Our findings can be powerfully interpreted through the framework of CLT. Our results reveal a productive tension with traditional CLT applications in VR.

While environmental richness theoretically increases extraneous load, participants perceived these elements as essential for realism rather than distraction. This contradiction suggests that for experienced practitioners, the distinction between "extraneous" and "germane" load may be context-dependent. Elements classified as extraneous in traditional learning contexts (e.g. background workers chatting) may actually constitute germane load when the learning objective is situational awareness in complex environments. Although cognitive load was not directly measured, we infer its profile from design controls and participant reports. The "bare" environment, while intentionally low in extraneous cognitive load, may have failed to induce sufficient germane load, the cognitive effort required for the construction of a realistic mental schema of a worksite. This is supported by qualitative feedback suggesting it felt sterile and unrealistic. Conversely, the "rich" environment introduced a host of additional nonhazardous elements, such as detailed terrain, climatic effects and social agents. While these elements could theoretically be classified as sources of extraneous load, our qualitative findings in Table 3 indicate that participants did not perceive them as mere distractions. Instead, they were viewed as vital cues for realism (e.g. "Normally the ground isn't graded that smooth," "I see heat waves, so the metal could be hot"). We posit that the cognitive effort required to process and integrate these realistic cues constituted a form of productive, germane load. Participants were actively investing mental resources to build a more ecologically valid representation of the environment. This increased investment in schema construction, we argue, is a key cognitive mechanism underlying the significantly higher sense of presence reported in the rich condition. This suggests that for experienced practitioners, a degree of environmental complexity is not a hindrance but a necessary component for activating the germane cognitive processes that lead to a feeling of "being there." However, it is also plausible that when the instructional objective is strictly individual hazard spotting, social agents that do not contribute information could impose purely extraneous cognitive load. Future work should therefore conduct cue-specific manipulations to isolate their costs and benefits.

An important contextual detail is that most participants entered the study with at least some VR experience, and roughly 71% of that subgroup described themselves as "somewhat" or "very" comfortable in head-mounted displays. Prior familiarity can elevate baseline presence ratings by reducing initial disorientation and freeing working-memory resources that would otherwise be spent on interface discovery (Weibel *et al.*, 2010; Cummings and Bailenson, 2016). Although the rich scene still produced significantly higher presence than the bare scene, the relatively experienced sample may have narrowed the between-condition gap or masked effects that only emerge when novices are struggling with locomotion or nausea. Future studies that stratify or statistically control for VR experience

Table 3. Aspects of a virtual construction environment impacting construction professionals' presence in VR

Aspects	Description	Quotes/memos
Busyness	References to the depiction of how busy the virtual construction site is	"Trucks parked everywhere, you're gonna have, you know, all your labor's vehicles parked" "There was a lot more going on (in the rich version). and for some reason, that was more engaging"
Social presence	References to the social nature of the construction site	"You know hearing those guys, you know, they're talking like normal guys so that was pretty cool" "Guys sitting around talking (referring to rich version) and when everybody's working in the second one (referring to bare version), I go, that's not a construction site, because, yeah, there's people milling about on construction site"
Immersive audio	References to the realism of the audio experience	"The sounds I think helped a lot" "Incorporate a little bit more that ambient noise"
Climatic conditions	References to the aspect of the game that simulates effects of the climate in the virtual environment	"The sense of feeling of like the wind or like dust on a construction site" "I see heat waves, so the metal could be hot" Participant guessed the engine was running because of emissions from the engine
User interface	References to the effect of controls and interactions a user has to make to be able to participate in the VR experience	"Having to remember which buttons to press to control to go somewhere that takes your mind off of the natural experience' "It won't take three seconds to press the home button" (in reference to using the in-game tablet)
Tools/ instruments	References to the accuracy of any tools or instruments that are required on the construction site	"I like the iPad; I've done exactly that. I've gone and taken pictures" "iPad was pretty realistic. I was pulling that up and interfacing with it. It was it was interesting"
Process accuracy	References to the accuracy of processes depicted on the virtual construction site	"Each piece of equipment had a guy kind of by the, you know, out at the boom and hoisting into the equipment" Participant identified missing taglines for the crane
Visual fidelity	References to the physical realism of 3D models on the virtual construction site	"Because there's vegetation and stuff on there, that it's real" "There were these big rocks, especially out in California in Arizona" "Normally the ground isn't graded that smooth" (in reference to Bare version)

Source(s): Authors' own work

could clarify whether richness offers proportionally greater benefits for first-time users, seasoned operators or both.

8. Limitations and future work

Our findings expose three critical gaps in current VR safety training design:

(1) *The authenticity paradox*: While richer environments enhanced presence, we cannot determine which specific elements are necessary versus sufficient. Future work must isolate individual cues to establish minimum viable richness.

(2) *The expertise threshold*: With 75% of participants having VR experience, we cannot determine whether environmental richness helps or hinders novices who lack robust mental models of construction sites.

(3) *The transfer gap*: Higher presence scores do not guarantee improved hazard recognition on actual sites. The relationship between presence and safety performance remains unvalidated.

This study offers initial evidence that scene richness can tip the cognitive-load balance toward productive processing, yet several factors narrow how far the findings can be stretched. First, cognitive load was inferred from design controls and participant comments rather than measured directly; future work should pair the same manipulation with tools such as the NASA-TLX or a simple dual-task probe. Second, the sample was small, drawn from a single training center and made up of seasoned practitioners. Of these, three-quarters had prior VR exposure, and most of those individuals reported feeling comfortable in head-mounted displays. Beginners who lack robust site schemas might find the same detail overwhelming, and outcomes could shift in other regions or trades. And because VR familiarity was measured but not used as a covariate, our ability to separate richness effects from comfort-with-technology effects was limited. Third, presence was recorded immediately after the VR session, and nothing was done to test longer-term hazard-recognition gains, so it remains unclear whether the richer scene translates into safer behavior on an actual jobsite. A natural next step is a longitudinal field experiment that measures participants' hazard-identification accuracy on real worksites at several delayed intervals (e.g. immediately, one month and six months post-training) to examine the durability and transfer of any presence-related gains. Fourth, finally, multiple cues, such as terrain detail, weather, co-workers and interface tweaks, were added as a bundle, and the richer scene consumed slightly more GPU power while being shown first for many participants. Disentangling individual cues, counter-balancing scene order and logging real-time frame rates would help rule out novelty or hardware effects and yield sharper design guidance. Furthermore, future researchers should also focus on site-specific richness cues since different construction site typologies (e.g. high-rise building, heavy civil and industrial) are likely to require unique combinations of richness cues.

9. Conclusion

This study targets the research gap in understanding the impact of environmental richness in VR on construction practitioners' behavior and presence. The aim was to explore how different levels of environmental richness in virtual construction environments affect user behavior and experience in VR, and to identify elements within the VE that significantly contribute to this experience. A study involving 28 full-time employees in the construction industry was carried out, who participated in a VR activity in both rich and bare versions of a virtual construction environment. The participants' behavior was analyzed qualitatively and quantitatively, and presence scores were compared. This was followed by a thematic analysis of postactivity interview transcripts to identify aspects of the VE that had a notable impact on the participants' experience.

The study found that incorporating nonhazardous elements into virtual construction environments can increase presence and realism for construction practitioners. The rich version of the VE had a statistically significant increase in presence, and qualitative inquiry showed that nonconstruction specific elements were important for enhancing presence. The counter-intuitive findings about the role of developing "background" items or aspects not directly related to the construction process will inform researchers who may have typically ignored them due to resource constraints and enable a higher sense of presence for participants by strategically investing development hours for specific site elements.

In conclusion, this study provides valuable insights into the impact of environmental richness on construction practitioners' behavior and presence in VEs. While the findings indicate fundamental aspects that are generally applicable to virtual construction environments, it should be noted that aspects of the VE were limited by the level of richness included for the specific scene developed for this study. Therefore, future researchers should not interpret aspects that were not studied in this VE as not worthy of development and continue exploration to systematize the development of construction specific VEs. Based on the findings of this paper, while ecological validity for hazardous construction environments may be complex to attain and validate, future researchers can aim to achieve a more accurate replication of behaviors that would be expected on real construction sites by targeting the level of presence that practitioners experience in the VE.

Data availability

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Some or all data, models or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions:

- Anonymized personal details of participants in the subject testing from construction companies.

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Appendix. Slater–Usoh–Steed (SUS) presence questionnaire items adapted from Usoh *et al.* (2000) reproduced for scholarly use with citation

(1) Please rate your sense of being in the office space on the following scale from 1 to 7, where 7 represents your normal experience of being in a place
   - I had a sense of "being there" in the office space: (1) Not at all and (7) Very much.

(2) To what extent were there times during the experience when the office space was the reality for you?
   - There were times during the experience when the office space was the reality for me. (1) At no time and (7) Almost all the time.

(3) When you think back about your experience, do you think of the office space more as images that you saw or more as somewhere that you visited?
   - The office space seems to me to be more like (1) Images that I saw and (7) Somewhere that I visited.

(4) During the time of the experience, which was the strongest on the whole, your sense of being in the office space or of being elsewhere?
   - I had a stronger sense of (1) Being elsewhere and (7) Being in the office space.

(5) Consider your memory of being in the office space. How similar in terms of the structure of the memory is this to the structure of the memory of other places you have been today? By "structure of the memory," consider things like the extent to which you have a visual memory of the office space, whether that memory is in color, the extent to which the memory seems vivid or realistic, its size, location in your imagination, the extent to which it is panoramic in your imagination and other such structural elements.
   - I think of the office space as a place in a way similar to other places that I have been today. (1) Not at all and (7) Very much so.

(6) During the time of the experience, did you often think to yourself that you were actually in the office space?
   - During the experience, I often thought that I was really standing in the office space. (1) Not very often and (7) Very much so.

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