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VIRTUAL REALITY INTEGRATION IN CONSTRUCTION PRE-TASK PLANNING: A QUALITATIVE CASE STUDY OF IMPLEMENTATION CHALLENGES AND OPPORTUNITIES

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SUMMARY: *This qualitative case study examines the integration of virtual reality (VR) into the Pre-task Planning (PTP) process in construction projects. While previous research has demonstrated VR's effectiveness, limited evidence exists regarding its implementation in daily safety practices. This study synthesizes practitioner perspectives on VR-based hazard identification. Seven construction professionals working on projects value between $1 million and $160 million participated in semi-structured interviews and performed hands-on VR evaluations using Oculus Quest 2 to simulate hazard identification during PTP. Four project sites were observed during morning PTP sessions. Data analysis employed Braun and Clarke's Reflexive Thematic Analysis, generating eight themes from 350 coded comments. Findings indicate that VR functions as a selective boundary object that bridges linguistic barriers and experience gaps. Participants reported varied levels of comfort—some noted mild dizziness or physical discomfort, while others adapted quickly. Since standard VR devices cannot replicate touch-based sensations without haptic feedback add-ons, this limitation can sometimes affect hazard recognition. Participants preferred trade-specific applicability of VR in PTP; spatial-coordination trades (e.g, electrical, plumbing) can benefit more than manual trades (e.g., concrete, excavation). A preference for collective viewing through projection over individual headsets was also discussed. Critical barriers to VR use in PTP include funding unavailability, connectivity limitations, and reluctance among experienced workers. The authors propose a three-stage implementation framework: Preparation, Implementation, and Finalization. This hybrid approach enhances rather than replaces existing practices. This research offers practical guidance for organizations pursuing digital transformation in safety-critical settings.*

KEYWORDS: *virtual reality, pre-task planning, construction safety, technology adoption, qualitative case study, hazard identification.*

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1. INTRODUCTION

The construction industry continuously struggles to improve workplace safety. Despite decades of regulatory oversight, technological progress, and ongoing safety initiatives, construction workers continue to face significantly higher risks than workers in most other industries. In 2023, the industry recorded 1,075 fatalities, representing about 20.4% of the 5,283 workplace deaths, while the construction workforce accounted for only around 5% of U.S. employment (U.S. Bureau of Labor Statistics (BLS), 2024). Falls, slips, and trips were the leading causes of construction worker fatalities in 2023, accounting for 421 deaths. Other causes were struck-by incidents, electrocutions, and caught-in/between accidents, together known as the "Fatal Four" (U.S. Bureau of Labor Statistics (BLS), 2024). From 2011 to 2022, the number of fatal injuries increased by 39.8% (Trueblood *et al.*, 2024). These figures indicate that the benefits of traditional safety measures have leveled off, and new strategies are necessary to make additional progress.

Pre-task Planning (PTP), also called Job Hazard Analysis (JHA) or Job Safety Analysis, is a proactive approach used in construction projects for methodically recognizing and controlling safety risks, and it is recommended to be done before beginning task performance (Rozenfeld *et al.*, 2010). PTP consists of dividing a task into sequential steps, identifying hazards related to each step, and suggesting controls to eliminate or mitigate risks before starting work. Studies have demonstrated the usefulness of such approaches (Xu *et al.* 2023). Speiser and Teizer (2024) found that using a systematic process for hazard identification and controls has the potential to prevent as many as 67% of fall-related incidents.

Despite their benefits, traditional PTP approaches continue to face significant challenges. Hazard identification often relies on individual experience, making the process subjective. Communicating complex spatial relationships can be difficult using only two-dimensional drawings and verbal instructions. Time constraints sometimes lead to rushed or superficial evaluations (Memarian *et al.*, 2025). Furthermore, the effectiveness of PTP depends largely on the active role of participants in identifying hazards. Research by Albert *et al.* (2014) reported that even seasoned workers identified just 45–55% of potential hazards during PTP, while less experienced staff found fewer than 30%.

Other challenges are workforce demographics and diversity. In 2024, the average age of U.S. construction workers is 41, and the proportion of workers aged 55 or older has nearly doubled from 11.5% in 2003 to 22.7% in 2020 (U.S. Bureau of Labor Statistics (BLS), 2025). Older workers have valuable experience and tacit knowledge but tend to be less likely to adopt new technologies. At the same time, workers under 25 represent just 9% of the construction workforce, compared to 13% in all industries (U.S. Bureau of Labor Statistics (BLS), 2025). This creates a risk of losing critical knowledge as seasoned personnel retire.

In addition to age-related issues, cultural and linguistic diversity increases the complexity of safety management in construction. In 2020, Hispanic workers comprised 30% of U.S. construction workers, though only 17.6% of total employment. Their fatality rate was 41% higher than the industry average, often due to language and cultural barriers (CPWR, 2022). Menzel and Gutierrez (2010) reported that Latino construction workers in Southern Nevada highlighted language and communication challenges, along with other concerns, as major occupational risks. They suggested that small contractors should offer more effective safety training in Spanish and that unions provide bilingual, simulation-based English classes to enhance workers' understanding and awareness of workers' compensation. Moreover, challenges extend beyond language barriers, as cultural differences in risk perception, communication styles, and knowledge of local safety norms affect how safety information is interpreted and used (Starren et al. 2013).

In this context, virtual reality (VR) has the potential to be a valuable tool in tackling some of these challenges. VR provides an immersive, interactive learning experience involving multiple human senses, including touch and hearing (Kim, 2024). In a comparative study with 80 participants, it was ranked as more beneficial and effective than traditional education media (Xing *et al.*, 2021). In VR, detailed 3D models of construction sites allow workers to recognize hazards more effectively. Li et al. (2018) recognized VR's ability to improve hazard detection, boost spatial awareness, and support knowledge sharing across different experience levels.

Up to now, most VR research has focused on using it as a training tool rather than integrating VR tools into daily operational safety practices such as PTP. This distinction is important because construction site settings face unique limitations that might not be present in classroom settings where VR is typically implemented. Integrating immersive visualization into construction hazard identification workflows can help identify safety risks that are not easily recognized otherwise (Vercelli *et al.*, 2024). However, while hazard identification can be improved in controlled trials, its implementation in construction projects frequently faces challenges due to factors such as employee resistance and practical barriers related to work settings (Yap *et al.*, 2022).

Theoretical perspectives from organizational psychology, human factors, and socio-technical systems help explain adoption challenges. The Technology Acceptance Model (Davis, 1989) highlights perceived usefulness and ease of use, which in construction are shaped by transient labor, project-specific workflows, and conservative safety norms (Sherratt *et al.*, 2025). Human factors such as device comfort, interaction ease, and cognitive load also influence these perceptions. Organizational learning theory (Levitt and March, 1988) indicates that temporary projects limit knowledge retention and transfer; VR initiatives should therefore capture, curate, and redeploy learning across projects. A socio-technical perspective (Baxter and Sommerville, 2011; Trist, 1981) views safety outcomes as emerging from interactions between social and technical systems. From this standpoint, introducing VR is both a technical innovation and a change in how safety knowledge is produced, shared, and applied on-site.

This study fills these gaps by examining VR integration into PTP. Using a qualitative case study method, the authors conducted this research in real-world projects with construction professionals, rather than in controlled laboratory conditions. Accordingly, this study aimed to investigate how virtual reality can be effectively integrated into daily safety planning in real-world construction settings. The investigation was guided by three interrelated research questions:

RQ1. How do construction safety professionals perceive and experience the integration of VR into pre-task planning (PTP) activities on active construction sites?
RQ2. What organizational, technical, and human factors shape the feasibility and sustained use of VR in construction safety workflows?
RQ3. How can insights from practitioners inform a practical framework for implementing VR-enhanced PTP that complements, rather than replaces, existing practices?

The research makes three key contributions: it offers practical insights into how construction practitioners perceive and use VR on active projects, adapts traditional technology adoption theories to fit the construction sector, and presents a practical PTP approach for implementing VR that addresses both technical and organizational considerations. These contributions address industry demands for digitalization and the increasing accessibility of affordable VR technologies.

The subsequent sections present a review of relevant literature on pre-task planning and virtual reality in construction, outline the research methodology employed in this study, and report the key findings from interviews, observations, and VR evaluations. The paper then discusses the theoretical and practical implications of these findings, concluding with a discussion of the study's limitations and recommendations for future research.

2. LITERATURE REVIEW

2.1 A brief overview of pre-task planning

Pre-task Planning (PTP) is performed routinely before the beginning of construction tasks. The procedure is relatively simple, as described by CPWR (2023), and it involves task breakdowns, hazard identification, and control measures. However, ethnographic research reveals greater complexity. Rozenfeld et al. (2010) explain that an ethnographic-style investigation into construction work found that traditional hazard identification processes do not cover the full intricacy of hazards because they assume steady work settings and independent tasks, similar to manufacturing. Construction sites are dynamic, with constantly changing topography, varying numbers of workers, evolving activities, and overlapping tasks that can create hazards for all workers (Albeaino and Gheisari, 2021).

Generally, PTP differs significantly across different construction sites. Memarian et al. (2023) found that the most effective JHA or pre-task planning sessions were interactive, encouraging worker participation, rotating leadership, and incorporating real near-miss and incident examples to clearly illustrate hazards. The ever-changing nature of construction tasks, due to the project-based structure of the industry, makes each project unique, hindering the effective capture and reuse of knowledge across project boundaries (Gherardi and Nicolini, 2000). Projects limit opportunities for sustained interaction between teams, while time pressure reduces capacity for communication beyond immediate project tasks. Consequently, these factors diminish the ability to share knowledge across projects, resulting in limited knowledge transfer in project-based organizations (Ren *et al.*, 2018). Persistent challenges in knowledge sharing, communication, and hazard identification among construction teams can be addressed with emerging technologies like VR, which help bridge gaps and foster shared understanding.

2.2 Virtual Reality as a boundary object

Boundary objects are shared tools or ideas that facilitate collaboration among diverse groups. They retain a stable, recognizable form that helps coordinate collective work, yet remain flexible enough to be understood and adapted differently within each group's specific context (Nathues *et al.*, 2025). In construction projects, documents such as drawings, technical specifications, and safety standards act as shared reference points that facilitate coordination among diverse participants, while still allowing each discipline to interpret and apply them according to its own professional context (Rodrigues *et al.*, 2017). VR can act as a boundary object in safety management by connecting designers, field workers, experienced tradespeople, novices, and workers of different languages. VR enables designers and stakeholders to experience and interpret planned environments in an immersive and intuitive way, making design intentions more comprehensible, enhancing spatial understanding, and facilitating communication across diverse professional and cultural backgrounds (Portman *et al.*, 2015).

To succeed, VR must address Carlile's (2004) three boundary types. At the syntactic level, it must provide shared and interpretable representations. At the semantic level, it should support different professional perspectives on the same hazard. At the pragmatic level, it must manage the operational consequences of making certain hazards visible while omitting others. BIM adoption demonstrates that digital boundary objects, while promising, require substantial preparation and cross-disciplinary collaboration to succeed (Golizadeh *et al.*, 2018; Zielinski Nguyen Ajslev and Elisabeth Ejstrup Nimb, 2022). VR will face similar demands, including bridging formal organizational boundaries and the informal boundaries that develop through everyday work.

2.3 Technology adoption in construction: a socio-technical challenge

Construction adopts technology selectively. The industry is advanced in materials and engineering, but cautious with information systems (Haikal, 2024). This pattern reflects its project-based structure, which limits innovation diffusion. Innovations must navigate networks of firms with different capabilities, incentives, and risk tolerances. Institutional theory explains technology adoption through three mechanisms: coercive (regulatory), mimetic (peer imitation), and normative (professional standards) pressures—each shaping how innovations navigate diverse organizational networks (Asadi *et al.*, 2017; Correia Simões *et al.*, 2020). In safety, coercive pressures often drive initial uptake, while long-term use depends on peer and professional acceptance.

Organizational culture also plays a role. Polarization among stakeholders in construction project management, for example, technologically adept project managers advocating for VR integration and field supervisors expressing skepticism due to unfamiliarity and perceived disruption, contributes to uneven adoption outcomes by reinforcing fragmented engagement, inconsistent implementation, and resistance to procedural standardization (Fernandes *et al.*, 2006). Orlikowski's (2000) concept of "technology-in-practice" shows that users adapt tools to fit existing routines. Construction teams often adjusted BIM to current practices rather than reorganizing around the technology (Hartmann *et al.*, 2012), a pattern likely with VR.

Individual factors also influence adoption. Cohen (2023) reported that participants with greater gaming experience more readily understood and used VR art-making tools, leading to higher engagement. This suggests that prior experience with interactive digital technologies, such as gaming, can facilitate quicker adoption and greater ease in using VR tools in other contexts, including workplace applications.

Substantial upfront costs, lack of established protocols, insufficient expertise, difficulties in stakeholder coordination, and cybersecurity concerns create additional obstacles to adoption. These factors underscore the need for regulatory support and industry-wide standards (Brandín and Abrishami, 2024). VR faces compounded difficulties through hardware and software licensing costs, rapid technological obsolescence, and ongoing requirements for content creation.

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3. METHODOLOGY

3.1 Research design and philosophical approach

The authors conducted an interpretivist qualitative case study on VR integration in construction PTP. This paradigm recognizes that safety practices are socially constructed and context-dependent, necessitating understanding of how practitioners create meaning within their specific work environments (Creswell and Clark, 2017). Zou et al. (2014) advocate for increased use of mixed methods in construction safety research, criticizing the current emphasis on quantitative approaches that view safety knowledge as static and easily transferable. Instead, they emphasize that safety learning is a social and cultural process that occurs through on-site interactions. Their suggested approach combines qualitative methods, such as ethnography and observation, with quantitative tools.

3.2 Case selection and participants

This study examined five construction sites operated by five distinct organizations in Southeast Texas, selected through purposive sampling to maximize variation in project size (ranging from approximately $1 million to $160 million), organizational structure, and safety management practices. Consistent with Eisenhardt and Graebner (2007) recommendations for theory building from cases, theoretical (purposive) sampling was employed to capture diversity across contexts, not to achieve statistical representativeness, but to enhance theoretical insight.

The seven participants comprised five senior construction professionals with 5–20 years of experience—an Area Environmental, Health, and Safety Manager overseeing $160 million in projects (Participant T), a Construction Superintendent with Occupational Safety and Health Administration (OSHA) liaison experience (Participant A), an EHS Safety Manager for small projects (Participant F), and two Area Safety Managers for large commercial projects (Participants AU and V), along with two construction workers with 2–10 years of field experience (Participants W1 and W2). According to Morse (2000), rich, detailed data from experienced participants can reduce the number of cases needed while still yielding meaningful and relevant insights.

The study primarily emphasized the managerial perspective, as these professionals oversee the organization, facilitation, and enforcement of PTP. Their insights provided a strategic understanding of implementation barriers, policy implications, and training needs associated with VR adoption. To broaden stakeholder representation, Participants W1 and W2 were interviewed following their participation in a VR-based PTP demonstration. Their field-based perspectives offered valuable feedback on usability, realism, and the practical integration of VR tools in real-world settings.

The sample represented both managerial and field perspectives. This composition was appropriate for a qualitative case study, emphasizing information power rather than numerical sufficiency (Morse, 2000). Data saturation was monitored throughout the data collection and analysis process. After the seventh interview and fourth site observation, new information primarily reinforced existing patterns without introducing novel concepts, indicating conceptual saturation (Braun and Clarke, 2006; Guest *et al.*, 2006).

3.3 Data collection

Data collection was conducted using a sequential three-phase design from September 2023 to October 2025, facilitating iterative refinement informed by emerging insights.

3.3.1 Phase 1: Semi-structured interviews

Initial semi-structured interviews (45 to 75 minutes) explored participants' current PTP practices, challenges, and perspectives on technology integration. The interview guide, refined through pilot testing, was structured to move from contextual background and current practices toward discussions of potential VR applications, following Rubin and Rubin's (2011) responsive interviewing approach. Questions were deliberately open-ended to get deep insights. Three interviews were conducted in person at participants' offices, and four via Microsoft Teams due to geographic constraints. All interviews were audio-recorded and transcribed verbatim.

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3.3.2 Phase 2: Site observations

Ethnographic observations of morning PTP sessions were conducted at four construction sites (three participant lacked active projects during the observation period). Following Hammersley and Atkinson's (2007) ethnographic approach, observations began at 6:00 AM to capture the full context of morning safety activities, from informal coffee conversations through formal PTP meetings. The researcher adopted an observer-as-participant role (Gold, 1958), primarily observing while occasionally participating when invited. Field notes distinguished between descriptive observations, analytical insights, and reflexive commentary. Photographic documentation captured material artifacts and spatial arrangements with participant permission.

Table 1: Samples of coding process from interview data to thematic analysis.

Raw Data (Interview Excerpts)	Initial Codes	Focused Codes	Categories	Themes
"First of all, the knowledge of completing PTP—that's the first challenge. The second challenge is thinking sometimes that's not their job to do; it's the safety person's job." (Participant F)	Lack of PTP knowledge; Responsibility confusion; Safety ownership issues	Knowledge gaps in PTP process	Worker training and education	Current PTP implementation challenges
"The biggest challenge is probably communication with the workers. Right, there's a language barrier with a lot of workers." (Participant T)	Language barriers; Communication difficulties; Multicultural workforce	Communication barriers	Communication issues	Current PTP implementation challenges
"Time, I think that's a challenge because sometimes the tasks are quite involved, so it takes a long time to divide each step out and really describe the hazards." (Participant V)	Time constraints; Task complexity; Detailed hazard analysis	Time limitations in PTP	Process efficiency	Current PTP implementation challenges
"If we can have a BIM model that's uploaded and we can start seeing what the roof is going to look like at the end, we'll be able to identify where we can put anchor points." (Participant AU)	BIM visualization; Future planning; Anchor point identification	VR for hazard visualization	Safety planning enhancement	Potential benefits of VR integration
"I think it helps to zero in closer on the details and be more accurate. So I would say detailing and accuracy." (Participant V)	Enhanced detail; Improved accuracy; Better focus	Improved hazard identification accuracy	Enhanced hazard detection	Potential benefits of VR integration
"They don't know, right? So this could help them know some of the stuff that they don't know—for sure. Visualize it." (Participant T)	Unknown hazards; Visualization aid; Knowledge enhancement	VR for unknown hazard discovery	Hazard awareness	Potential benefits of VR integration
"Cost definitely is a barrier... especially for smaller contracting companies." (Participant F)	High costs; Small company limitations; Financial barriers	VR affordability issues	Economic barriers	Challenges for VR implementation
"Construction is very active... it will be more challenging, and then the lack of experience too on using technology." (Participant AU) "I started feeling a little dizzy and had to pause the session. It's not very comfortable at the beginning." (Worker 1)	Active environment; Technology inexperience; Implementation difficulty	Technology adoption challenges	Technical barriers	Challenges for VR implementation
"You have to consider the labor force, right? It's just different approaches, different abilities." (Participant T) "I'm used to gaming, so it didn't take me long. But I can imagine someone without experience would struggle." (Worker 2)	Workforce diversity; Varying tech abilities; Training needs	Workforce readiness for VR	User adoption	Challenges for VR implementation
"We have these boards. So instead of doing them on paper, we have them do them on here." (Participant T)	Visual PTP boards; Non-paper methods; Interactive tools	Visual communication methods	Current best practices	Existing PTP practices
"We have stop work authority here for anybody in the building." (Participant F)	Safety empowerment; Worker authority; Safety culture	Safety culture elements	Safety culture	Existing PTP practices
"Perform the PTP every day, for every task, at the work location with all workers involved." (Participant V)	Daily PTP; All worker involvement; Location-specific	Comprehensive PTP approach	Standard procedures	Existing PTP practices
"Workers arrive on site, they gather up... the PTP gets created at the point of work." (Participant AU)	Point-of-work planning; Team gathering; On-site assessment	Field-based PTP creation	Field implementation	Existing PTP practices
"I think you're just adding an additional step to the JHA process, which is already limited in time." (Participant V)	Additional complexity; Process extension; Time pressure	VR as added burden	Process integration	Challenges for VR implementation

3.3.3 Phase 3: VR-Based PTP Evaluation

Participatory evaluation sessions (about 2 hours each) engaged participants as co-evaluators rather than test subjects. Using an Oculus Quest 2 headset with custom-developed construction scenarios, participants explored virtual job sites while employing think-aloud protocols (Ericsson, 2017). Three scenarios, such as fall protection, crane operations, and excavation safety, were selected based on common challenges identified in earlier phases.

4. DATA ANALYSIS

To ensure analytical transparency, all stages of coding were documented through NVivo memos linking raw data excerpts to developing codes and theme clusters. This process generated 350 initial codes, consolidated into 28 categories and finally into eight overarching themes. Each theme was supported by multiple data sources (interviews, observations, and VR evaluations), ensuring triangulation and internal validity. Representative quotations for each theme to capture both consensus and dissenting views, in line with reflexive thematic analysis principles. An excerpt of this coding trail is shown in Table 1.

The study received Institutional Review Board approval (STUDY00004688) from the University of Houston. All participants provided informed consent, with identities protected through pseudonyms.

5. RESULTS

5.1 Themes overview

Analysis of interviews, site observations, and VR evaluations revealed eight interconnected themes related to VR integration into construction PTP practices. From 350 initial codes refined through iterative analysis, these themes capture shared patterns across the seven participants while highlighting differences in perspective and experience. Table 2 summarizes the eight final themes, including concise definitions and illustrative quotations that reflect the participants' diverse viewpoints.

Table 2: Overview of final themes generated through reflexive thematic analysis.

Theme	Definition	Representative Quote (abridged)
1. Collaborative foundation of current PTP	PTP as a social activity promoting collective hazard recognition and crew cohesion.	"It brings the team together... everyone's on the same page." – Participant A
2. Limitations of current PTP practices	Persistent challenges such as language barriers, time pressure, and inconsistent participation.	"Communication with the workers... there's a language barrier." – Participant T
3. VR's perceived potential	Participants' expectations of VR to enhance visualization, accuracy, and understanding.	"It helps zero in on details and be more accurate." – Participant V
4. Observed PTP innovations	Existing creative adaptations (e.g., pictorial boards, visual hazard sketches) that align with VR's logic.	"We have them draw a sketch to show hazards." – Participant V
5. VR evaluation insights	Reflections from hands-on VR use, highlighting both immersion benefits and sensory limitations.	"You can't feel the power... very different from the real machine." – Participant AU
6. Implementation barriers	Organizational, technical, and cultural constraints affecting VR integration.	"You'll have to go through a lot of approval... company policy." – Participant F
7. Proposed implementation strategies	Hybrid models combining VR visualization with traditional group meetings.	"Take them into the conference room... walk through the building together." – Participant T
8. Framework development	Stepwise integration model outlining preparation, implementation, and finalization stages.	"Start with receptive crews... use it for high-value applications." – Field observation notes

5.1.1 Theme 1: Collaborative foundation of current PTP

PTP sessions observed across four different sites demonstrated strong collaborative elements that went beyond simply identifying hazards. As Participant A noted, *"This does two things. One, it brings the team together, so if we understand that everybody, including contractors who have nothing to do with each other, all understand that we're on the same page."* At all locations, morning meetings started between 6:45 and 7:00 a.m., with crews gathering around makeshift tables or designated areas, often sharing coffee as the conversations shifted from informal chats to formal safety discussions.

While the overall procedure was comparable on all sites, the authors observed major differences in PTP implementation. For example, at Participant T's site, morning sessions included body stretches, light exercises, while at Participant V’s site, workers were asked to draw a pictorial depiction of tasks. These variations reflected unique organizational cultures and safety risk identification approaches. Participant AU's weekly "all-hands meetings" brought together contractors and subcontractors to convey "one message" for weekly work coordination for the multi-contractor projects.

5.1.2 Theme 2: Limitations of current PTP practices

Several factors affect PTP quality. For example, verbal communication was the most common challenge. Participant T stated that "*A major challenge is communicating with the workers. Right!, there's a language barrier with many workers*." Observations confirmed widespread code-switching between English and Spanish, often with technical terms lacking precise translations. In addition to language barriers, participants highlighted difficulties with new crews unfamiliar with site-specific hazards, resistance to change from seasoned workers, diverse education levels impacting understanding, and time constraints that hindered comprehensive hazard discussions.

Participant AU articulated the new crew challenge: "*If it's a new crew, sometimes when they have new employees, the challenge would be... are they familiar with creating the PTP as some small contractors or small subs?"* This was not merely about training but about disrupting established communication patterns and trust networks. Participant F emphasized knowledge gaps: "*First of all, the knowledge of completing PTP, that's the first challenge."* Time constraints emerged repeatedly, with Participant V explaining: *"Time, I think that's a challenge because sometimes the tasks are quite involved, so it takes a long time to divide each step out and describe the hazards."*

5.1.3 Theme 3: VR's perceived potential

Before hands-on experience, participants expressed cautious optimism about VR's potential to address identified limitations. Visualization capabilities dominated initial perceptions, with Participant AU envisioning: "*If we can have a BIM model that's uploaded and we can start seeing what the roof is going to look like at the end, we'll be able to identify where we can put anchor points instead of having to go last minute."* Participant T saw potential for experiential bridging: *"New, inexperienced construction professionals... I would definitely say that's probably pretty strong. They don't know, right? So, this could help them know some of the stuff that they don't know.*"

However, uncertainty tempered enthusiasm. Participant F admitted: *"I really don't know. That's a good question because I'm trying to picture the technology itself and how we used it."* This honest uncertainty reflected limited prior exposure to VR technology and difficulty imagining implementation within existing practices.

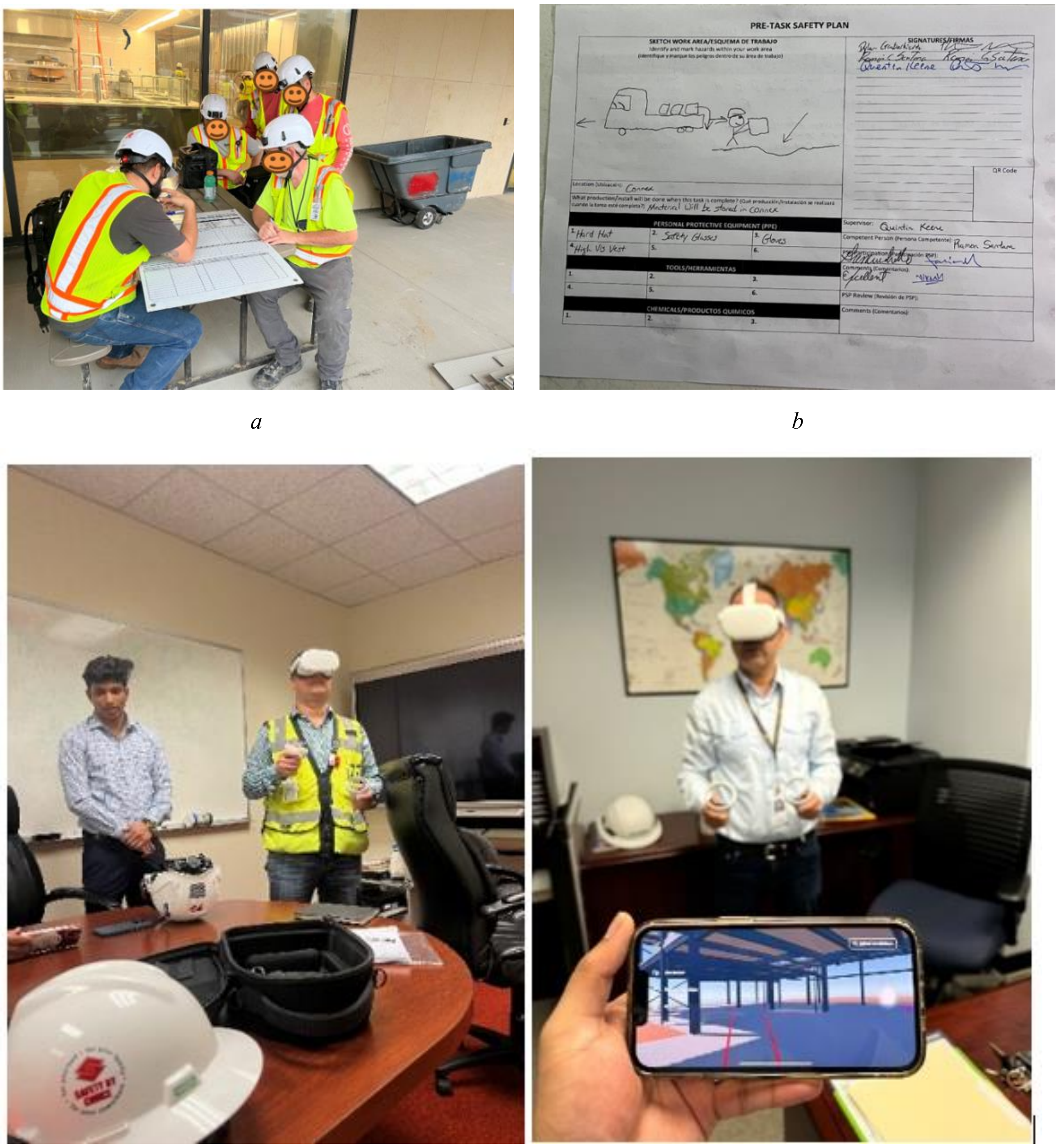
5.1.4 Theme 4: Observed PTP practices and innovations

Site observations documented diverse innovations that suggested receptivity to change while highlighting the embedded nature of current practices. Each organization had developed unique approaches addressing specific challenges, see Figures 1a and 1b.

Participant T's innovations included cardboard PTP forms posted in work areas, *"So we have these boards. So instead of doing them on paper, we have them do them on here"*, ECB (Environment, Capability, Behavior) hazard categorization systems, and four-point chin strap hard hats based on fall injury data. These material innovations demonstrated a willingness to modify traditional practices based on evidence and experience.

Participant V's visual communication methods required workers to create pictorial representations: "*We have them draw just a tiny little sketch to visually represent in a pictogram type thing... We can use any symbol, like stick figures."* This existing practice of visual hazard communication suggested natural alignment with VR's visualization capabilities.

Participant F's empowerment approaches included "stop work authority," where *"anyone in the building can ask to see your STA [Safety Task Assessment], and that same person... can stop work."* This distributed safety responsibility model indicated an organizational culture supporting worker participation in safety decisions.



a *b* *c* *d*

Figure 1: Comparative analysis of PTP implementation methods: (a) traditional paper-based PTP meeting with construction crew; (b) completed PTP form documenting hazards and controls; and (c–d) VR-based PTP sessions conducted by study participants.

5.1.5 Theme 5: VR evaluation insights

Hands-on VR evaluation sessions revealed both enthusiasm for the technology's potential and practical concerns about its limitations. Positive responses centered on visualization and hazard-recognition benefits, with participants successfully identifying risks in virtual environments that might otherwise be overlooked in two-dimensional drawings (see Figure 1c-d). Participant T explained, *"I don't think there's a logistics challenge because it's just everything that is battery-operated, so you can move them around."*

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Cost-effectiveness through shared viewing also emerged as a practical advantage. As Participant T noted, *"I think the most practical solution is to have one unit and project it on screen. Yeah. So that the cost wouldn't be that much."* This collective-viewing approach aligned with participants' preference for maintaining group discussion during PTP.

However, several critical limitations surfaced during actual use. Participant AU highlighted the embodied-knowledge gap, stating, *"You can't feel that power, the strength, the exhaustion on the machine... I've used a few virtual realities that you're playing with cranes, and it's pretty good to the naked eye, but it's very different when you feel the force in your hands of the actual equipment."* This gap between visual representation and tactile experience proved particularly challenging for tasks that depend on physical feedback.

User familiarity and comfort with digital technologies also influenced learning curves and engagement. Worker 2 reflected, *"I'm used to gaming, so it didn't take me long. But I can imagine someone without experience would struggle."* This comment illustrated that prior exposure to interactive media may accelerate adaptation, whereas less-experienced users may require additional orientation or gradual training to fully benefit from VR-based PTP.

5.1.6 Theme 6: Implementation barriers

Participants identified multiple organizational, technical, and human factors that constrained the effective implementation of VR in PTP. Some barriers were experienced firsthand during VR use, as illustrated by Worker 1, who remarked, "*I started feeling a little dizzy and had to pause the session. It's not very comfortable at the beginning."* This reflected early user adaptation and ergonomics challenges, particularly for individuals new to immersive technologies.

Company policy and procedural approvals also emerged as significant obstacles. Participant F explained, *"Because of the company policy, you'll have to go through a lot of approval."* Cost considerations appeared paradoxical—viewed as both a financial constraint and a manageable investment if implemented selectively.

Trade-specific applicability further shaped participants' perceptions. Participant AU provided a nuanced assessment: *"Construction is very active... usually the heavy workers come at the beginning, which is the concrete, the excavations... that one is harder to identify on VR. In my opinion, electricians... would be a great benefit because they're able to see beams and obstructions."* This observation highlighted how the nature of the work trade influences VR's practicality and value. Time constraints represented a persistent tension. Participant V noted, *"I think you're just adding an additional step to the PTP process, which is already limited in time. Already, we're not having enough time."*

Technical limitations, such as connectivity and power issues, were also frequently mentioned. Participant AU emphasized, *"Power and Internet, because sometimes we don't have connectivity, especially at the beginning of the projects."*

Finally, user acceptance and generational differences played a role in shaping adoption readiness. Participant AU observed, "*The seasoned workers... they don't use technology, so it's hard for them to."* Conversely, younger workers familiar with digital tools and gaming appeared more comfortable adapting to VR, suggesting that user experience strongly mediates acceptance.

5.1.7 Theme 7: Proposed implementation strategies

Participants envisioned hybrid approaches preserving social dynamics while leveraging VR capabilities. Participant T suggested collective viewing: *"You could sit like... take them into the conference room. We're going to walk through this whole building, and we're going to talk about it all."* Participant V proposed live integration: *"A live image, then at that point everybody could be on. They could get to the area where they're working. Everybody takes their phone out, and the foreman has these headsets on."*

These suggestions consistently emphasize VR as a complement to, not a replacement for, existing practices, thereby supporting the collaborative foundation of PTP with added visualization features. The preference for projection and shared viewing rather than individual headset use highlights the desire to maintain collective discussion and knowledge sharing.

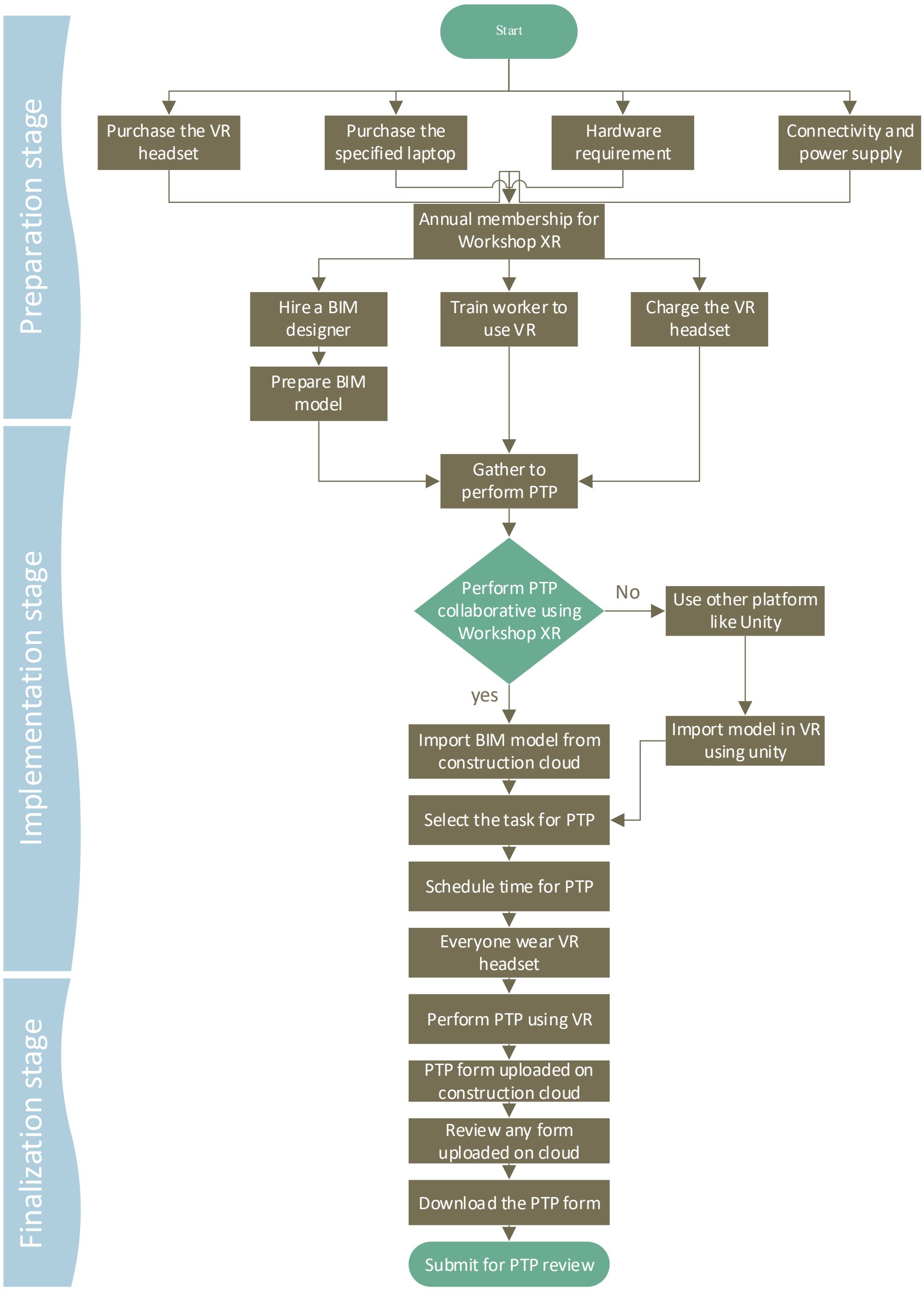

Figure 2: VR implementation framework in PTP.

5.1.8 Theme 8: Framework development

Based on participant feedback and observed practices, a three-stage implementation framework was developed. The Preparation Stage includes building the technical infrastructure (hardware, software, and connectivity), assessing organizational readiness through policy reviews and stakeholder mapping, and developing skills such as VR training for safety managers and crew leaders. Participants recommended starting with receptive crews and focusing on high-value applications.

The Implementation Stage involves using a hybrid approach that incorporates traditional PTP meetings and uses VR devices for enhancement. Rather than replacing morning meetings, VR can provide visualization for complex tasks, while regular task planning continues through discussions. Participants highlighted the need to maintain

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flexibility and local adaptation throughout. The Finalization Stage involves the safety manager reviewing each task's JHA to ensure alignment with daily assignments. The JHA form is accessed through the construction cloud and can be reviewed online or downloaded based on company policy. See Figure 2.

6. DISCUSSION

6.1 Theoretical implications

This research demonstrates that integrating VR into construction PTP is not simply a matter of introducing a new digital tool into existing routines, but rather of understanding how human, technological, organizational, and cultural factors intersect to shape practice. Rather than presenting a definitive model for all contexts, the findings offer exploratory insights grounded in the lived experiences of five safety professionals in Southeast Texas and two construction workers. Their reflections illustrate both the opportunities and tensions that accompany digital transformation within safety management.

Importantly, these findings should be interpreted within their contextual boundaries. The views expressed represent both experienced safety professionals and construction workers who participated in the study, reflecting insights from individuals involved in planning, facilitating, and performing pre-task activities. While safety managers provided strategic, organizational-level perspectives, the workers contributed practical, field-based observations on the usability and realism of VR applications. Together, their perspectives highlight how managerial and frontline experiences intersect to shape technology adoption. The concept of boundary objects further helps explain why VR's effectiveness varies across different contexts and user groups. Star and Griesemer (1989) introduced the concept of boundary objects to describe artifacts that enable cooperation across different communities of practice by maintaining a shared identity while holding distinct meanings for each group. The findings show VR works well as a boundary object in some areas but fails in others. For instance, VR–based safety training has been shown to improve Spanish-speaking workers' understanding of spatial hazards by using immersive visual representations that reduce the language barriers common in traditional verbal briefings (Akhanova and Ko, 2025). While VR enhances visual hazard awareness, it cannot replicate the physical sensations—such as balance, motion, and tactile feedback—that experienced workers depend on for real-world hazard detection (Carrigan *et al.*, 2025). When Participant AU described being unable to "feel the force in your hands" when operating virtual equipment, he identified a fundamental boundary that current technology cannot cross.

The findings indicate that successful technology adoption in construction depends on what is called "practice compatibility." This means that new technology must retain the beneficial aspects of current practices while solving existing issues (Zhang *et al.*, 2023). Conventional models like the Technology Acceptance Model emphasize perceived usefulness and ease of use; however, the participants consistently highlighted a different point. They liked the option to use VR to add value to their morning safety meetings, not to replace them. They wanted to have coffee conversations, gatherings, and in-person discussions that ultimately build trust and provide a shared understanding of the tasks. This is in agreement with Davila Delgado et al. (2020), who reported that construction professionals resist new technology that impacts regular communal practices, even when technical advantages are proposed.

6.2 Practical significance

The participants identified distinctions between various trades that can benefit from VR applications. Electrical and plumbing work, which requires spatial planning, can ideally use VR visualization. On the other hand, trades like concrete and excavation work, which require observing equipment use, feeling materials, and sensing equipment vibrations, might be less suitable for VR, though modifications like adding haptic feedback could improve the experience, as research has shown this creates greater immersion (Bouzbib *et al.*, 2021). These findings suggest that selective, trade-specific deployment offers the most feasible path for early VR adoption. By prioritizing spatial-coordination trades (electrical, plumbing, HVAC) where visualization benefits are highest, companies can minimize costs while demonstrating value before scaling.

The proposed hybrid setup, linking a single VR headset to a projector for collective viewing, was consistently endorsed by participants as both cost-effective and operationally feasible. This approach preserves group interaction, facilitates shared learning, and effectively mitigates common field challenges related to headset hygiene and logistical management.

The economic estimate of potential VR implementation on a commercial construction project projected an annual selective deployment cost of approximately $6,605 (Table 3). This estimate represents a baseline scenario that includes one shared Oculus Quest 2 headset, projection equipment for group viewing, and annual software and maintenance expenses. Rather than serving as a fixed financial model, this figure functions as a conceptual benchmark to illustrate affordability relative to standard training or safety equipment budgets. Actual costs may vary depending on factors such as whether organizations already possess BIM-capable laptops, the subscription tiers selected for modeling and visualization software (e.g., Revit, Unity Pro, Autodesk XR).

Table 3: Estimated Annual cost breakdown for selective VR implementation in PTP for one VR device and projection (As of Jan 2025).

Category	Description	Cost ($)	Percentage (%)
Hardware	Oculus Quest 2 headset, laptop for BIM-VR integration, cables, and projection equipment	2,640	40
Software	Revit for BIM modeling, Unity for VR development, annual subscriptions	1,981	30
Training	Initial training for safety managers on VR use in PTP (e.g., 10 hours at $132/hour)	1,320	20
Maintenance	Device maintenance, electricity, and minor updates	664	10
Total	Annual cost for selective deployment (excludes BIM designer salary of ~$10,000)	6,605	100

Time limitations in morning PTP meetings were recognized as critical factors that could potentially affect VR implementation. Generally, morning PTP sessions are quick, with crews ready to start construction work. Although using VR alongside PTP sessions could increase hazard identification, it might also impact tight schedules. However, in many cases, PTP serves as a constructability review mechanism that enables early identification and resolution of potential challenges, thereby improving project coordination and ultimately saving time (Al Hamadani *et al.*, 2022). Participants proposed solutions to make work smoother, like pre-loading BIM scenarios onto VR and focusing on VR use for unusual or high-risk tasks. These recommendations show the practical insights workers gained that allow for balancing safety and production work pressures.

6.3 Addressing the embodied knowledge challenge

Although VR offers strong 3D visualization, it still falls short of representing all the complex information needed for effective hazard identification in construction. Construction experience is mostly tacit (Abu Adi *et al.*, 2021). For example, when an experienced carpenter feels scaffolding shift or an equipment operator finds unusual resistance in hydraulic controls, they gather safety information that is not always feasible through viewing 3D models. This personal experience is based on years of interaction with materials, tools, and environments.

Rather than viewing experience as a limitation of VR technology, participants suggested redefining VR's role in task planning. VR can prepare workers for complex tasks by allowing them to visualize the final product and understand spatial relationships with other building elements and hazards. Participant V proposed using live video feeds to integrate real site conditions into VR visualizations, highlighting both the technology's strengths and its constraints. This hybrid approach combines real-world environments with VR's visualization capabilities, though it may reduce the level of immersion.

The challenges are more than individual sensory feedback, like the feel of materials and vibration of equipment; they also include environmental factors that affect work, like weather, time of day, fatigue, and crew sizes. Hazard perception changes when workers are fatigued (Taşdelen and Özpınar, 2020), and current VR cannot mimic the level of tiredness occurring from 95-degree heat or slick surfaces due to morning dew. These environmental factors are not present in virtual scenes.

6.4 Organizational change implications

The implementation barriers the participants recognized are also organization-related, not just technical difficulties. Company policies may hinder new technological interventions, especially if they require financial investment. Hence, companies may demand multiple approvals for adopting new technology. Other non-technical challenges include experienced workers who are often skeptical and see VR as a threat to their expertise, while rugged construction sites make it difficult to keep VR equipment safe. These issues are legitimate and cannot be addressed without organizational buy-in.

Younger workers, particularly those familiar with video games, expressed greater interest in using VR tools. As one participant noted, *"I'm used to gaming, so it didn't take me long. But I can imagine someone without experience would struggle"* (Participant W2). In contrast, older staff were less inclined to adopt or modify established procedures. These differences extend beyond technological familiarity, reflecting distinct learning styles within construction. Experienced workers, whose hazard recognition stems from firsthand experience, questioned whether VR-based training can cultivate the same intuitive safety awareness developed through years on-site.

The findings show that organizations can adapt effectively when new practices meet practical needs. Examples include Participant T's cardboard PTP forms, Participant V's pictorial hazard representations, and Participant F's stop work authority, all safety innovations that originated from workers' practices rather than being externally imposed. This indicates that VR implementation is likely to be more successful if it arises from worker-identified needs rather than top-down management mandates.

6.5 Methodological contributions

This study illustrates the value of qualitative research in understanding technology adoption within construction. While quantitative studies can measure whether VR improves hazard identification rates, they cannot explain why certain implementations succeed while others fail. Morning PTP sessions show that safety depends on both formal procedures and informal actions. Casual chats, workers' strategic positioning, and unspoken negotiations all shape safety results but are difficult to measure quantitatively.

The participatory evaluation approach, which positioned safety professionals as co-researchers rather than test subjects, uncovered insights that traditional usability testing often overlooks. When participants struggled with VR controls while wearing gloves or noted the unnatural motion of virtual workers, they revealed practical challenges rarely captured in laboratory settings. Their implementation suggestions reflected a nuanced understanding of construction culture that external researchers might take years to acquire.

6.6 Limitations and future directions

The seven-participant sample provided rich insights into VR implementation through extended engagement, combining managerial and field-level perspectives. The inclusion of two construction workers added valuable, practical viewpoints from daily site operations, complementing the strategic perspectives of safety and management personnel. However, larger studies across different regions and construction sectors—such as infrastructure or commercial construction—would strengthen confidence in the findings. The Southeast Texas context, with its unique climate conditions and workforce demographics, shaped the results in ways that may not generalize to other regions; for instance, construction in Alaska poses different challenges than in Arizona. Future research should engage a broader range of on-site roles, including foremen and specialized trades, using participatory or ethnographic methods to better understand how VR integration varies across the construction workforce and regional contexts.

7. CONCLUSION

This qualitative case study examined the integration of virtual reality (VR) into pre-task planning (PTP) to understand how technological innovation influences safety practices in construction. Through engagement with seven professionals—five safety managers and two field workers—on projects valued between \$1 million and \$160 million, the study combined observation of PTP sessions with participatory VR evaluations. The findings show that effective VR adoption requires rethinking how safety knowledge is produced and shared, rather than simply replacing traditional tools with digital ones.

The results offer valuable, context-specific insights drawn from the Southeast Texas construction environment, where unique climate conditions and workforce characteristics provided a rich setting for understanding VR implementation. The future research can build on this work by engaging foremen, craft workers, and other trades across different project types and organizational structures to further validate and expand the conclusions.

Previous research has shown VR's effectiveness for hazard identification in controlled settings, but such studies often overlook practitioners' real-world experiences. By using a qualitative approach, this study captured how construction professionals perceive both the potential and the limits of VR in practice. The study also estimated the annual cost of selective VR deployment for a typical mid-sized project, providing a benchmark for assessing feasibility.

PTP offers benefits beyond identifying hazards and controls. When enhanced with VR, it can serve as a constructability review tool, helping teams visualize tasks, anticipate challenges, and reduce rework. For trades performing spatially complex work, VR-supported PTP can improve communication, coordination, and safety outcomes.

Future research should use longitudinal methods to examine how VR-integrated PTP influences project performance over time and to establish best practices for implementation.

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