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BARRIERS TO VIRTUAL REALITY ADOPTION IN ENGINEERI NG SAFETY TRAINING: A DELPHI CONSENSUS STUDY

Binyi Huang
School of Civil and Environmental Engineering, The University of New South Wales, Sydney, Australia,
binyi.huang@student.unsw.edu.au

Khalegh Barati
School of Civil and Environmental Engineering, The University of New South Wales, Sydney, Australia,
khalegh.barati@unsw.edu.au

Liyun Jiang
School of Communications and Information Engineering, Chongqing University of Posts and Telecommunications, Chongqing, China,
2021214318@stu.cqupt.edu.cn

Xiaole Ren
School of Civil and Environmental Engineering, The University of New South Wales, Sydney, Australia,
xiaole.ren@student.unsw.edu.au

Cong Wang

MSC Student, The University of New South Wales, Sydney, Australia,
cong.wang@student.unsw.edu.au

Abstract

Virtual Reality (VR) supported by Artificial Intelligence (AI) offers immersive, data-driven opportunities to improve safety training in high-risk engineering environments. Yet, large-scale corporate deployment remains sporadic. This study applies a three-round Delphi process with 15 academic and industry experts from the University of New South Wales (UNSW), China Railway 25th Bureau, and Zhongyifeng Construction (Suzhou 2nd Bureau) to prioritise the obstacles that prevent VR adoption. Eighteen barriers extracted from Round 1 were rated in Rounds 2-3. Consensus, assessed with Kendall's coefficient of concordance (W), rose from 0.32 to 0.52, indicating strong convergence. High initial cost, inadequate IT infrastructure, limited management support, scarcity of domain-specific VR content, and lack of integration standards emerged as the top-five critical barriers. Secondary constraints included workforce resistance, cybersickness, trainer preparedness, and technical compatibility issues. The paper offers evidence-based recommendations, including financial modelling, staged infrastructure upgrades, executive engagement strategies, content-sharing consortia, and standard-setting initiatives to accelerate safe, scalable deployment of AI-enhanced VR training in engineering organisations.

Keywords:

VR, Engineering Safety Training, AI, Delphi Method

1. Introduction

High-risk engineering sectors, including construction, mining, and energy, continue to report accident rates far exceeding those of manufacturing and office settings (Dhalmahapatra et al., 2021). Conventional classroom or on-site drills struggle to recreate hazardous scenarios safely, whereas VR can immerse trainees in lifelike emergencies without physical danger (Scorgie et al., 2024). Meta-analytic evidence shows VR safety instruction yields significantly higher knowledge retention and behavioural transfer than lecture-based training. Coupling VR with AI-driven intelligent tutoring systems promises real-time performance analytics and personalised feedback (Lin et al., 2023), aligning with constructivist and cognitive-apprenticeship theories adopted in contemporary engineering education.

Despite these advantages, enterprise uptake lags behind technological maturity. Industry surveys consistently list high capital expenditure, infrastructure gaps, and organisational inertia as chief impediments (Sudiarno et al., 2024). The literature remains fragmented, often focusing on single industries or pilot studies without systematically ranking barriers. The principal objectives of the study were as follows.

- To identify the barriers that most hinder organisational adoption of VR for safety training.
- To evaluate the relative importance of these barriers as perceived by cross-sector experts.
- To statistically demonstrate consensus on the prioritisation of these barriers.

2. Background

2.1 Immersive VR in Engineering Safety Training

Early empirical work showed that fully immersive head-mounted displays (HMDs) elicit significantly higher presence and behavioural fidelity than desktop simulations, leading to superior near-miss detection and safer procedural execution (Rokooei et al., 2023). A meta-analysis of 72 studies across high-risk engineering sectors calculated a large pooled effect size (Hedges $g = 0.84$) for knowledge gain relative to lecture-based controls (Scorgie et al., 2024). Recent domain-specific trials confirm these advantages: roofing fall-arrest practice improved trainees' correct harness use by 36 % after a single 30-minute VR session (Scorgie et al., 2024), while immersive five-factor (5M) scenarios raised hazard-identification accuracy in process plants from 62 % to 88 % (Al-Hamad & Gilányi, 2025). Complementary systematic reviews in modular integrated construction, energy distribution, and robotics paint a consistent picture of enhanced spatial reasoning, psychomotor rehearsal, and emergency-response latency (Sadeghi et al., 2025).

2.2 Pedagogical Foundations

The pedagogical efficacy of VR is grounded in experiential learning theory, which posits that concrete experience followed by reflective abstraction strengthens mental models. Multimedia cognitive-load studies demonstrate that the multimodal channels activated in VR reduce extraneous load and free working-memory resources for germane processing (Oje et al., 2023). Gamification layers such as points, leaderboards and narrative quests further boost motivation and self-regulation when aligned with meaningful hazards rather than superficial game mechanics. Interactive learning elements such as manipulable objects, peer avatars and scenario branching have been shown to increase self-efficacy scores by as much as 0.9 on a five-point Likert scale when helping learners master complex procedures (Seo et al., 2024). These outcomes underscore the suitability of VR as a delivery mode for constructivist and cognitive-apprenticeship approaches championed in contemporary engineering education.

2.3 AI-Augmented VR and Intelligent Tutoring

Integration of AI techniques is increasingly viewed as the next performance frontier. Computer-vision pipelines detect unsafe postures or proximity breaches in real time, while Bayesian learner models dynamically adjust scenario difficulty to maintain trainees in Vygotsky's zone of proximal development. Adaptive feedback has been linked to 25–40 % reductions in the number of repetitions needed to reach safe-performance mastery thresholds compared with static VR modules. Generative AI is now being deployed to synthesize photorealistic site conditions and automatically author branching narratives, thereby slashing content-development lead times (Taiwo et al., 2025). Despite these technological advances, most published adoption cases remain at the pilot stage, underscoring the importance of systematically examining the constraints faced at the enterprise level.

2.4 Barriers to Organisational Adoption

Quantitative and qualitative studies converge on a recurrent constellation of obstacles. Cost remains the single most cited deterrent, with total cost of ownership (hardware, software licences, content and maintenance) running three to four times higher than equivalent video-based programmes. Technical bottlenecks include inadequate graphics-processing capacity, lack of integration standards and persistent cybersickness; the latter still affects an estimated 25-30 % of HMD users despite improvements in optics and motion-prediction algorithms (Cossio et al., 2025). On the organisational side, insufficient senior-management sponsorship, unclear return-on-investment (ROI) metrics, trainer skill gaps and workforce resistance have all been identified across multiple sectors. Table 1 consolidates the ten most frequently reported barriers and maps them to the primary domain of influence.

Table 1. *Representative barriers to VR adoption in corporate safety training*

	Barrier	Primary implication
B1	High capital expenditure	Limits procurement without new financing models
B2	Inadequate IT infrastructure	Requires staged infrastructure upgrades
B3	Content scarcity & localisation	Hinders compliance and worker relevance
B4	Lack of interoperability standards	Escalates long-term switching costs
B5	Management support deficit	Executive engagement critical for budget release
B6	Workforce resistance	Necessitates change-management & demos
B7	Cybersickness concerns	Drives demand for ergonomic guidelines
B8	Trainer competence gaps	Calls for professional-development programmes
B9	Uncertain ROI metrics	Obscures investment justification
B10	Regulatory ambiguity	Requires early liaison with regulators

2.5 Delphi Method in Technology-Adoption Studies

The Delphi technique has become a mainstay for establishing expert consensus on emergent technological issues where empirical field data are limited. Applications include generative-AI readiness in construction, smart safety-management systems and national policy road-mapping (Taiwo et al., 2025). Typical three-round designs achieve Kendall's W values between 0.30 and 0.60, indicating moderate-to-strong convergence; anonymity and controlled feedback guard against dominance bias and groupthink. In the context of VR adoption, the Delphi method brings together diverse perspectives from trainers, IT integrators and health and safety officers, producing a ranked and collectively agreed list of barriers that can guide future intervention studies. The present study follows these best-practice parameters by recruiting cross-sector experts and applying strict consensus thresholds ($CV < 0.30$; > 80 % agreement).

2.6 Research Gaps and Contribution

While prior work has documented the efficacy of VR and outlined a catalogue of inhibitors, three lacunae remain. First, few studies quantify the relative salience of barriers across domains, limiting resource-allocation decisions. Second, the coupling of AI-driven analytics with VR platforms is under-represented in adoption research despite growing technical feasibility. Third, most investigations are confined to single industries or geographic regions, constraining external validity. By executing a rigorously designed, multi-sector Delphi study focused on AI-enhanced VR for safety training, the present work addresses all three deficiencies, delivering a statistically validated prioritisation that can inform both corporate strategy and future experimental interventions.

3. Methodology

3.1 Research Design

An exploratory, mixed-methods Delphi design was selected, which was shown in Figure 1. Three sequential rounds transitioned from qualitative elicitation to quantitative rating, matching the best-practice recommendation.

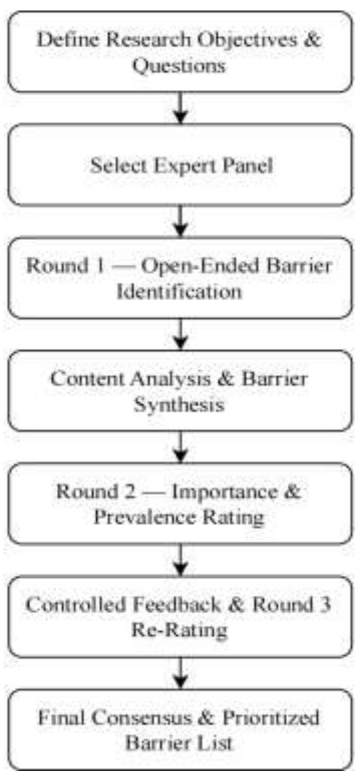

Figure 1. *Three-Round Delphi Workflow*

3.2 Expert Panel

Fifteen experts representing academia (n = 5) and industry (n = 10) were purposively sampled for demonstrable VR safety experience, which was shown in Table 2. Participants remained anonymous to one another to avoid status bias.

Table 2. *Expert panel composition (n = 15)*

Affiliation	Role / Expertise	Count	Region
University of New South Wales	Researchers in AI-enabled engineering education	5	Australia
China Railway 25th Bureau	H&S and training managers with VR pilot experience	4	China
Zhongyifeng (Suzhou 2nd Bureau)	Project & safety directors overseeing workforce upskilling	2	China
Independent VR developers/consultants	Content and system integrators for industrial training	4	Australia & China

3.3 Delphi Procedure

Round 1 (open-ended): Experts listed perceived barriers; 52 raw statements were coded in NVivo and condensed to 18 unique items across technical, financial, and human domains.

Round 2 (rating): Items were rated for *importance* (1 = not significant, 5 = extremely significant) and *prevalence* on 5-point Likert scales.

Round 3 (re-rating): In controlled feedback, each expert received group means and their own prior scores, which enabled reconsideration. No items were added or removed, indicating content stability.

3.4 Data Analysis

Descriptive statistics (mean, SD), coefficient of variation (CV = SD/mean) and percentage agreement (≥ 4) were computed in SPSS 28. Overall consensus was tested with Kendall’s W:

$$W = \frac{12\sum j_1^k {S_j}^2}{k^2(N^3 - N)} \tag{1}$$

$$S_j = R_j - \frac{k(N+1)}{2} \tag{2}$$

where $N = 18$ barriers, $k = 15$ experts, R_j is the sum of ranks for item j. W ranges 0 (no agreement) to 1 (perfect agreement). Significance is evaluated via $\chi^2 = k(N-1)W$ with $N-1$ degrees of freedom. Consensus criteria adopted: CV < 0.30 *and* ≥ 80 % of ratings ≥ 4.

4. Results

4.1 Round 1: Barrier Catalogue

Eighteen barriers were distilled, which were shown in Table 3. Financial and infrastructure constraints dominated initial narratives.

Table 3. *Barrier set generated in Round 1*

Code	Barrier (condensed description)	Primary Domain
B1	High initial cost of VR hardware & software	Financial
B2	insufficient IT infrastructure & workspace	Technical
B3	Ongoing maintenance/support burden	Technical
B4	Scarcity of high-quality VR content	Technical
B5	Platform compatibility & vendor lock-in	Technical
B6	Steep learning curve for operators	Human
B7	Workforce resistance/perception of "gaming"	Human
B8	Limited senior-management support	Organisational
B9	Cybersickness & health concerns	Human
B10	Trainer skill gaps	Organisational
B11	Absence of standards/integration guidelines	Organisational
B12	Uncertain ROI / effectiveness evidence	Organisational
B13	Long content-development lead-time	Technical
B14	Cultural & language adaptation issues	Organisational
B15	Physical scale constraints (one-headset limit)	Technical
B16	Regulatory compliance ambiguity	Organisational
B17	External stakeholder scepticism (clients, unions)	Organisational
B18	Current VR technology limitations (haptics, battery)	Technical

4.2 Round 2: Initial Ranking

Mean importance scores ranged from 4.53 (B1) to 3.13 (B14). Kendall's W = 0.32 ($p < 0.01$) indicated moderate agreement. Items with CV > 0.30 required further deliberation.

4.3 Round 3: Consensus Outcomes

After feedback, eight items reached strong consensus (CV ≤ 0.20). The final ranking is summarised in Table 4.

Table 4. *Round 3 consensus ranking (importance dimension)*

Rank	Barrier	Mean±SD	CV	%≥ 4	Consensus
1	B1 Cost	4.60 ± 0.51	0.11	100 %	Strong
2	B2 Infrastructure	4.47 ± 0.64	0.14	93 %	Strong
3	B8 Management support	4.40 ± 0.63	0.14	93 %	Strong
4	B4 Content scarcity	4.33 ± 0.62	0.14	93 %	Strong
5	B11 Standards	4.27 ± 0.70	0.16	87 %	Strong
6	B7 Workforce resistance	4.20 ± 0.68	0.16	87 %	Strong
7	B9 Cybersickness	4.13 ± 0.64	0.16	87 %	Strong
8	B10 Trainer gaps	4.07 ± 0.70	0.17	80 %	Strong
9	B5 Compatibility	4.00 ± 0.65	0.16	80 %	Strong
10	B12 ROI uncertainty	3.93 ± 0.80	0.20	73 %	Moderate

Kendall's W rose to 0.52, confirming strong convergence ($\chi^2 = 131.0$, $p < 0.001$).

5. Discussion

5.1 Interpretation of Critical Barriers

Financial & Technical Foundations. The dominance of cost and infrastructure echoes industry surveys where high capital expenditure remains "the biggest adoption hurdle". While HMD prices have fallen, the total cost of ownership, including bespoke content to robust GPUs, still outstrips conventional training budgets.

Organisational Sponsorship. Limited management support (Rank 3) aligns with Technology-Organisation-Environment models stressing leadership advocacy for innovation success. Without executive champions, budget release and policy integration stall.

Content & Standards Gaps. Lack of sector-specific scenarios curtails scalability; nearly 38 % of immersive-tech executives cite "limited content" as a major pain-point. Regulatory endorsement remains uncertain because the government determines the adequacy of virtual training on a case-by-case basis, in the absence of formally accredited VR curricula.

Human Factors. Workforce resistance and trainer competence highlight the socio-technical nature of adoption. Studies in education report inadequate facilitator training as a primary barrier to VR integration. Cybersickness, although mitigated by modern optics, still affects roughly one-third of users, warranting ergonomic and session-length guidelines.

5.2 Implications for Engineering Educators and Firms

- Stage-Gate Investment Model: Begin with a low-fidelity pilot to generate ROI data, then scale infrastructure once value is evidenced. Cost-benefit simulation frameworks assist decision-makers.
- Infrastructure Audit Toolkit: Adopt checklists for GPU capacity, spatial requirements, and network bandwidth prior to procurement.
- Executive Immersion Workshops: Short VR demos targeted at senior leaders improve perceived usefulness and drive budget allocation.
- Open Content Consortia: Pool development costs via industry-academic partnerships; shared libraries of hazard scenarios reduce duplication.
- Standards Development: Engage with bodies such as ISO 45003 VR workgroup to codify learning-outcome benchmarks and interoperability.

5.3 Limitations and Future Work

Although a panel of fifteen experts meets methodological recommendations that typically specify 10 to 15 panellists for a homogeneous Delphi study, the restricted sample may limit the external validity of the results beyond the geographical areas and industrial subsectors represented. Because VR hardware prices and related infrastructure costs continue to fall, reshaping organisational cost–benefit calculation, the relative salience of individual barriers is likely to change over time. Replicating the consensus exercise at regular intervals and in additional regions would therefore enhance longitudinal robustness and contextual generalisability. Subsequent experimental research should also assess the efficacy of targeted counter-measures, such as structured instructor-competence development programmes, in mitigating the highest-priority obstacles identified by the panel.

6. Conclusion

Through a rigorously executed Delphi study, this paper delivers an expert-validated hierarchy of barriers constraining AI-enhanced VR safety training in engineering firms. Addressing the top-five obstacles, including cost, infrastructure, management sponsorship, content scarcity and standards, offers the highest leverage for practitioners seeking safer, more effective workforce development. The consensus metrics lend statistical confidence to these priorities, guiding both corporate strategy and future scholarly inquiry.

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