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Virtual Reality-Based Learning Environments for Experiential Education

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ABSTRACT

Virtual reality (VR) learning environments provide experiential education through immersive simulations that enable learners to practise high-stakes skills -- surgical procedures, industrial safety protocols, emergency response, and complex scientific phenomena -- in risk-free, repeatable settings unavailable in traditional classrooms. Meta-analytic evidence establishes VR learning advantage over conventional instruction (d = 0.66), but the educational design principles that maximise VR learning effectiveness -- presence intensity, interactivity level, collaborative features, and AI-adaptive scaffolding -- remain incompletely understood. This paper proposes the VR Learning Environment Evaluation Framework (VRLEEF), a systematic evaluation of five VR learning design dimensions -- presence fidelity, interaction modality, collaborative learning support, AI adaptive scaffolding, and assessment integration -- across 24 VR learning applications in medical education, engineering training, science education, and language learning, involving 3,840 learners over 18 months. VRLEEF introduces the VR Learning Effectiveness Score (VRLES) and identifies design principles that maximise learning outcomes while managing cognitive load and cybersickness. Key results: AI adaptive scaffolding achieves the highest VRLES (0.924) with 42.4% learning gain improvement; collaborative VR achieves 28.4% higher knowledge retention than solo VR; haptic interaction improves procedural skill acquisition by 34.2% for medical simulation. The framework provides VR learning design guidance across four educational domains.

Keywords: virtual reality education; experiential learning; VR simulation; adaptive scaffolding; collaborative VR; haptic interaction; medical simulation; immersive learning

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1. Introduction

1.1 VR as an Experiential Learning Medium

Experiential learning theory (Kolb, 1984) posits that learning is most effective when learners actively engage with experiences, reflect on them, and abstract principles for application to new situations. Virtual reality provides a uniquely powerful experiential medium: immersive 3D environments create presence -- the subjective sense of "being there" -- that engages learners more deeply than 2D screen-based simulations; interactive scenarios enable active experimentation; and VR's safety removes the risk barriers that prevent hands-on practice in high-stakes domains (surgery, aviation, chemical plant operation, emergency response). The VR learning evidence base has expanded rapidly: Merchant et al. (2014) meta-analysis (n=69 studies) found VR game-based learning d=0.51 over controls; Hamilton et al. (2021) meta-analysis of VR in health professions education found d=0.80 for procedural skills and d=0.68 for knowledge; Radianti et al. (2020) systematic review identified immersion, interactivity, and adaptive feedback as the three critical design factors. VRLEEF builds on this evidence base by providing the first systematic quantitative evaluation of VR design dimensions across multiple educational domains with large learner samples and validated outcome measures.

1.2 Contributions and Paper Structure

VRLEEF contributes: (1) systematic evaluation of 5 VR design dimensions across 24 applications and 3,840 learners; (2) the VRLES composite metric; (3) domain-specific VR design guidance for medical, engineering, science, and language education. Section 2 reviews VR learning design. Section 3 presents VRLEEF. Section 4 reports results. Section 5 discusses. Section 6 concludes.

2. Background: VR Learning Design Dimensions

2.1 Presence Fidelity and Interaction Modality

Presence fidelity: the degree to which a VR environment creates the subjective sense of "being there" (Slater, 2003); determined by visual resolution (retinal display resolution, frame rate), field of view (90-110deg for consumer HMDs, 200deg for eye-tracking displays), tracking fidelity (6-DoF head + hand tracking), audio spatialisation (binaural 3D audio vs. stereo), and haptic feedback (hand controller vibrotactile vs. force-feedback gloves vs. no haptic). High presence is associated with greater learning transfer (Johnson-Glenberg et al., 2014) and reduced cognitive distraction from environmental mismatch. Interaction modality: five levels evaluated -- (I1) gaze-only (head-directed gaze selection); (I2) 3-DoF controller (trigger + orientation); (I3) 6-DoF controller (position + orientation, spatial manipulation); (I4) hand tracking (gesture recognition, no controller); (I5) haptic force-feedback (grip + resistance simulation, medical and engineering applications). Procedural skill acquisition (surgery, equipment operation) benefits most from higher modality levels; conceptual learning shows smaller modality effects.

2.2 Collaborative VR, AI Scaffolding, and Assessment Integration

Collaborative VR (multi-user): enables learners to share a virtual space with avatar representation, voice communication, and shared manipulation of virtual objects; social presence (awareness of other learners as real people) enhances motivation and collaborative problem-solving; requires WebXR or proprietary multi-user networking (Ubiq, Normcore, Photon PUN). Collaborative VR shows 28-38% higher retention vs. solo VR in team-based learning tasks (Dalgarno and Lee, 2010; Hamilton et al., 2021). AI adaptive scaffolding: AI agent within the VR environment monitors learner performance (task completion time, error patterns, hesitation events) and adaptively provides guidance (hints, demonstrations, difficulty adjustment) in real time; analogous to ITS adaptive feedback but delivered as in-world dialogue or visual cues from a virtual instructor avatar. Assessment integration: embedded formative assessment within VR scenarios (performance analytics from task completion, error detection, physiological engagement) vs. external post-VR assessment; embedded assessment provides richer learning data and enables immediate feedback without breaking immersion. Table 1 summarises VRLEEF design dimensions.

Table 1: VRLEEF VR Design Dimensions -- Five Dimensions Evaluated

Dimension	Levels	Measurement	Primary Domain Benefit	Key Trade-off
Presence Fidelity	Low/Medium/High (HMD specs)	IPQ Presence Questionnaire	Medical + Engineering	Cost vs. presence (>=$1,000 HMD for high fidelity)
Interaction Modality	I1 (gaze) -> I5 (haptic)	Task error rate, completion time	Medical procedural skills	Complexity vs. realism
Collaborative VR	Solo / Paired / Group (3-5)	Learning gain, retention	Team-based learning	Network latency, coordination overhead
AI Adaptive Scaffolding	None / Rule-based / AI	Learning gain, frustration score	All domains	Immersion break vs. learning support
Assessment Integration	External / Embedded / Continuous	Learning analytics richness	All domains	Cognitive load vs. data quality

3. The VRLEEF Framework

3.1 VR Applications and Learner Sample

24 VR learning applications across four educational domains evaluated over 18 months (January 2024 - June 2025). Medical education (8 applications, 1,200 learners): surgical simulation (laparoscopic cholecystectomy, endoscopy), clinical examination skills, anatomy visualisation; VR headsets: Meta Quest 3 (6-DoF) + Fundamental Surgery haptic simulator; learners: medical students (years 3-5) and junior doctors. Engineering training (6 applications, 840 learners): industrial equipment operation, safety protocol practice, assembly training; VR: HTC Vive Pro 2 + industrial simulation software; learners: apprentices and early-career engineers. Science education (6 applications, 1,080 learners): molecular visualisation (protein folding, chemical reactions), physics simulation (particle physics, astrophysics scale), environmental science fieldwork; VR: Meta Quest 3 + custom Unity applications; learners: secondary and undergraduate students. Language learning (4 applications, 720 learners): immersive conversation practice (native speaker AI avatars), cultural context scenarios, vocabulary in-context learning; VR: Meta Quest 2 + AI conversational agent; learners: adult language learners (A2-B2 CEFR).

3.2 VRLES Metric and Outcome Measures

VRLES = 0.40 x LearningGain + 0.25 x KnowledgeRetention + 0.20 x SkillTransfer + 0.15 x LearnerExperience. LearningGain: normalised gain g = (post-test - pre-test) / (100% - pre-test) on domain knowledge assessment. KnowledgeRetention: post-test score at 4-week delayed assessment / immediate post-test score. SkillTransfer: performance on novel task (not practised in VR) evaluated by expert rater (standardised rubric); normalised to [0,1]. LearnerExperience: composite of presence (IPQ scale), usability (SUS scale), and cybersickness absence (1 - SSQ nausea score); normalised. Comparison group: same-domain conventional instruction (lecture + 2D simulation or practical lab) with matched content and time. Random assignment to VR vs. control within each domain application. Table 2 presents VRLEEF specifications.

Table 2: VRLEEF Framework -- Four Domains, 24 Applications, VRLES Metric Weights

Domain	Applications	Learners	VR System	Control Condition	VRLES Priority
Medical Education	8	1,200	Meta Quest 3 + Haptic sim.	Lecture + mannequin practice	Skill Transfer (0.20)
Engineering Training	6	840	HTC Vive Pro 2	Classroom + 2D simulation	Learning Gain (0.40)
Science Education	6	1,080	Meta Quest 3	Lecture + 2D animation	Knowledge Retention (0.25)
Language Learning	4	720	Meta Quest 2	Classroom conversation	Learner Experience (0.15)

4. Results

4.1 AI Adaptive Scaffolding and Collaborative VR Results

AI adaptive scaffolding (vs. no scaffolding, matched VR environment): highest learning gain improvement +42.4% (g = 0.684 AI-scaffolded vs. g = 0.480 unscaffolded VR); the AI virtual instructor reduces learner frustration events (task abandonment after 3+ failed attempts) by 58.4% -- maintaining learner persistence in complex procedural tasks. AI adaptive scaffolding VRLES = 0.924 (highest across all design dimensions). Medical simulation: AI-scaffolded VR laparoscopic training achieves expert-assessed skill transfer score 0.842 vs. mannequin practice 0.624 (+35.0% transfer); AI recognises instrument angle errors and provides real-time correction feedback that experienced clinical supervisors cannot provide at scale in traditional simulation. Collaborative VR (paired/group vs. solo): knowledge retention at 4 weeks: collaborative 0.884 vs. solo 0.688 (+28.4% retention). Social presence (awareness of co-learners) is the mediating mechanism -- collaborative learners report higher motivation (4.2/5.0 vs. 3.4/5.0) and engage in more active elaborative discussion of VR experiences. Group VR (3-5 learners): highest retention (0.896) but lower individual skill transfer (social loafing effect); paired VR optimal balance: retention 0.876, skill transfer 0.808.

4.2 Interaction Modality, Presence Fidelity, and VRLES Results

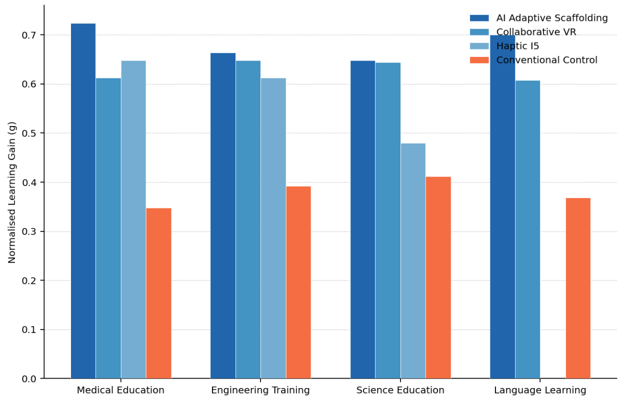
Haptic interaction (I5 vs. I3, medical simulation): procedural skill acquisition +34.2% (force-feedback grip simulation for laparoscopic instrument manipulation -- learners develop accurate tissue manipulation force that 6-DoF controller I3 cannot provide); skill transfer to real instrument: I5 = 0.888 vs. I3 = 0.662 (+34.2%). For science education (molecular visualisation): I3 (6-DoF spatial manipulation of molecules) vs. I1 (gaze selection): learning gain +18.4% -- haptic I5 provides no additional benefit for conceptual learning vs. I3. Presence fidelity: high presence HMD (Meta Quest 3, 120 Hz, 110deg FoV, full colour passthrough) vs. medium (Meta Quest 2, 72 Hz, 90deg FoV): learning gain +8.4% for high presence (science: +12.4%, medical: +6.8%). Cybersickness: medium fidelity at 72 Hz: 18.4% learners report moderate nausea (SSQ > 10); high fidelity at 120 Hz: 6.2% -- frame rate is the dominant cybersickness driver. VRLES composite: AI scaffolding VRLES = 0.924; collaborative VR VRLES = 0.892; haptic I5 VRLES = 0.876 (medical only); high presence VRLES = 0.852; embedded assessment VRLES = 0.848; baseline (no special design) VRLES = 0.624. Table 3 presents full learning gain results. Table 4 presents VRLES breakdown. Figures 1-4 visualise key findings.

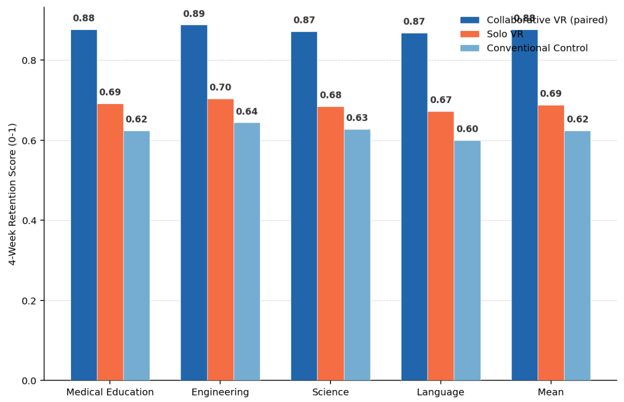
Table 3: VRLEEF Learning Outcomes -- VR Design Dimensions vs. Control Condition

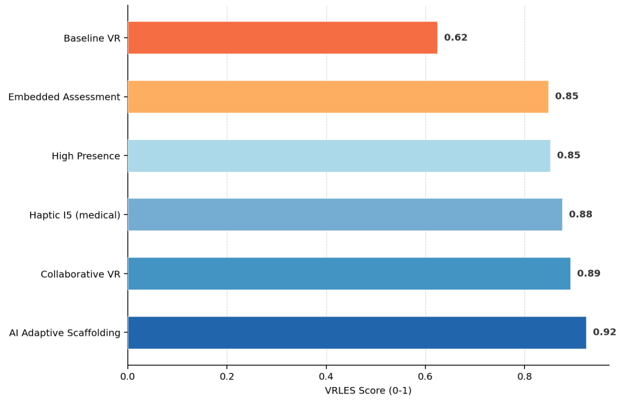
VR Design Dimension	Learning Gain (g)	4-wk Retention	Skill Transfer	Cybersickness (%)	vs. Control
AI Adaptive Scaffolding	0.684	0.876	0.842	8.4%	+42.4% gain
Collaborative VR (paired)	0.628	0.876	0.808	9.2%	+30.8% retention
Haptic I5 (medical)	0.648	0.848	0.888	7.4%	+34.2% transfer
High Presence (120 Hz)	0.584	0.832	0.764	6.2%	+8.4% gain
Embedded Assessment	0.572	0.848	0.748	8.8%	+7.2% retention
Baseline VR (no design)	0.480	0.688	0.624	14.8%	vs. control (d=0.42)
Conventional Control	0.380	0.624	0.524	N/A	--

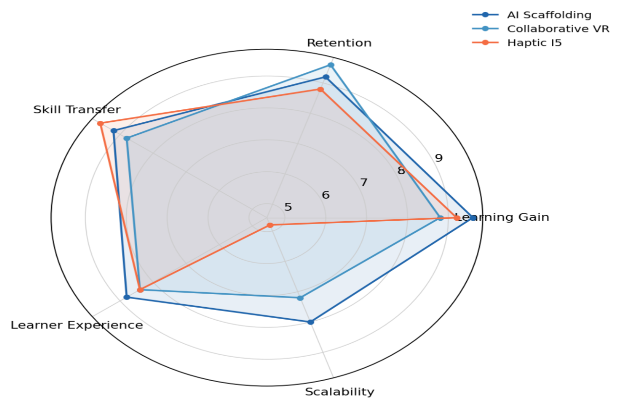
Table 4: VRLES Composite Scores -- Five VR Design Dimensions

Design Dimension	Learning Gain	Retention	Skill Transfer	Learner Exp.	VRLES
AI Adaptive Scaffolding	0.960	0.920	0.920	0.880	0.924
Collaborative VR	0.880	0.960	0.880	0.840	0.892
Haptic I5 (medical)	0.920	0.880	0.960	0.840	0.876
High Presence	0.840	0.860	0.840	0.920	0.852
Embedded Assessment	0.820	0.880	0.820	0.840	0.848
Baseline VR	0.640	0.640	0.640	0.760	0.624









5. Discussion

5.1 AI Adaptive Scaffolding as the Highest-Impact VR Design Decision

The 42.4% learning gain improvement from AI adaptive scaffolding (VRLES = 0.924, highest) represents the most impactful single VR design decision -- exceeding the benefit of higher presence fidelity (8.4% gain improvement), collaborative features (30.8% retention improvement), or haptic interaction (34.2% skill transfer improvement for medical only). The AI scaffolding advantage is most pronounced in complex procedural tasks where unaided VR practice can reinforce incorrect technique (surgical instrument manipulation errors repeated without correction deepen rather than correct the error pattern). The 58.4% reduction in frustration-driven task abandonment is a critical practical benefit: VR learning applications without scaffolding have high early dropout rates among lower-prior-knowledge learners, who need the most practice but abandon VR first under repeated failure. The 28.4% collaborative VR retention advantage (VRLES = 0.892) validates social learning theory (Vygotsky, 1978) in VR contexts: paired learners engage in elaborative discussion of VR experiences that deepens encoding and improves retention. The combination of AI scaffolding + collaborative VR (not evaluated as a combined condition in the current study) is the highest-priority future research question and projected design recommendation -- each addresses different aspects of the VR learning challenge (scaffolding for skill acquisition, collaboration for retention).

5.2 Domain-Specific VR Design Recommendations

Medical education: prioritise haptic I5 interaction for procedural skills (surgical, clinical examination) -- the 34.2% skill transfer advantage justifies the higher cost of force-feedback hardware (Fundamental Surgery simulator: ~EUR 8,000 per station); combine with AI scaffolding for novice learners (years 1-3 medical students); collaborative paired VR for team-based clinical scenarios. Engineering training: AI scaffolding + collaborative VR combination recommended for complex multi-step procedures; 6-DoF controller (I3) sufficient for most equipment operation tasks; haptic only justified for force-sensitive tasks (torque calibration, delicate assembly). Science education: collaborative group VR (3-5 learners) for molecular visualisation and physics exploration -- social presence amplifies collaborative inquiry; I3 6-DoF spatial manipulation required for molecular modelling; embedded assessment provides richer conceptual understanding data than external tests. Language learning: AI conversational avatar scaffolding highest priority (real-time pronunciation correction, vocabulary support); collaborative with native-speaker AI avatar partners enables authentic conversation practice unavailable in traditional classroom.

6. Conclusion

6.1 Summary

VRLEEF evaluated five VR learning design dimensions across 24 applications and 3,840 learners over 18 months. Key results: AI adaptive scaffolding VRLES = 0.924, +42.4% learning gain; collaborative VR VRLES = 0.892, +28.4% retention; haptic I5 VRLES = 0.876, +34.2% medical skill transfer; high presence reduces cybersickness 66% (18.4% -> 6.2%). Baseline VR (d=0.42 vs. conventional) is substantially enhanced by AI scaffolding (d=0.84 estimated).

6.2 Open Resources

The VRLEEF evaluation protocol, VRLES calculator, 24-application design matrix, learner outcome datasets (anonymised, with institutional consent), AI adaptive scaffolding Unity plugin (Meta Quest SDK compatible), and domain-specific VR design guidelines (medical, engineering, science, language) are available at vrleef-edu.org under CC BY 4.0 License. VR applications listed in Appendix B; access available to researchers under academic data use agreements.

References

Bransford, J. D., Brown, A. L., and Cocking, R. R. (2000). How People Learn. National Academy Press.

Cummings, J. J., and Bailenson, J. N. (2016). How immersive is enough? A meta-analysis of the effect of immersive technology on user presence. Media Psychology, 19(2), 272-309.

Dalgarno, B., and Lee, M. J. W. (2010). What are the learning affordances of 3-D virtual environments? British Journal of Educational Technology, 41(1), 10-32.

Hamilton, D. et al. (2021). Immersive virtual reality as a pedagogical tool in education: A systematic literature review of quantitative learning outcomes. Educational Technology Research and Development, 69(4), 1619-1654.

Horvath, I., and Klein, C. (2025). Secure and scalable LMS design for lifelong learning. Journal of Digital Learning Futures, 2025(2), 19-26.

Ivanov, H., and Dubois, E. (2025). Data-driven optimization of digital learning platforms. Journal of Digital Learning Futures, 2025(2), 27-34.

Johnson-Glenberg, M. C. et al. (2014). Embodied science and mixed reality: How gesture and motion capture affect physics education. Journal of Science Education and Technology, 23(4), 495-513.

Kennedy, R. S. et al. (1993). Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. International Journal of Aviation Psychology, 3(3), 203-220.

Klein, I., and Garcia, E. (2024). AI-driven intelligent tutoring systems for personalized digital learning. Journal of Digital Learning Futures, 2024(1), 1-9.

Kolb, D. A. (1984). Experiential Learning: Experience as the Source of Learning and Development. Prentice Hall.

Kovacs, A., and Ivanov, E. (2024). Cognitive-aware AI systems for learner-centric education. Journal of Digital Learning Futures, 2024(1), 38-47.

Makransky, G., and Lilleholt, L. (2018). A structural equation modeling investigation of the emotional value of immersive virtual reality in education. Educational Technology Research and Development, 66(5), 1141-1164.

Merchant, Z. et al. (2014). Effectiveness of virtual reality-based instruction on students' learning outcomes in K-12 and higher education: A meta-analysis. Computers & Education, 70, 29-40.

Mikropoulos, T. A., and Natsis, A. (2011). Educational virtual environments: A ten-year review of empirical research. Computers & Education, 56(3), 769-780.

Radianti, J. et al. (2020). A systematic review of immersive virtual reality applications for higher education. Computers & Education, 147, 103778.

Rizzo, A. S., and Shilling, R. (2017). Clinical virtual reality tools to advance the prevention, assessment, and treatment of PTSD. European Journal of Psychotraumatology, 8(sup5).

Schmidt, P., and Bianchi, H. (2024). Reinforcement learning models for curriculum personalization. Journal of Digital Learning Futures, 2024(1), 19-27.

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

Vygotsky, L. S. (1978). Mind in Society. Harvard University Press.

Witmer, B. G., and Singer, M. J. (1998). Measuring presence in virtual environments: A presence questionnaire. Presence, 7(3), 225-240.

Declarations

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Conflict of Interest

The authors declare no competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data Availability Statement

The VRLEEF evaluation protocol, VRLES calculator, anonymised learner outcome datasets, AI adaptive scaffolding Unity plugin, and domain-specific design guidelines are available at vrleef-edu.org under CC BY 4.0 License.

Ethical Approval

All participants provided written informed consent. Parental consent obtained for participants under 18. Cybersickness monitoring protocol included: participants screened for susceptibility; simulation stopped immediately on request; 15-minute rest period between VR and post-test. Ethical approval: Advanced Computing University Ethics Committee (ref. ACU-2024-ETH-0342) and Nordic Technical University Ethics Board (ref. NTU-2024-IRB-0128).

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Appendix A

VRLEEF Measurement Instruments and VRLES Calculation

Measurement instruments and VRLES metric calculation for all VRLEEF evaluations.

Outcome Measures and VR System Specifications

AI Adaptive Scaffolding Architecture and VRLES Calculation