AAM/Final draft:

This is the accepted version of the paper published in the Proceedings of the 2026 49th MIPRO ICT and Electronics Convention (MIPRO). The final authenticated version is available from IEEE via DOI: https://doi.org/10.1109/MIPRO70003.2026.11591996

The Experiential Quantum Framework: Design Principles for Immersive Virtual Reality in Quantum Mechanics Education

Athanasios Christopoulos[1], Stylianos Mystakidis[2], Mikko-Jussi Laakso[1]
[1]Turku Research Institute for Learning Analytics, University of Turku, Finland
[2]School of Natural Sciences, University of Patras, Greece
atchri@utu.fi

Abstract—**Quantum Mechanics (QM) education presents diverse pedagogical challenges as the observed phenomena occur at scales invisible to human perception, unfold across timescales inaccessible to human cognition, and contradict intuitions developed through lifelong interaction with classical objects. Virtual Reality (VR) has attracted interest as a technology capable of addressing such challenges though recent reviews reveal that existing implementations follow technological capability instead of pedagogical rationale. In response to this observation, we propose the Experiential Quantum Framework—an extension of the Cognitive Affective Model of Immersive Learning adjusted to the requirements of QM instruction. The framework identifies four VR affordances—presence, agency, embodiment, and scale-time transformation—and maps them to six documented quantum learning challenges through theoretically-grounded paths wherein, four represent direct positive relationships; one is conditional, predicting that VR visualisation can either reinforce or remediate misconceptions depending on the design choices; and one is negative, capturing the cognitive load risk that immersion imposes on already-complex content. Based on the aforementioned paths, six design principles derive that translate theoretical rationale into actionable specifications for instructional designers. The framework generates testable propositions, provides diagnostic criteria for educators evaluating VR implementations, and offers theoretically-grounded design guidance for Immersive VR applications for QM instruction.**

Keywords—virtual reality; quantum mechanics education; immersive learning; design principles; embodied cognition; cognitive load theory

I. Introduction

Quantum Mechanics (QM) holds a distinct status in physics education. The theory is, after all, foundational to technologies that students encounter daily—semiconductor devices, laser-based medical imaging, and much else—and yet it remains one of the most difficult subjects to teach. Interestingly, the difficulty in understanding the related concepts does not primarily stem from mathematical complexity, as students struggle to develop accurate conceptual understanding even when the mathematics is deliberately simplified [1]. As such, it can be argued that the problem lies in the fact that quantum phenomena: (1) occur at scales invisible to human perception, (2) evolve on timescales imperceptible to human cognition, and (3) contradict intuitions that students have developed through lifelong interaction with classical objects [2]. The wave function, for example, which is central to quantum description, cannot be directly observed; students have no macroscopic analogue for superposition—nothing in everyday experience that might serve as an intuition pump. The measurement problem adds to this: observation alters the quantum system in ways that conflict with assumptions students hold about the objective nature of physical reality. Traditional instruction relies on demonstration, analogy, and the systematic building of understanding from everyday experience. Such approaches, however, face fundamental barriers when the phenomena themselves cannot be directly experienced.

Virtual Reality (VR) has attracted much interest as a technology capable of addressing such challenges. To this end, systematic reviews and meta-analyses of VR in science education report moderate-to-positive effects on learning outcomes with the strongest impact identified on interventions that involve visualisation of non-observable phenomena [3, 4] and practice in simulated immersive settings [5]. Indeed, one of the greatest affordances of VR is the capacity to make visible what is inherently invisible. It can ‘shrink’ learners to atomic and subatomic scales, where quantum effects dominate, slow femtosecond processes to human-perceptible timescales, and allow embodied interaction with entities that have no tangible existence in the macroscopic world. On the surface, the match between what VR offers and what QM education needs appears compelling.

Nevertheless, the aforementioned alignment has not been translated into principled instructional design grounded in educational theory. A recent systematic review [6], which remains—to the best of our knowledge based on database searches of Scopus and Web of Science—the most comprehensive survey of Extended Reality applications in quantum education, reveals that the field demonstrates a dominance of design-development research with a corresponding scarcity of pedagogically-guided empirical studies. Another frequently noted shortcoming is that many education applications are developed according to technological capability instead of pedagogical rationale by prioritising what the technology can do rather than what the learners need. Without theoretical guidance, VR deployment in quantum education risks what the authors in [7] have termed as the “immersion paradox” wherein engagement occurs without learning. The risk is amplified for quantum content as the intrinsic complexity of the material already places heavy demands on learners' cognitive resources.

Notwithstanding the foregoing, theoretical frameworks for understanding learning in VR do exist. For instance, the Cognitive Affective Model of Immersive Learning (CAMIL), proposed by [8], synthesises existing research to describe how learning occurs in immersive environments. CAMIL identifies presence, the psychological experience of being there in a virtual environment, and agency, the sense of generating and controlling one's actions, as the principal psychological affordances that VR provides. The model also describes how technological features facilitate such psychological affordances by specifying six affective and cognitive factors (interest, intrinsic motivation, self-efficacy, embodiment, cognitive load, self-regulation) through which presence and agency influence learning outcomes.

CAMIL has generated substantial subsequent research as it provides robust theoretical foundations for understanding VR-based learning. Nonetheless, as it happens with every domain-general framework, it does not address the specific challenges that distinguish QM instruction from other educational domains nor does it guide designers in leveraging VR's unique capabilities for such a content-demanding domain.

In consideration of the above, the aim of the present paper is to address the identified theoretical shortcoming by proposing the Experiential Quantum Framework (EQF), a conceptually-grounded design framework for VR learning environments in QM education. The framework extends CAMIL by: (1) identifying QM-related learning challenges that VR affordances can address; (2) mapping relationships between affordances and challenges through explicit paths that enable systematic derivation of design guidance; and (3) specifying the design principles that translate theoretical rationale into actionable recommendations for instructional designers.

II. Theoretical Foundations

A. Sources of Difficulty in Quantum Mechanics Learning

Bouchée et al. [2] categorised four sources of QM's abstractness that distinguish it from other physics domains and contribute to the difficulties students experience. First, the mathematical formalism is disconnected from physical experience. The Schrödinger equation, for instance, describes probability amplitudes that have no classical analogue—i.e., students cannot relate mathematical operations to observable phenomena in the way they can for classical mechanics. Second, quantum phenomena contradict classical intuition in fundamental ways. In the double-slit experiment, single electrons produce interference patterns as though each particle passes through both slits simultaneously—behaviour that defies any classical explanation. Third, QM requires probabilistic rather than deterministic reasoning. Students who are accustomed to calculate definite trajectories must, instead, work with probability distributions (e.g., one cannot predict when a specific radioactive atom will decay, only the probability that decay will occur within a given interval). Fourth, everyday language proves to be inadequate for expressing quantum concepts. The term 'spin', for example, suggests that a particle rotating on its axis but electron spin has no classical rotational analogue—the mathematics describes an intrinsic angular momentum that cannot be visualised as physical spinning.

The aforementioned sources of difficulty manifest as documented misconceptions that persist despite conventional instruction. For instance, students commonly interpret superposition as the particle existing in two places simultaneously rather than understanding the probability amplitude of superposition [1]. To this end, the uncertainty principle is frequently attributed to measurement limitations or instrument imprecision instead of being recognised as an intrinsic quantum property which reflects the fundamental nature of quantum systems. Likewise, the wave-particle duality, is conceived as particles switching modes depending on observation rather than as complementary aspects of quantum description. Such misconceptions represent coherent alternative frameworks and mental nodes that students construct when attempting to reconcile quantum formalism with classical intuition [9].

Synthesising the issues identified in the QM instructional literature, we identify a set of challenges that any educational intervention must address (Table I).

TABLE I. Instructional Challenges in Quantum Mechanics Education

Code	Challenge	Characteristics
C1	Inaccessibility	The quantum realm cannot be visited or directly experienced through any physical means available to learners.
C2	Passivity	Learners cannot manipulate quantum systems; real experiments require apparatus beyond educational settings.
C3	Abstraction	Quantum concepts lack sensorimotor grounding that supports understanding elsewhere in physics.
C4	Imperceptibility	Relevant scales (e.g., 10^{-10} m) and timescales (e.g., 10^{-15} s) exceed human perception.
C5	Misconceptions	Incorrect mental models actively interfere with learning.
C6	Complexity	Intrinsic cognitive load leaves limited working memory for generative processing.

The key implication of the literature findings for instruction is that presenting correct information is insufficient; instead, teaching must confront and remediate knowledge directly. A possible way forward to tackle the abovementioned challenges emerges from the visualisation research as the adoption of such techniques to facilitate physics learning has been proven to be highly effective. For instance, the authors in [10] reported substantial improvements in student performance on photoelectric effect examination questions when PhET interactive simulations were integrated into instruction. However, despite the observed benefits, desktop simulations cannot fully exploit spatial visualisation, embodied interaction or the transformative capabilities that VR uniquely affords.

B. Virtual Reality Affordances for Learning

CAMIL identifies the Sense of Presence and the Sense of Agency as the principal psychological affordances of VR which facilitate the learning process and influence the learning outcomes [8]. To this end, the authors elaborate on the specific elements that contribute to the psychomotor development of these states with the Presence emerging from: (1) immersion factors, including sensory fidelity and field of view; (2) control factors, including degree and immediacy of control over the virtual environment; and (3) the representational fidelity, which refers to the realism and consistency of the virtual environment. In simple terms, presence (a) drives interest in the learning content, (b) increases intrinsic motivation to engage with the material, and (c) sustains engagement throughout the learning experience. Agency, on the other hand, emerges from: (1) interactivity factors, including the range and meaningfulness of actions available to the learner; (2) feedback factors, including the immediacy and contingency of the environmental responses to learner actions; and (3) autonomy factors, which refer to the degree of learner control over pacing, sequencing, and exploration paths. In essence, Agency predicts learners' self-efficacy with regard to their capability to succeed, supports the development of causal mental models through action-consequence relationships, and facilitates embodied learning through active participation.

Beyond the general affordances that CAMIL maps, VR offers two additional capabilities which are of great relevance to quantum content; these are: (1) *Embodiment*, the sensation of inhabiting and controlling a virtual body, enables sensorimotor grounding for abstract concepts that otherwise lack physical referents; and (2) *Scale-Time Transformation*, which refers to VR's capacity to place learners at arbitrary scales and to manipulate the flow of time, thereby addressing the fundamental perceptual barriers that distinguish quantum education from other domains.

Research in *embodied cognition* demonstrates that physical experience with physics concepts activates sensory-motor brain regions during subsequent reasoning about those concepts [11] with relevant experimental studies concluding that high-embodiment conditions produce greater learning gains than low-embodiment alternatives [12]. *Scale-Time Transformation* draws theoretical support from the perceptual learning research which demonstrates that direct sensory experience with phenomena—even simulated ones—facilitates improvements in information extraction that cannot be achieved through symbolic instruction alone [16]. Therefore, by rendering imperceptible scales and timescales accessible to human perception, VR enables the formation of what might be termed as the "naive quantum intuitions", a symbolic parallel to the naive physics that children develop through everyday interaction with the world.

C. The Immersion Paradox and the Resolution

The so called 'immersion paradox' demonstrates that VR does not automatically improve learning outcomes simply by increasing presence and engagement. Makransky et al. [7] found that increased immersion imposed higher extraneous cognitive load by consuming processing capacity that would otherwise support learning of the instructional content. For quantum content, where intrinsic complexity already taxes working memory capacity, additional extraneous load from navigating novel interfaces introduces the risk of undermining learning despite high engagement.

Subsequent research has identified design strategies that resolve this issue. For instance, generative learning strategies—such as summarising, enacting, explaining, and teaching—have been proven to be quite effective in converting engagement into meaningful learning in VR contexts. Klingenberg et al. [13] found that teaching a fellow student in immersive VR conditions improved retention, transfer, and self-efficacy. However, such effects were not observed in desktop conditions; a media-method interaction that CAMIL also predicts and explains with Petersen, Klingenberg, and Makransky [14] demonstrating that collaborative generative activities outperform individual activities in immersive environments.

Similarly, the authors in [15] suggest that pre-training, segmentation of learning experiences, and embedded reflection activities further support learning outcomes. Therefore, it can be argued that the resolution to the immersion paradox is not to avoid immersion but to design experiences where cognitive and pedagogical considerations guide development from the outset.

III. The Experiential Quantum Framework

A. Framework Overview

The EQF operates through a three-stage logic. First, it identifies the VR affordances relevant to quantum instruction (Table II). Second, it maps these affordances to six documented quantum learning challenges through theoretically-grounded paths (Table I). Third, it derives design principles that translate each affordance-challenge relationship into actionable guidance. The six challenges (C1–C6) derive from the categorisation in [2] supplemented by [1, 9, 10], selecting only barriers—perceptual, conceptual, or reasoning—that VR affordances could plausibly address. The four affordances extend CAMIL's core constructs with two domain-specific capabilities from the VR literature [3, 11, 12]. Internal consistency was ensured by requiring each affordance-challenge link in Table I to be supported by at least one theoretical or empirical source. Completeness is not claimed; the mapping is intended for refinement as empirical evidence accumulates.

TABLE II. VR AFFORDANCES FOR QUANTUM MECHANICS INSTRUCTION

Code	Affordance	Description
A1	Presence	Subjective experience of “being there”.
A2	Agency	Sense of generating and controlling one’s actions.
A3	Embodiment	Sensorimotor grounding through gesture-concept mappings.
A4	Scale-Time	Capacity to place learners at arbitrary scales and control time.

Fig. 1 presents the structure of the framework wherein: solid arrows indicate positive relationships (i.e., cases where an affordance directly addresses a challenge) and dashed arrows indicate conditional relationships which depend on specific design choices. The dashed box around *Immersion* captures the cognitive load risk that the immersion paradox describes.

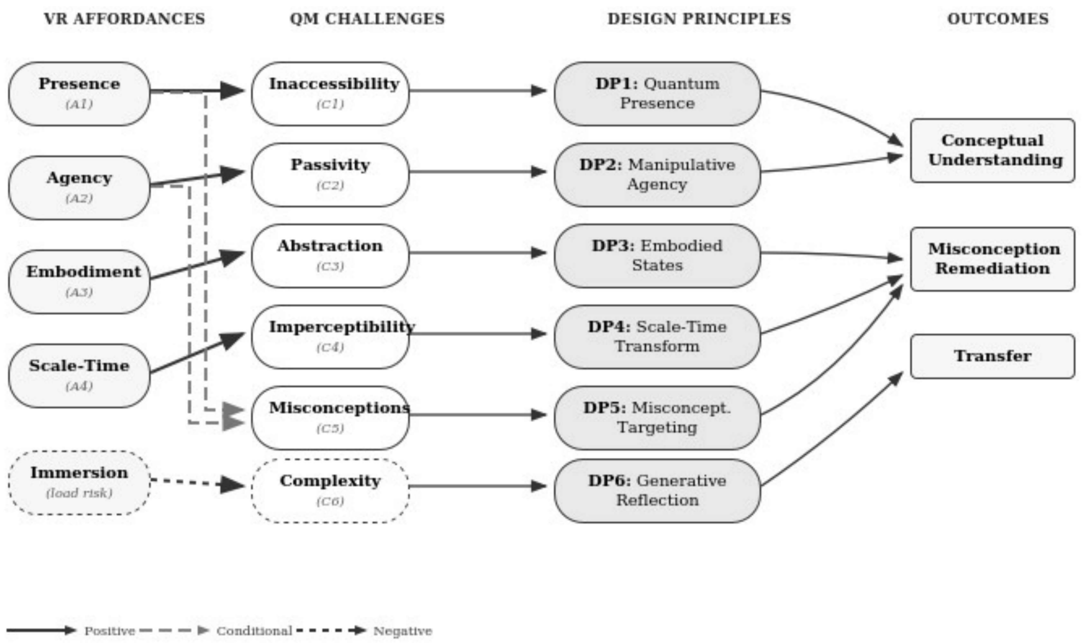

Fig. 1. Overview of the Experiential Quantum Framework

B. Mapping Affordances to Challenges

The framework outlines six theoretical paths that link specific VR affordances to quantum learning challenges. Four paths represent direct positive relationships, one is conditional, and one is negative. Each path is described below with its theoretical mechanism and design implication.

1) ***(A1) Presence → (C1) Inaccessibility [+]:***

Symbolic instruction (e.g., decoding formulae, simulating behaviour) demands a costly cognitive sequence which exhausts working memory before any conceptual work begins. *Presence* sidesteps such burden: a probability distribution becomes somewhere to *be*, not something to *parse*. *Design implication: Learners should be somewhere, not be told something.*

2) ***(A2) Agency → (C2) Passivity [+]:***

Authentic quantum apparatus excludes students entirely. *Agency* hands them the controls (e.g., adjusting barrier widths, sweeping photon energies, timing measurements). Manipulating parameters and watching consequences unfold is cognitively distinct from watching a demonstration. As such, it enables learners to build understanding through prediction error. *Design implication: Enable parameter manipulation with immediate observable consequences.*

3) ***(A3) Embodiment → (C3) Abstraction [+]:***

No bodily experience maps onto spin or entanglement. *Embodiment* bridges this gap by enabling learners to interact with the content. For instance, when such concepts are enacted via gestures (e.g., hands tracing orbital densities, posture encoding spin orientation) the brain lays down multimodal traces anchored in proprioception. *Design implication: Gestures must be congruent and should structurally mirror the concept.*

4) ***(A4) Scale-Time Transformation → (C4) Imperceptibility [+]:***

At 10^{-10} m and 10^{-15} s, quantum dynamics lie far outside perceptual reach. *Scale-Time Transformation* dissolves this barrier by placing learners inside an orbital or slow femtosecond events to a pace that permits reflection—no other medium offers this other than VR. *Design implication: Position learners within phenomena at arbitrary scales.*

5) ***(A1+A2) Presence + Agency → (C5) Misconceptions [±]:***

Risk: Scientifically loose visualisations become encoded as perceptual facts which are (potentially) more resistant to remediation than textbook-acquired misconceptions. *Opportunity:* In line with the conceptual change theory [17], Presence makes misconceptions visible while Agency enables falsification. *Design implication: Shift design logic from illustration to falsification.*

6) ***Immersion → (C6) Complexity [−]:***

Deep immersion imposes extraneous cognitive load wherein learners must parse novel interfaces, navigate virtual space, and manage sensorimotor adaptation alongside conceptual processing. As such, it risks the immersion paradox due to the fact that attentional resources are consumed by the medium instead of the message [18]. *Design implication: Integrate generative learning strategies (self-explanation prompts, prediction tasks) to restore metacognitive distance.*

C. Derivation of Design Principles

Each path generates a design principle that translates the theoretical relationship into actionable guidance. Table III presents the six principles with their derivation paths and implementation specifications.

TABLE III. DESIGN PRINCIPLES FROM THE EXPERIENTIAL QUANTUM FRAMEWORK

Principle	Path	Core Specification
DP1: Quantum Presence	A1→C1	Immerse learners within quantum phenomena using HMD with first-person perspective.
DP2: Manipulative Agency	A2→C2	Enable direct manipulation of quantum parameters with observable consequences.
DP3: Embodied States	A3→C3	Map quantum concepts to congruent bodily actions.
DP4: Scale-Time Transform	A4→C4	Implement smooth scale transitions and temporal controls.
DP5: Misconception Target	A1+A2→C5	Design visualisations against documented misconceptions.
DP6: Generative Reflection	Imm→C6	Segment experiences, embed reflection prompts, require peer explanation.

IV. DISCUSSION AND IMPLICATIONS

The EQF represents a domain-specific parameterisation of CAMIL rather than a straightforward application. CAMIL identifies Presence and Agency as general drivers of immersive learning but it assumes a neutral relationship between learner intuition and instructional content. Quantum Mechanics violates the abovementioned assumption as the content is not difficult per se but adversarial. The EQF specifies where CAMIL's positive feedback loops become negative—where Presence validates misconceptions rather than building understanding, and where immersion competes with instead of supporting cognition. Collectively, by synthesising insights from embodied cognition research and findings from physics education on quantum misconceptions, the framework provides the theoretical traceability that [6] identified as missing from current implementations.

A. Implications for Instructional Designers

The framework provides decision criteria for when VR deployment is justified. VR should be selected for quantum concepts where its distinctive affordances address documented challenges—including, visualisation of non-observable phenomena (DP1, DP4), manipulation of inaccessible systems (DP2), embodied grounding for abstract concepts (DP3)—rather than deployed as a generic delivery medium for content teachable through conventional means. Most importantly, designers must treat misconception targeting (DP5) and generative reflection (DP6) as non-negotiable; without explicit attention to misconceptions, visualisations risk reinforcement rather than remediation.

The framework also provides criteria for resource allocation decisions. It goes without saying that not every quantum topic justifies the development investment required for immersive VR; designers should prioritise concepts where the affordance-challenge mappings are strongest. Quantum tunnelling, for instance, benefits from Scale-Time Transformation (A4) and Presence (A1). On the other hand, topics such as the Pauli exclusion principle, which rely heavily on mathematical formalism rather than spatial intuition, may derive less benefit from immersive treatment.

B. Implications for Educators

The EQF also reframes the educator's role from content deliverer to cognitive load manager. Given that immersive quantum environments risk triggering the immersion paradox, the educator's primary task is to protect learners' limited working memory by employing strategic pedagogical sequencing (e.g., interface navigation must be automated through pre-training before high-intrinsic-load quantum content is introduced).

In addition, educators must manage the classroom ecology. HMD-based learning is inherently isolating; each learner inhabits a private perceptual world which fragments the shared attention that characterises physics instruction. In order to counter this obstacle, the framework positions VR as a pre-reflective encounter which requires structured social consolidation instead of a standalone intervention. For instance, activities like post-VR discussion, peer explanation, and collaborative prediction tasks can help to transform private sensory experiences into shared scientific understanding.

C. Implications for Research

The framework also generates research directions—in the form of testable propositions—in line with the proposed paths. First, future studies should evaluate comparatively whether VR-based quantum instruction (DP1–DP4) produces better conceptual understanding as measured by validated instruments such as the Quantum Mechanics Conceptual Survey in relation to desktop simulations and/or traditional approaches, while controlling for prior VR experience and novelty effects through delayed post-tests. Second, the conditional nature of the misconceptions path (DP5) should be examined by comparing learning outcomes from misconception-targeted versus non-targeted VR visualisations, using pre/post misconception inventories to isolate visualisation-induced conceptual change. Third, research should also investigate the optimal segmentation and reflection intervals (DP6) by determining the generative activity intensity required to resolve the immersion paradox, operationalised through metrics such as transfer task performance and cognitive load self-reports. Collectively, the aforementioned propositions outline a phased research programme: establishing efficacy (first), isolating design-contingent mechanisms (second), and optimising implementation parameters (third).

V. Limitations and Future Work Directions

As with every theoretical/conceptual work, the EQF is subject to its own limitations. The most fundamental is the lack of empirical research to validate the claims put forward. The framework functions as a deductive model based on learning science principles but each of the proposed affordance-challenge mappings requires validation to determine whether they translate into measurable gains.

A second cluster involves the technological scope. The framework assumes HMD-based immersive systems. Its applicability to lower-immersion platforms (e.g., desktop VR, Mixed Reality) remains to be explored. Since HMD dependency also introduces institutional barriers (e.g., capital costs, dedicated physical space), future work should examine whether the core principles hold under reduced-immersion conditions.

Finally, the framework does not account for learner-level variability in prior VR familiarity, which affects both presence and extraneous load, or susceptibility to cybersickness. Future work should develop adaptive implementations that accommodate diverse learner profiles.

Acknowledgment

The work is part of the ExQuMe (Experiential Quantum Mechanics) project funded by the European Union's Erasmus+ Programme (Project Code: 2025-1-FI01-KA220-HED-000362170).

References

[1] C. Singh and E. Marshman, "Review of student difficulties in upper-level quantum mechanics," *Physical Review Physics Education Research,* vol. 11, no. 2, p. 020117, 2015.

[2] T. Bouchée, L. de Putter-Smits, M. Bzura, and M. van Joolingen, "Towards a better understanding of conceptual difficulties in introductory quantum physics courses," *Studies in Science Education*, vol. 58, no. 2, pp. 183–219, 2022.

[3] M. Coban, Y. G. Bolat, and I. Goksu, "The potential of immersive virtual reality to enhance learning: A meta-analysis," *Educational Research Review,* vol. 36, p. 100452, 2022.

[4] X. Yang et al., "The impact of virtual reality on practical skills for students in STEM education: A meta-analysis," *International Journal of STEM Education*, vol. 11, no. 1, 2024.

[5] I. Lainidis and S. Mystakidis, "Systematic Literature of Immersive Learning Design with Virtual Reality for STEM Education in Higher Education," in *11th International Conference of the Immersive Learning Research Network (iLRN 2025),* 2026, pp. 219–233.

[6] Y. Song, Y. Wang, and R. Ghannam, "Immersive quantum: A systematic literature review of XR in quantum technology education," *Computers & Education: X Reality,* vol. 4, p. 100057, 2024.

[7] G. Makransky, T. S. Terkildsen, and R. E. Mayer, "Adding immersive virtual reality to a science lab simulation causes more presence but less learning," *Learning and Instruction*, vol. 60, pp. 225–236, 2019.

[8] G. Makransky and G. B. Petersen, "The Cognitive Affective Model of Immersive Learning (CAMIL): A theoretical research-based model of learning in immersive virtual reality," *Educational Psychology Review*, vol. 33, pp. 937–958, 2021.

[9] K. Krijtenburg-Lewerissa, H. J. Pol, A. Brinkman, and W. R. van Joolingen, "Insights into teaching quantum mechanics in secondary and lower undergraduate education," *Physical Review Physics Education Research*, vol. 13, no. 1, p. 010109, 2017.

[10] S. B. McKagan, K. K. Perkins, and C. E. Wieman, "Why we should teach the Bohr model and how to teach it effectively," *Physical Review Special Topics—Physics Education Research*, vol. 4, no. 1, p. 010103, 2008.

[11] C. Kontra, D. J. Lyons, S. M. Fischer, and S. L. Beilock, "Physical experience enhances science learning," *Psychological Science*, vol. 26, no. 6, pp. 737–749, 2015.

[12] M. C. Johnson-Glenberg and C. Megowan-Romanowicz, "Embodied science and mixed reality: How gesture and motion capture affect physics education," *Cognitive Research: Principles and Implications*, vol. 2, no. 1, pp. 1–28, 2017.

[13] P. J. Kellman, C. M. Massey, and J. Y. Son, "Perceptual learning modules in mathematics: Enhancing students' pattern recognition, structure extraction, and fluency," *Topics in Cognitive Science,* vol. 2, no. 2, pp. 285–305, 2010.

[14] S. Klingenberg et al., "Investigating the effect of teaching as a generative learning strategy when learning through desktop and immersive VR," *British Journal of Educational Technology*, vol. 51, no. 6, pp. 2115–2138, 2020.

[15] G. B. Petersen, S. Klingenberg, and G. Makransky, "Collaborative generative learning activities in immersive virtual reality increase learning," *Computers & Education,* vol. 207, p. 104931, 2023.

[16] J. Parong and R. E. Mayer, "Learning science in immersive virtual reality," *Journal of Educational Psychology,* vol. 110, no. 6, pp. 785–797, 2018.

[17] C. Pacaci, U. Ustun, and O. F. Ozdemir, "Effectiveness of conceptual change strategies in science education: A meta-analysis," *Journal of Research in Science Teaching*, vol. 61, no. 6, pp. 1263–1325, 2023.

[18] L. Fiorella and R. E. Mayer, "Eight ways to promote generative learning," *Educational Psychology Review*, vol. 28, pp. 717–741, 2016.