

FROM ABSTRACTION TO INTERACTION: A CROSS-NATIONAL STUDY ON STUDENT EXPECTATIONS FROM VIRTUAL REALITY-BASED QUANTUM MECHANICS EDUCATION

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Abstract

Quantum Mechanics (QM) is considered to be one of the most demanding subjects in the undergraduate physics curriculum due to the abstract mathematical formalism on which it relies and its departure from the intuition that students develop from everyday experiences. In response to these challenges, Virtual Reality (VR) has, on numerous occasions, been suggested as the medium to support STEM education. Nevertheless, the question of what students actually expect from VR-based QM learning environments has received limited empirical attention with most of the available evidence drawn from single-country studies. The present work draws qualitative data from university students (N=247) across five European countries (Cyprus, Greece, France, Finland, and Croatia). Specifically, three open-ended questions were analysed using the Reflexive Thematic Analysis approach in its deductive application, operationalised through keyword-based pattern matching against thirteen pre-defined categories. The key findings suggest that students ask for real-world contextualisation, concrete examples drawn from everyday life, as well as opportunities to visualise and interact with quantum phenomena in immersive settings. Furthermore, certain cross-national and gender-based differences were identified which indicate the need for culturally responsive instructional design. Based on the findings, a concrete set of design priorities for the next generation of immersive QM learning tools is provided.

Keywords: *Virtual Reality, quantum mechanics education, student needs analysis, physics.*

1. Introduction

Quantum Mechanics (QM) is considered to be among the most conceptually demanding subjects of the physics curriculum. The reliance on abstract mathematical formalism, the departure from everyday intuition, as well as the density of interrelated concepts (e.g., the Born interpretation, the uncertainty principle, the superposition) generate learning difficulties that have been reported across diverse educational systems (Nyirahabimana, Minani, Nduwingoma, & Kemeza, 2023; Nikolaus, Dželalija, & Weber, 2024). To this end, the most problematic aspect of QM instruction is that many of the identified difficulties remain even after formal instruction has been completed with students managing, on the one hand, to pass their examinations but, on the other, with fundamental misconceptions on key topics still intact (Didiş Körhasan & Pospiech, 2024). The recent systematic review that Donhauser et al. (2024) conducted on research-based teaching strategies in quantum education revealed that most of the pedagogical tools that have been developed lack empirical evidence regarding their effectiveness, thereby offering limited guidance to practitioners.

In view of the aforementioned shortcomings, Virtual Reality (VR) has attracted increasing attention as a candidate medium to address such instructional limitations. The added-value of this technology is identified on its capacity to provide three-dimensional (3D) interactive environments in which learners can visualise atomic orbitals (Suno & Ohno, 2024), manipulate Bloch sphere representations of qubits (Zable, Hollenberg, Velloso, & Goncalves, 2020) or explore the Bell test through a virtual laboratory (Song, 2026); affordances that, in principle, align well with the challenges of quantum instruction.

Notwithstanding, systematic reviews from neighbouring STEM fields provide cautious support regarding the potential of VR. For instance, the work that Santilli, Ceccacci, Mengoni, and Giaconi (2025) performed concluded that interactivity—as opposed to immersiveness—is the most critical feature for VR-mediated learning efficacy. In the same vein, Tene et al. (2024) reported positive effects of immersive technologies on students' engagement and academic performance and further advocated for more globally inclusive evaluation frameworks. Nevertheless, a critical asymmetry persists in the relevant literature as the majority of the available studies focus on the design and evaluation of VR tools from the developer's or the researcher's perspective whereas, the learner's voice (i.e., what students themselves expect from such learning environments), remains largely unheard. The asymmetry is further amplified by the geographic fragmentation of the evidence base as most relevant works are confined to single-country contexts (Alnuaimi & Awad, 2025).

In view of the abovementioned shortcomings, the present work foregrounds the student voice in a research area dominated by developer-driven design narratives and does so through a cross-national lens that brings curricular and cultural variations to the surface. On this basis, the study addresses the following research questions: (a) what pedagogical approaches do students identify as necessary for making QM more engaging and understandable? (b) what features and functionalities do they expect from VR-based QM learning environments? and (c) how do these needs differ across national and gender-based contexts? Accordingly, the contributions of the present work are threefold: (i) it provides an empirically grounded, multi-country mapping of student needs for VR-based QM education, (ii) it operationalises a transparent and replicable deductive coding framework for needs analysis in immersive STEM learning research, and (iii) it translates the qualitative findings into a concrete set of design priorities that can directly inform the development of pedagogically sound VR tools for QM.

2. Method

2.1. Participants and data collection

The sample comprised students (N=247) recruited from five European Higher Education institutions. The distribution across countries was as follows: Cyprus (n = 65), Greece (n = 65), France (n = 61), Finland (n = 37), and Croatia (n = 19). Of these, 64% identified as male and 36% as female. Data collection was performed through an online questionnaire, administered in the respective national languages and subsequently translated into English by bilingual members of the research team. The questionnaire included three open-ended items. Two of them asked students what would make QM more engaging and more understandable whereas, the third, invited them to describe what they would like to see developed in VR for the learning of the subject. Substantive responses were received from 109 (44%), 105 (43%), and 66 (27%) participants for each of the three items, respectively. Entries which were not substantive (such as "I don't know" or single punctuation marks) were removed from the dataset prior to the analysis.

2.2. Analytical approach

The qualitative data were analysed using the Reflexive Thematic Analysis framework of Braun and Clarke (2022) given that the applied orientation of this work called for a primarily deductive rather than a purely inductive coding approach. Recent reviews of thematic analysis in education research also underline the need for consistency between the epistemological basis of the framework and the coding practices that are eventually employed (Braun & Clarke, 2024; Kushnir, 2025). Therefore, the decision was based on the applied orientation of this work as our objective was not to generate theory but to map student needs onto dimensions that could directly feed into the design of VR learning environments.

The coding framework was constructed in three steps. Initially, a preliminary inductive familiarisation exercise was performed on a 20% random subset of the responses by two members of the research team in order to identify the candidate categories. Subsequently, the identified candidates were consolidated against the prior literature on VR for STEM education (Santilli et al., 2025; Tene et al., 2024) and the documented difficulties in QM learning (Donhauser et al., 2024; Nikolaus et al., 2024). The procedure returned a stable set of thirteen pre-defined categories spanning the three research questions. In greater detail, nine categories were related to engagement and comprehensibility (real-world applications, concrete examples and analogies, teaching quality, experiments and hands-on activities, interactive and immersive methods, multi-perspective explanations, video and multimedia content, visualisation, and interactive digital tools), four were related to VR-specific expectations (visualisation of quantum phenomena, virtual experiments, direct manipulation and interaction, gamified and challenge-based elements), and one cut across both (guided learning with virtual tutors). At the final step, each response was coded through keyword-based pattern matching against the framework with the option for responses to receive multiple codes.

In order to ensure analytical consistency, the keyword lists associated with each category were iteratively refined. Specifically, a 15% subset of the corpus was coded independently by two researchers, the discrepancies were then discussed, and the keyword lists were further adjusted until convergence was reached. Once the procedure was completed, the remaining responses were coded against the finalised framework. Frequencies were tabulated for the full sample as well as by country and by gender to enable the cross-cohort comparisons that are reported below. Illustrative quotations were retained verbatim in order to preserve the student voice and are reproduced here with anonymised participant identifiers (e.g., [GR-047] denotes a Greek participant).

3. Findings

3.1. Making quantum mechanics more engaging

Across all five cohorts, the need for real-world contextualisation was the most frequently reported demand. Students asked to move beyond abstract treatments and encounter QM in contexts that bear some relation to their everyday experiences or their future professional practice. One student, for example, mentioned that what was needed was “giving examples, visiting sites that use it, seeing objects—seeing in a real case what it actually feels like to apply a quantum theory in practice” [FR-098]. Another student noted that engagement would increase “if I knew I could use it for something concrete in my work, in teaching students, and in the domain of computer simulations” [CR-181]. The engagement problem, in other words, was framed by the students themselves more in terms of relevance than in terms of interest.

A second, related demand, concerned the provision of concrete examples and analogies even though not all students were aligned on this. Several Greek participants explicitly pushed back against oversimplification; one of them insisted that what was needed was “a thorough historical development, clarification of its concepts and demarcation of the limits of its knowledge as a physical theory” [GR-017]. Clear differences also emerged across the five cohorts. Cypriot students leaned toward interactive and immersive approaches—one participant suggested that QM teaching should “start with the mysteries, not the maths” and be “visual and interactive” [CY-197]. Finnish students, by contrast, asked mostly for concrete examples and showed almost no interest in interactive technologies; an outcome likely related to the fact that the Finnish curriculum already foregrounds hands-on methods which may shift the residual demand toward applicability rather than technological novelty. With respect to gender, female students were more oriented toward teaching quality and interactive methods whereas male students leaned toward experiments and hands-on activities.

3.2. Making quantum mechanics more understandable

As far as comprehensibility is concerned, a recurring demand concerned clearer, multi-perspective explanations. One student, for example, expressed this as a desire for “multiple versions of explanation from multiple contributors—students, doctoral candidates, professors—offering different angles” [FR-089]. The same request was reported by several other participants suggesting that students perceive QM as a domain in which a single representational lens is not enough. Closely related to this theme was the call for concrete examples and analogies; as a Cypriot student put it, comprehension improves “through examples with things we actually see, because a purely theoretical approach in this field is difficult to understand for the average person” [CY-218].

Video, multimedia content, and visualisation were also frequently mentioned. A clear gender-based difference was observed in this category as female students valued visual aids more than their male counterparts; a finding with clear implications for inclusive instructional design. As far as the demand for interactive digital tools is concerned, Finnish and Croatian students showed a stronger preference than students from the other three countries. A Croatian participant further added that what was needed was “appropriate learning materials—quantum mechanics is difficult to understand and it is necessary to develop an environment where this complex subject can be clarified accessibly” [CR-181]. In other words, students did not ask for technology per se but for technology that can serve as a vehicle for accessibility.

3.3. VR-specific expectations

The responses to the VR-focused question were the most heterogeneous across the dataset. A possible explanation might be the fact that many students had limited prior experience with the technology. Nevertheless, three coherent expectations could be identified. The first—and most frequently reported—concerns the visualisation of quantum phenomena; that is, the ability to see what textbooks can only describe in equations. One Greek student provided a detailed articulation for that: “Visualisation of solutions to the 3D time-dependent and time-independent Schrödinger equation for various problems and potentials. Visualisation of coherent states, the harmonic oscillator, and dynamic parameter adjustment with observation and interaction” [GR-047]. Responses of this kind point to a fairly high expected level of pedagogical detail from VR applications in the subject.

The second expectation concerns the conduct of virtual experiments which are impractical or impossible to conduct in a conventional teaching laboratory. Finnish students expressed this with clarity with one suggesting “a multiplayer mode where students can collaboratively solve quantum mechanics problems in a VR laboratory” [FI-127]; an idea that combines the VR, experimentation, and collaborative learning dimensions. The third expectation concerns the direct manipulation of quantum objects and their parameters (i.e., adjusting values, observing outcomes, and developing an embodied intuition for phenomena that resist everyday analogy). Smaller, but nonetheless noteworthy, themes included the use of gamified and challenge-based elements and the desire for a virtual guide that “corrects and explains” [FR-081]. Greek students placed the strongest emphasis on visualisation—a need which is consistent with their formalism-heavy curricular tradition—whereas Cypriot students were the only cohort to express intense interest in gamification.

4. Discussion

The findings converge on a central message: students across the European countries, despite differing curricular traditions and institutional contexts, share a common frustration with the abstraction-heavy and application-poor character of conventional QM instruction. The recurrent call for real-world contextualisation, concrete exemplification, and visual or interactive engagement is in line with constructivist accounts of learning which hold that meaningful knowledge construction requires active engagement with the material rather than the passive reception of formal treatments (Ubben, Veith, Merzel, & Bitzenbauer, 2023; Zuccarini & Malgieri, 2024).

The VR-specific findings further add a more granular understanding of the functionalities that students expect from immersive learning environments. The three core demands (i.e., visualisation, virtual experimentation, and interactive manipulation) map closely onto the affordances that recent VR-for-quantum prototypes have begun to exploit (Suno & Ohno, 2024; Zable et al., 2020; Song, 2026). What the student voice introduces, however, is a qualification of some consequence: students do not ask for spectacle but for interactivity that serves a clear pedagogical purpose; a finding which is in line with the conclusions that Santilli et al. (2025) reached. In simple words, developers who tend to prioritise visual fidelity over pedagogical depth risk producing experiences that are visually impressive but pedagogically inert.

The cross-national variations identified cannot be attributed to random noise as they follow interpretable patterns with direct design implications. The emphasis that Greek students placed on visualisation reflects a formalism-heavy curricular tradition that leaves them in need of visual representations of the formalism whereas the preference of the Finnish students for interactive tools and concrete examples plausibly reflects a national educational philosophy that already privileges experiential learning, thus raising the baseline of interactivity against which any prospective VR tool will be judged. The gender-based differences—especially the stronger orientation that female students demonstrated toward visual aids—suggest that VR tools designed without attention to gendered learning preferences risk reproducing—instead of mitigating—the existing inequities; an outcome which is further underlined in comparative studies in physics education (Pongsophon, 2025; Sudirman et al., 2023).

In view of the above, the findings of the present work translate into three core design priorities for VR-based QM learning: (a) interactivity should take precedence over visual immersion, (b) contextualisation should take precedence over abstraction, and (c) adaptability to the cultural and curricular traditions of the target population should take precedence over context-blind design.

Each of the abovementioned priorities admits a concrete instantiation that follows directly from the patterns reported above. The first (i.e., interactivity over immersion) implies that development effort should be invested in manipulable parameters, collaborative problem-solving spaces of the kind that the Finnish cohort articulated, and challenge-based progression rather than in photorealistic laboratory replicas; the marginal pedagogical return of the latter is, on the available evidence, low. The second (i.e., contextualisation over abstraction) implies a deliberate “from-application-to-formalism” sequencing in which abstract constructs are anchored in familiar referents (e.g., medical imaging, semiconductor logic, quantum-key cryptography) before the underlying mechanics are unpacked; an approach that aligns with the request for “sites that use it” that several participants articulated. The third (i.e., adaptability over context-blindness) implies that VR tools should ship with switchable curricular presets—formalism-heavy, application-heavy, and interactive-discovery—so that the same underlying environment can serve the visualisation needs of Greek students, the application-oriented expectations of Finnish students, and the gamification preferences of Cypriot students without locking instructors into a single pedagogical default.

5. Conclusions

The present study set out to foreground the student voice in a research area where developer and researcher perspectives have so far tended to dominate. The qualitative evidence collected from students across European countries points to a coherent set of needs including real-world contextualisation, concrete

exemplification, multi-perspective explanations and—especially for VR—the ability to visualise quantum phenomena, conduct virtual experiments, and manipulate quantum systems interactively. The cross-national and gender-based variations identified herein further indicate that VR designs which are blind to cultural and curricular context are unlikely to serve all learners equally well. The findings are translated into an explicit set of design priorities and the coding framework is operationalised in a transparent and replicable manner such that other researchers can adopt and extend it.

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