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Computer-Supported Collaborative Learning Pillars in Physics Education: A Systematic Review on Enhancing Conceptual Understanding in Quantum Mechanics

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Systematic Review

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Abstract

Quantum mechanics is one of the most conceptually challenging topics in physics education. It encompasses abstract and probabilistic ideas, such as superposition, tunnelling phenomena, wave-particle duality, and entanglement, that can conflict with students' conceptual understanding. Computer-Supported Collaborative Learning (CSCL) emerges as a useful, innovative pedagogy for teaching abstract quantum mechanics across various educational contexts. In our systematic review, we used PRISMA 2020 guidelines to synthesize 22 empirical studies published between 2017 and 2025. It aims to investigate how CSCL pillars (technological affordances, instructional designs, and collaborative modes) enhance conceptual understanding, foster critical thinking and problem-solving, and support knowledge construction in quantum mechanics. Guided by the integration of Sociocultural and Conceptual Change Theory, the review shows that digital affordances serve as visual bridges that create cognitive dissonance and enable conceptual understanding of abstract quantum mechanics concepts. However, it further shows that technological affordances work better when embedded into scaffolding-structured instruction designs that foster critical thinking and problem-solving skills. However, when learning is implemented with both synchronous (real-time) and asynchronous (self-paced) peer-led collaboration for real-time, a dynamic Zone of Proximal Development is created that gives learners the chance to co-construct knowledge collaboratively. Despite these results, there are significant gaps that need special attention; few studies are conducted in low-resource countries, and no empirical studies synthesize the optimization of three CSCL pillars simultaneously, particularly in physics education. In this review, we recommend that educators, curriculum developers, and future researchers synergize CSCL pillars in physics education.

Keywords: Collaborative Modes, Computer-Supported Collaborative Learning (CSCL), Quantum Mechanics Education, Conceptual Understanding, Technological Affordances, Instructional Designs

Introduction

Background of the study

To ensure learners acquire meaningful learning in physics education, conceptual understanding is given priority. Learners must grasp physics principles, interpret the physical meaning, and be able to move beyond solving equations and memorizing formulas (Mbonyiryivuze et al., 2019). Scholars have defined conceptual understanding; for example, Banda and Nzabahimana (2021) defined it as the learner's ability to synthesize information from what is known, in primary schemas, and implicitly apply it to a new environment. Further, Gunawan et al. (2018) and Ismail et al. (2019) defined it as the capability of learners to record information, analyze it, and transfer it in solving new problems. Merging these perspectives, we define conceptual understanding as the learners' ability to integrate prior knowledge, synthesize and interpret principles physically in a meaningful way, and be able to apply them flexibly in a new, unfamiliar context. It lays the foundation of scientific reasoning that entails understanding physics principles, enabling knowledge transmission across contexts, strengthening problem-solving, critical thinking, and knowledge construction in physics education.

Quantum mechanics is characterized by abstract, probabilistic, and counterintuitive principles that contrast with classical intuition, making it a highly conceptually challenging topic in physics education (Rodriguez et al., 2020). It introduces microscopic phenomena that defy common sense, such as uncertainty, superpositions, entanglement, wave-particle duality, and quantum tunneling, requiring learners to relate mathematical calculations to physical interpretation. Viewing science and technology expansions, quantum mechanics is indispensable in innovations such as quantum computing, nanotechnology, semiconductors, and advanced materials that are useful in daily activities (Nita et al., 2023). These applications and innovations require students to equip their conceptual understandings, reduce rote calculation memorization, and allow them to interact meaningfully in diverse contextualized environments.

In developing learners' conceptual understanding of abstract physics concepts, traditional teaching methods are discouraged as they reinforce rote calculations and memorization (Nyirahabimana et al., 2023a). In other words, innovative tools such as simulations have demonstrated positive effects in teaching abstract physics concepts (Banda & Nzabahimana, 2021; Susilawati et al., 2022; Hoe et al., 2024). According to their findings, this implies that the visualization of manipulatives in technological tools enhances conceptual understanding. Conversely, the 21st-century technology itself is not sufficient to enhance conceptual understanding without inclusion of structured inquiry-instruction designs scaffolded with interactive collaborative modes. Addressing these difficulties requires pedagogical approaches that deepen conceptual reasoning, encourage active engagement, and integrate collaborative and technology-driven learning strategies.

Computer-Supported Collaborative Learning (CSCL) has been proposed as an innovative methodology to address these issues. CSCL incorporates three pillars (technological affordances, instructional designs, and interactive collaborative modes) that have been proven to enhance conceptual understandings and foster conceptual gains, especially in STEM fields where tangible reasoning is crucial (Hoe et al., 2024). Nonetheless, the affordances that are restricted in conventional physics teaching approaches are enhanced by CSCL settings. Through incorporating simulations, virtual laboratories, and interactive modes, learners visualize unobservable phenomena, which promotes critical thinking, conceptual improvement, and knowledge co-construction (Chen et al., 2018; Hernández-Sellés et al., 2019, 2020). For example, students may

create arguments and make analogies with classical physics by manipulating parameters in potential steps and the quantum tunnelling phenomenon using digital tools like PhET simulations. Dialogue-based enquiry, a collaborative mode, is effective in promoting scientific literacy, critical thinking, problem-solving, and memory retention (Gnesdilow & Puntambekar, 2025). Students actively co-construct knowledge, assess each other's work, investigate difficult concepts, and synthesize new conceptual understanding when they work in peer groups in these settings.

The empirical evidence shown Computer-Supported Collaborative Learning (CSCL) pillars enhance conceptual understanding, critical thinking, problem-solving, and knowledge construction when integrated separately in physics education. However, there remains a lack of systematic synthesis on its specific role in quantum mechanics education. For example, research by Mukama and Gapfizi (2025), Nyirahabimana et al. (2023a), Rehman et al. (2021), and Uwambajimana et al. (2023) on CSCL technologies such as multimedia and simulations enhanced conceptual understanding of abstract physics concepts. Further, the studies conducted by Andrini (2016), Testa et al. (2020), and Vilarta Rodriguez et al. (2020) examined the integration of inquiry-instructional strategy in fostering critical thinking and problem solving. Similarly, Hoe et al. (2024) demonstrated the influence of peer-scaffolding in a dynamic collaborative mode to enhance learners' construction in STEM.

Therefore, this systematic review is effective in assessing, analyzing, and interpreting the existing literature on the impact of Computer -Supported Collaborative Learning (CSCL) pillars on quantum mechanics instruction. Research in physics education related to quantum mechanics frequently demonstrates that the three underlying pillars such technologies, instructional designs, and collaborative modes use different labels. Others label it as simulation-based peer instruction or collaborative digital enquiry, even though the term "CSCL" is well-established in general educational technology literature. In the unified CSCL framework, the review identifies the current gap and limitations in the scattered literature that will potentially guide educators, researchers, and curriculum developers in physics education. It further presents CSCL as a transformative pedagogical approach essential in quantum mechanics instruction through enhancing conceptual understanding, higher-order (critical and problem-solving) skills, as well as knowledge construction. The review intends to answer the following research questions.

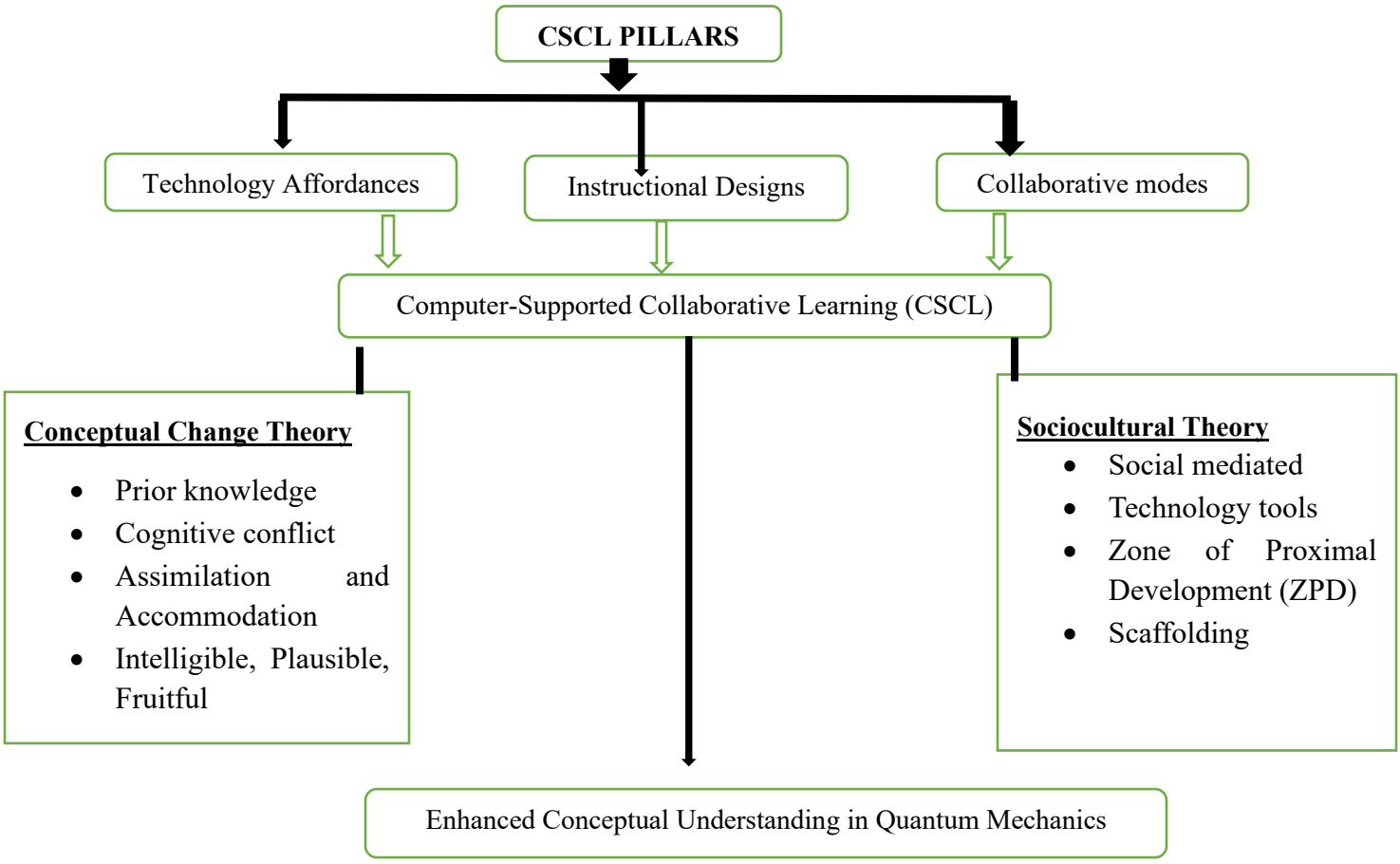
i. How do technological affordances in the CSCL environments facilitate conceptual understanding of core quantum mechanics principles?
ii. In what ways do structured CSCL instructional designs foster critical thinking and problem-solving skills in quantum mechanics education?
iii. How do varied collaborative interaction modes in the CSCL influence knowledge construction during quantum mechanics instruction?

Theoretical Context

The review is guided by the integration of Conceptual Change Theory (Posner et al., 1982) and Sociocultural Theory (Vygotsky, 1978). Conceptual Change Theory explains how learners update their prior understanding when confronted with scientific concepts that challenge their everyday intuitions. Posner et al. (1982) argue that meaningful learning demands more than assimilation, in which information is fitted into existing mental frameworks. It requires accommodation, where learners recognize, identify, or replace their misconceptions. Through this process, learners are encouraged to refer to their initial beliefs to determine whether it will be applicable to that scenario or not. When new ideas are intelligible, plausible, and fruitful, we acknowledge the conceptual

change has occurred (Manunure et al., 2020). Concepts like superposition uncertainty, wave-particle duality, or entanglement that are found in quantum mechanics often give learners misconceptions because they conflict with classical mechanics intuitions. However, instructional designs such as simulation-based learning, inquiry-based learning, and collaborative learning in the Computer-Supported Collaborative Learning (CSCL) environments offer opportunities for learners to confront these conceptual challenges, reflect critically, and restructure their understanding (Vilarta Rodriguez et al., 2020).

Sociocultural Theory complements these perspectives by providing the social and cultural dimensions of learning. Vygotsky (1978) proposed that knowledge construction occurs at the interpersonal level through dialogue and collaboration before being internalized to the intrapersonal level. Tools such as language, symbols, and digital technology mediate this process, enabling learners to analyze the complex concepts in a meaningful way. (Castro-Gutiérrez et al., 2021). Within CSCL, simulations, multimedia, and virtual labs serve as the cultural tools that enable learners to visualize the abstract phenomena, scaffold each other's reasoning, and co-construct their ideas. However, through interacting with tools synchronously or asynchronously in peer-to-peer, small group, or whole-class collaboration on modern platforms, a zone of proximal development (ZPD) is attained. In this space, complex tasks to be handled by the students can handle individually become manageable when they collaborate together. Therefore, the theory highlights that CSCL environments provide shared inquiry and scaffolded learning, enabling students to internalize physics abstract concepts more effectively. The interaction between these two theories in the CSCL and conceptual understanding of quantum mechanics is illustrated in **Figure 1** below.



Methodology

Review Design

The study adopted the systematic review design guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) 2020 guidelines(Page et al., 2021). These guidelines enable the researcher to conduct transparent, comprehensive, and reproducible systematic review reporting. It is intended to synthesize the evidence for the impact of Computer-Supported Collaborative Learning (CSCL) on improving conceptual understanding, fostering critical thinking and problem-solving skills, and knowledge construction for quantum mechanics education.

Search Strategy

The search strategy was developed to discover the full spectrum of relevant literature by specifically considering variances in terminology in physics education research (PER). While 'CSCL' is a well-established term in educational technology, PER studies in quantum mechanics often examine its parts through terms like simulation-based peer instruction or collaborative digital inquiry. Therefore, the inclusion criteria included studies that examined technological affordances, instructional designs, or collaborative modes in quantum mechanics learning environments, regardless of whether the original authors explicitly used the acronym 'CSCL'

A comprehensive search was conducted in the major academic databases, including SCOPUS, Web of Science, ERIC, SpringerLink, and ScienceDirect, and an extensive follow-up in Google Scholar, Academia, ProQuest, and Research Gates to retrieve studies not accessible in the designated databases to ensure the wider coverage of the relevant literature. The search was limited to articles published between 2017 and 2025 to capture all studies. The keywords and Boolean operators were used: "Computer-Supported Collaborative Learning," OR "CSCL" AND "quantum mechanics" AND "conceptual understanding". To broaden the scope and include the studies that explicitly not use CSCL or Computer-Supported Collaborative Learning, the search was extended to its pillars namely, technologies, such as "Simulations, Virtual Labs, and Multimedia"; Instructional Designs such as "Inquiry-based, collaborative learning, simulation-based learning"; and Collaborative mode such "peer-to-peer, small group, whole class groups, synchronous, asynchronous" AND "quantum mechanics" AND "conceptual understanding". To ensure higher-order and collaborative outcomes in quantum mechanics are captured in all pillars, the outcome-related terms such as "critical thinking", "problem-solving and "knowledge construction" were incorporated

Inclusion and Exclusion Criteria

The review defined the explicit eligibility criteria to guarantee methodological rigor and ensure that studies included are transparent, comprehensive, and reproducible with reference to the research questions (See **Table 1**).

Inclusion Criteria	Exclusion Criteria
Published peer-reviewed articles between 2017 and 2025	Published non-peer-reviewed articles outside the range between 2017 and 2025

Focus on the CSCL pillars (technologies, instructional designs, collaborative modes)	Non-CSCL pillars studies
Quantum mechanics learning outcomes attained (conceptual understanding, critical thinking, problem-solving, or knowledge construction in quantum mechanics) or closely related quantum physics contexts relevant to CSCL	Studies without quantum mechanics educational outcomes (conceptual understanding, critical thinking, problem-solving, or knowledge construction)
Empirical studies and conference proceedings in quantum mechanics and related subtopics like charged particles (electrons)	Editorials, book reviews, opinion pieces
Articles published in English language	Non-English language published articles
Full-text available	Duplicate records, incomplete manuscripts, inaccessible full text

Table 1: Inclusion and Exclusion Criteria

Screening and Selection

To ensure selected studies aligned with the review objective, we conducted systematic screening. A total of 1886 published articles were retrieved across all databases and imported into the reference management system. In the system, 1224 duplicates were identified and removed, and then 662 records remained for title and abstracts screening. In the pre-defined inclusion criteria benchmark, 565 studies were excluded because they did not meet the measures stated. The removal left 97 published articles for the full-text assessment. In the full article screening assessment activity, the review excluded 75 articles because they were focusing on unrelated subject areas, e.g., STEM in general, excluding CSCL pillars (technological tools, instructional designs, and collaborative modes), or not addressing outcomes in quantum mechanics education. Ultimately, 22 studies satisfy all inclusion criteria and were retained for literature review synthesis and illustrated in the PRISMA flow diagram (**Figure 2)**

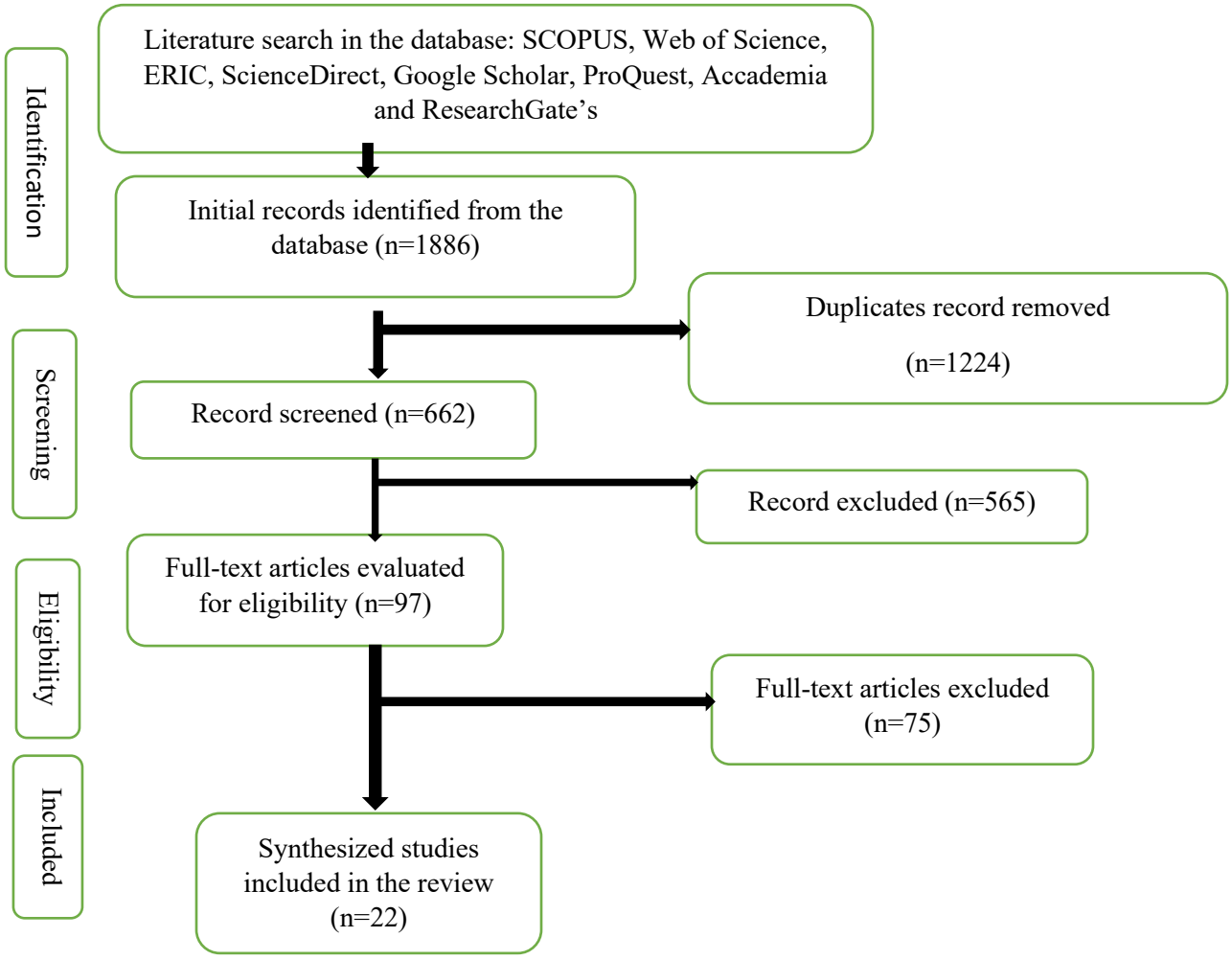


Figure 2: Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) 2020 guidelines

Methodological Quality and Assessment

To ensure methodological quality and assess risk of bias, the review employed the Mixed Methods Appraisal Tool (MMAT, 2018 edition) in the 22 synthesized studies. We selected to adopt MMAT because it provides an established framework to analyze varied study designs in qualitative, quantitative, and mixed-methods research. Two reviewers were assigned separately to assess the studies with regard to two initial screening questions and five categories, such as particular methodological criteria, graded as YES (Criteria satisfied), No (criteria not met), or Can't tell (insufficient reporting). The interrater agreement was high (k=0.89), with small inconsistencies handled throughout the conversations. The methodological quality was not utilized as an exclusion criterion, but the scores were used to judge the strength of the research concerning the CSCL pillars.

Data Extraction and Analysis

To ensure the data involved in the review are reliable and valid as per the research questions, a standardized template was used. The information was systematically recorded and detailed in each article, including authors and year, country/ context of the study, CSCL pillar(s), and the learning outcome measured in quantum mechanics education. Data were analyzed thematically and comprehensively, subsequent to the specific research question, to avoid redundancy and misinterpretations. Patterns, strengths, and literature gaps were noted to inform the potential of the review.

Results

A total of 22 articles published between 2017 and 2025 met the inclusion criteria and were used to provide a comprehensive overview of the review evidence base (see Table 2). In the 22 reviewed studies, eight examined technological affordances, thirteen scrutinized instructional design, two examined collaborative modes, while five explored two pillars (instructional design and collaborative modes) simultaneously. Each study is classified by the CSCL pillar(s) of technological affordances, instructional design, and collaborative modes, presenting the different strategies used to improve conceptual understanding, foster critical thinking and problem solving, and support knowledge construction in quantum mechanics education. The list provides the basis for the following theme tables, in which the studies are considered for the research questions.

SN	Author(s)	Study Context	Year	CSCL Pillar(s)
1	Borish and Lewandowski (2025)	USA	2025	Technological affordances
2	Xu et al. (2025)	China	2025	Technological affordances
3	Buzzell et al. (2025)	USA	2025	Instructional designs
4	Solorio et al. (2025)	USA	2025	Instructional designs and collaborative modes
5	George and Mthethwa (2025)	South Africa	2025	Instructional designs
6	Kim et al. (2025)	South Korea	2025	Instructional designs
7	Daoudi (2025)	Morocco	2025	Instructional designs
8	Borish and Lewandowski (2024)	USA	2024	Instructional designs
9	Keebaugh et al. (2024)	USA	2024	Instructional designs
10	Piña et al. (2024)	USA	2024	Instructional designs
11	Acevedo et al. (2024)	USA	2024	Technological affordances
12	Nyirahabimana et al. (2024)	Rwanda	2024	Technological affordances
13	Corsiglia et al. (2023)	USA	2023	Instructional designs and collaborative modes
14	Montagnani et al. (2023)	Italy	2023	Instructional designs and collaborative modes
15	Pollock (2023)	USA	2023	Instructional designs
16	Brundage et al. (2023)	USA	2023	Collaborative modes
17	Nyirahabimana et al. (2023b)	Rwanda	2023	Technological affordances
18	Chiofalo et al. (2022)	Italy	2022	Instructional designs and collaborative modes
19	Denisova et al. (2021)	Russia	2021	Technological affordances
20	Weissman et al. (2019)	Israel	2019	Instructional designs and collaborative modes
21	Freericks et al. (2019)	USA	2019	Collaborative modes
22	Tawil and Dahlan (2017)	Indonesia	2017	Technological affordances

Table 2: Total studies used in the review as per PRISMA 2020 guidelines

Technological Affordances in CSCL to Enhance Conceptual Understanding of Quantum Mechanics

Regarding the first research question, the review demonstrates that technological affordances in CSCL settings serve as critical cognitive bridges between abstract mathematical representations and the physical realism of quantum processes. The eight reviewed studies highlighted technological tools like interactive computer simulations, remote experiments via the cloud, virtual reality (VR) settings, and multimedia animations that make invisible, tiny, and counterintuitive concepts more visible. Learners classified classical intuitions through visualization of ideas in these tools, related them to quantum intuitions, and improved their conceptual understandings. More specifically, learners are intended to address recurring cognitive conflicts in quantum mechanics education, including wave-particle duality, potential barriers/tunneling, particle spin, and quantum computing concepts (e.g., superposition and quantum gates through these technological affordances. Learners can change variables dynamically, observing the wave functions immediately and being able to verify predictable behaviors in quantum mechanics using tools like PhET simulations, Moodle modeling tools, and interactive animations.

The tools like unique features like cloud-based quantum hardware laboratories and immersive VR have unique features that enable students to engage directly with microscopic particles and real-time quantum optics setups. These affordances reduce learners' cognitive barriers, like wave-particle duality, uncertainty, potential barriers, tunneling phenomenon, spin orientations, and quantum gates. It further shifts instruction from passive mathematical derivation to visualization, manipulation, and active learning that enhances conceptual understandings. Table 3 summarizes the literature by describing the technological tools used and the learning outcomes achieved.

SN	Author (s)	Study Context	Year	Technological tools	Learning outcomes attained
1	Borish and Lewandowski (2025)	USA	2025	Remote, cloud-accessible quantum experiments	Improved accessibility and conceptual understanding through remote experimentation.
2	Xu et al. (2025)	China	2025	Classical simulations of quantum computers	Learners gained conceptual understanding of quantum mechanics of how quantum computers function in superpositions, quantum entanglement, and quantum gates.
3	Nyirahabimana et al. (2024)	Rwanda	2024	Multimedia technologies (Animations, PhET and YouTube videos)	Improving conceptual understanding of quantum physics at undergraduate level
4	Acevedo et al. (2024)	USA	2024	Immersive VR simulations	Enhancing conceptual understanding of charged particles (electrons, protons, ions, positrons), microscopic particles found in quantum mechanics
5	Borish and Lewandowski (2023)	USA	2023	Quantum Optics Instructional Labs	Hands-on labs that lead to conceptual understanding; alignment of lab goals with Quantum Mechanics learning outcomes

6	Nyirahabimana et al. (2023b)	Rwanda	2023	Multimedia-aided technologies	Improving conceptual understanding of quantum physics at undergraduate level
7	Denisova et al. (2021)	Russia	2021	Learning Management System Moodle and Easy Gif Animator	Improved cognitive activity and quantum mechanics conceptual understanding among technical university students through visualization and modelling
8	Tawil and Dahlan (2017)	Indonesia	2017	Computer-based simulations	Improved the conceptual gains in quantum mechanics through visualization, making abstract ideas more concrete

Table 3: Technological Affordances in CSCL to Enhance Conceptual Understanding in Quantum Mechanics

Instructional Designs in CSCL to Foster Critical Thinking and Problem-solving in Quantum Mechanics

Analyzing the second research question, the review explored how instructional design in CSCL promotes critical thinking and problem-solving skills in quantum mechanics education. The synthesis highlights that technology itself cannot offer students critical thinking and problem-solving without pairing it with scaffolded instructional design. Effective CSCL implementations, according to the research, rely on structured pedagogical scaffolding, contextualized problem solving, and inquiry-driven activities that actively include students in higher-order thinking rather than a single "ideal" design. Contextualized problem-based learning (PBL), quantum interactive learning tutorials (QuILTs), experiment-based reasoning designs, and game-based strategies are the main teaching strategies examined in this review. Activities in these frameworks force students to think about quantum paradigm shifts, directly challenge conventional physics intuitions, and promote critical thinking. Students can break down multi-step complicated mathematical frameworks into conceptually understandable chunks by using scaffolding processes, which are comparable to those used to teach challenging subjects like perturbation theory or time evolution.

Similarly, contextual and historical/discipline-culture methods encourage students to examine the unconnected narratives between classical and quantum perspectives. As a consequence, students develop adaptive problem-solving abilities that extend beyond rote equation manipulation to the ability to properly apply quantum notions to new real-world or computational situations. The evidence is presented in Table 4, which outlines the instructional designs employed and the learning outcomes obtained.

SN	Author (s)	Study Context	Year	Instructional design	Learning outcomes attained
1	Buzzell et al. (2025)	USA	2025	Curriculum design analysis (instructional time and content)	Students were urged to consider how the curriculum design affected their conceptual journey and to think critically about the content's structure and order.

					They also gained insight into how to tackle challenging quantum mechanics problems.
2	Solorio et al. (2025)	USA	2025	Collaborative learning communities	Critical Thinking: Analysis of misunderstandings and contemplation of many viewpoints were encouraged via peer discussion. Problem-Solving: Adaptive solutions for handling challenging quantum mechanics issues were aided by group collaboration.
3	George and Mthethwa (2025)	South Africa	2025	Balanced student- vs teacher-centered design	Learners evaluated physics concepts actively and analytically and solved problems in diverse contexts.
4	Kim et al. (2025)	South Korea	2025	Quantum Interactive Learning Tutorial	Students enhanced their capacity to apply quantum concepts to new contexts, particularly in wave function analysis and time evolution; they also examined misconceptions and considered the logic behind quantum principles, which encourages critical thinking.
5	Daoudi (2025)	Morocco	2025	AI-Integrated historical contextualization	Learners analyze the disjoint narrative between classical and quantum mechanics to develop critical thinking; contextualizing knowledge helps learners to tackle conceptual difficulties in quantum mechanics that foster problem-solving skills.
6	Borish and Lewandowski (2024)	USA	2024	Experiment-based reasoning design	Improved learners' reasoning ability in quantum mechanics through analyzing experimental results and tackling mathematical experimental challenges.
7	Keebaugh et al. (2024)	USA	2024	Instructional scaffolding in perturbation theory	Learners attained critical thinking and problem-solving in perturbation theory in quantum mechanics.
8	Piña et al. (2024)	USA	2024	Contextualized problem-based learning (PBL)	Critical Thinking: Promoted contemplation of actual situations and assessment of various approaches to solving problems. Problem-Solving: Enhanced capacity to apply theoretical understanding to real-world situations.
9	Corsiglia et al. (2023)	USA	2023	Intuition-shaping instructional design	Students get the ability to assess their intuitions critically by contrasting them with the setting of quantum mechanics; Use reasoning techniques to tackle quantum physics challenges.

10	Montagnani et al. (2023)	Italy	2023	Digital Collaborative Learning design	Critical analysis of quantum concepts and problem-solving skills
11	Pollock (2023)	USA	2023	Research -based instructional materials	Learners are encouraged to make sense of quantum physics by reasoning through spin experimentation and conceptual questions; learners build computational abilities alongside conceptual reasoning.
12	Chiofalo et al. (2022)	Italy	2022	Game-based instructional design	Learners develop the ability to analyze game scenarios with respect to quantum mechanics and adapt problem-solving skills for complex quantum mechanics problems.
13	Weissman et al. (2019)	Israel	2019	Discipline-culture approach	Critical Thinking: Encouraged reflection on the cultural background and paradigm shifts. Problem-solving: Improved capacity to apply theory to abstract concepts.

Table 4: Instructional Designs in CSCL to Foster Critical Thinking and Problem-solving in Quantum Mechanics

Collaborative Modes in CSCL to Influence Knowledge Construction in Quantum Mechanics

In response to the third research question, the review investigated how the collaborative mode in CSCL affects knowledge construction in quantum mechanics. To understand the impact of collaborative structures on the construction of knowledge, the synthesized studies indicated that the interaction among peers was a significant factor in externalizing, negotiating, and restructuring abstract concepts. The collaborative learning modes in CSCL environments were classified along the dimensions of group size (peer-to-peer dyads, small groups, and large class groups) and temporal delivery (synchronous vs. asynchronous communication). Synchronous peer-to-peer and small-group discussions especially influenced real-time conceptual negotiation. Learners sharpen their intuitions through the tasks in the simulations, exercises given, and the game scenarios. When they work collaboratively, students express their cognitive modes, defending their scientific reasoning and co-evaluating misconceptions. This means that through peer scaffolding and group work, it creates a fluid Zone of Proximal Development (ZPD) that enables students to solve complex problems of wave functions and states initially challenging them to master when working individually.

In contrast, structured online discussion forums (asynchronous large group interactions) allow learners to debate paradigm shifts in quantum mechanics over a specific period and offer cognitive processing with enough reflection. It allows learners to develop fundamental quantum mechanics knowledge and be able to distinguish between classical mechanics principles useful over time. Structured collaboration, across all settings, moves the learning dynamic from one of individual memorization to a collective, social co-construction of scientific knowledge. Table 5 summarizes the data by presenting the collaborative methodologies used in various research studies, as well as the learning outcomes obtained.

SN	Author (s)	Study Context	Year	Collaborative mode	Learning outcomes attained
1	Solorio et al. (2025)	USA	2025	Peer, synchronous	Peer conversations critically examined discrete versus continuous quantum notions, improving collaborative thinking and knowledge creation within quantum mechanics.
2	Corsiglia et al. (2023)	USA	2023	Peer collaboration, synchronous	Students collaborated to analyze intuitions and misunderstandings, developing deeper thinking in quantum physics and improving knowledge creation.
3	Brundage et al. (2023)	USA	2023	Peer interaction, synchronous	Students established a shared grasp of quantum physics principles through peer dialogue.
4	Montagnani et al. (2023)	Italy	2023	Small group, synchronous	High school students cooperatively investigated core quantum concepts through experiential assignments and co-constructed knowledge in quantum mechanics.
5	Chiofalo et al. (2022)	Italy	2022	Small group, synchronous	Game-based collaborative learning facilitated the co-construction of quantum physics knowledge.
6	Weissman et al. (2019)	Israel	2019	Large group, synchronous	The discipline-culture approach facilitated collaborative reflection on paradigms and reasoning in quantum mechanics knowledge development.
7	Freericks et al. (2019)	USA	2019	Large group, asynchronous	Learners participated in collaborative online learning, building basic quantum knowledge collectively.

Table 5: Collaborative Modes in CSCL to Influence Knowledge Construction in Quantum Mechanics

Discussion of the findings

In our analysis of 22 published articles between 2017 and 2025, we evaluated the evidence of the impact of Computer-Supported Collaborative Learning (CSCL) pillars in quantum mechanics learning. The review highlighted three main CSCL pillars as technological affordances, instructional designs, and collaborative interaction modes within the quantum mechanics context. In the CSCL environments, we identified how technological affordances enhance conceptual understanding, instructional designs foster critical thinking and problem-solving, and collaboration modes affect knowledge construction in quantum mechanics. Quantum mechanics is often regarded as one of the most conceptually difficult topics in physics education. It introduces abstract, probabilistic, and counterintuitive concepts, such as superposition, wave-particle duality, potential barriers, and entanglement, that are in direct conflict with students' intuitive physical reasoning. In contrast, classical mechanics is often consistent with everyday macroscopic

observation. Our review discussion focuses on how technology-mediated collaborative environments respond to persistent cognitive challenges in physics education. We framed our discussion with two theoretical perspectives: Conceptual Change Theory (Posner et al., 1982) and Sociocultural Theory (Vygotsky, 1978).

Pillar 1: Technological Affordances in the CSCL

Synthesized literature suggests that technological affordances in CSCL serve as important cognitive and visual bridges that connect abstract mathematical formulations with physical meaning. Students often struggle to connect mathematical equations to the physical world because quantum phenomena are not directly observable in macroscopic physical laboratories. Microscopic dynamics can be visualized and made interactive with digital tools, such as classical simulations of quantum computing (Xu et al., 2025), immersive virtual reality environments (Acevedo et al., 2024), cloud-accessible quantum hardware labs (Borish and Lewandowski, 2025), multimedia animations and YouTube video integrations (Nyirahabimana et al., 2023b, 2024), Learning Management Systems with animation modules (Denisova et al., 2021), and computer-based simulations(Tawil & Dahlan, 2017). The technologies visually represent invisible quantum mechanics phenomena, dynamically rendering graphical representations of wave functions, probability densities, and state vectors.

Based on the perspective of Conceptual Change Theory (Posner et al., 1982), these technological tools contribute to establishing the basic conditions for intelligibility and plausibility. The real-time visual display, when students employ simulation parameters such as potential barrier heights in tunnelling problems or photon paths in quantum optics laboratories (Borish & Lewandowski, 2023), is at odds with their classical deterministic preconceptions. When learners visualize the ideas through the digital tools, they recognize the mental flaw and immediately compare it with their prior knowledge schemas. According to the study of Wokocha and Alle (2017), students do not passively learn mathematical equations, but they interact with models to test ideas and experience the effects. This facilitates the cognitive transitions from assimilation to accommodation. Considerably, technological affordances reduce intrinsic cognitive strain through dynamic representations that support conceptual understandings in quantum mechanics for physics students in both secondary and undergraduate.

We noted that conventional physics laboratories have some boundaries, such as the visualization of microscopic particles like electrons, which requires direct integration of genuine quantum hardware into collaborative learning environments. In our analysis, we found that immersive VR environments for subatomic particles (Acevedo et al., 2024) and cloud-based quantum experiments (Borish & Lewandowski, 2025) provide students opportunities to learn quantum mechanics in ways that were limited to physics laboratories. These tools have enabled students to engage in legitimate scientific investigation that was previously constrained to advanced research laboratories. In our synthesis, we also noted that these digital tools were not utilized as standalone media presentations but served as visual focal points for peer dialogues when integrated into CSCL platforms. Thus, we concluded that technological affordance functions as a cognitive scaffold for the individual learner and simultaneously as an anchor for collaborative inquiry.

Pillar 2: Instructional Designs in CSCL

In our systematic review, we discovered that technological affordances alone do not guarantee conceptual learning; rather, they must be integrated into structured, inquiry-driven instructional

designs. We have identified a long list of instructional models in our review that are useful to facilitate quantum mechanics instruction. These are Quantum Interactive Learning Tutorials (Kim et al., 2025), Contextualized Problem-Based Learning (Piña et al., 2024), AI-integrated historical contextualization (Daoudi, 2025), curriculum design analysis (Buzzell et al., 2025), experiment-based reasoning designs (Borish & Lewandowski, 2024), instructional scaffolding in perturbation theory (Keebaugh et al., 2024), intuition-shaping designs (Corsiglia et al., 2023), digital collaborative learning (Montagnani et al., 2023), research-based materials (Pollock, 2023), game-based strategies (Chiofalo et al., 2022), and discipline-culture approaches (Weissman et al., 2019). In learning quantum mechanics, cognitive misconceptions often occur in students due to high mathematical complexity that requires qualitative reasoning. Well-structured instructional designs reduce this danger by including explicit conceptual check-points and steering student inquiry toward higher-order analytical reasoning.

These pedagogical frameworks foster critical thinking and problem solving by systematically questioning classical intuitions and forcing students to consider paradigm shifts in quantum mechanics. For example, scaffolding difficult topics such as perturbation theory, tunneling, uncertainty, or time evolution allows students to decompose complex, multi-step mathematical problems into conceptually manageable pieces (Keebaugh et al., 2024; Kim et al., 2025). Contextualized problem-based learning (Piña et al., 2024) and historical/discipline-culture approaches (Daoudi, 2025; Weissman et al., 2019) promote students' critical engagement with the disjointed narratives between classical and quantum physics. Similarly, balanced student- versus teacher-centered designs (George & Mthethwa, 2025) and learning communities (Solorio et al., 2025) promote students' consideration of multiple perspectives, engagement in analysis of misconceptions, and modification of their problem-solving approaches in the face of unfamiliar physical situations.

Furthermore, game-based and intuition-shaping instructional designs also facilitate reflective learning by encouraging students to compare their initial physical intuitions with the rules of formal quantum mechanics. In game-based and tutorial-driven environments (Chiofalo et al., 2022; Kim et al., 2025), students are rewarded for understanding quantum state behaviours, wave function collapses, and spin interactions, rather than for mechanical formula manipulation. Research-based instructional materials (Pollock, 2023) combine qualitative reasoning tasks with quantitative calculations, and the development of computational skills is integrated with conceptual understanding. Consequently, effective CSCL instructional designs transform passive lectures into active, analytical environments where students acquire solid, transferable problem-solving skills.

Pillar 3: Collaboration Modes in CSCL

In our synthesis, we noted that collaborative interaction modes in CSCL are an important catalyst for externalizing, negotiating, and restructuring abstract concepts. We categorized studies by the social structures across which collaboration was evaluated: peer-to-peer dyads, small-group problem-solving teams, and large-group classroom networks; and the delivery modes of synchronous and asynchronous. In our review, we identified two advantages of synchronous peer engagement in small-group configurations (Brundage et al., 2023; Corsiglia et al., 2023; Montagnani et al., 2023; Solorio et al., 2025). First, we identified it as effective for real-time reconciliation of meaning; second, as ideal for misconception resolution for learners. In the same way, the studies of Chiofalo et al. (2022) on game-based tasks and Montagnani et al. (2023) on

simulation exercises emphasized that students must articulate their mental models. We then justified that, in small groups, learners can advance their scientific logic and critique the reasoning of their peers. This interpretation resonates with Funa's (2026) findings, which highlight the efficacy of integrated STEM and problem-solving learning modules in promoting critical thinking, conceptual knowledge, and collaborative reasoning in science education.

In our analyses, we noticed that digital platforms, shared simulation interfaces, and problem-solving prompts are acting as cultural tools that facilitate social interaction, as per Vygotsky's Sociocultural Theory (1978). We noted in the study of Solorio et al. (2025) that when students engage in the discussion of discrete and continuous concepts or quantum superposition, they reveal underlying presumptions that would be overlooked by a single individual. Learners assisted each other and be able to understand complex wave functions and quantum state matrices. This establishes a Zone of Proximal Development (ZPD) and scaffolding, and the cognitive dissonance of the individual is transformed into a shared understanding through social interaction.

Furthermore, in our analysis, we also found that different forms of collaboration provide cognitive advantages that suit knowledge construction. For instance, in the studies by Brundage et al. (2023) and Corsiglia et al. (2023), we found that learners correct errors quickly, engage in rapid debate, and provide feedback in real time through synchronous small-group collaborations. For asynchronous large group platforms, learners repeated difficult quantum mechanics concepts, interacted with peer feedback, and improved their basic knowledge at their own pace (Freericks et al., 2019). In fact, this is what needs to be accommodated in teaching and learning, justifying what is thought to be liable through constructive peer collaboration as very essential. In the discipline-culture strategies (Weissman et al., 2019), we identified that synchronous large-group reflections enable learners to engage in thorough class debates on philosophical underpinnings and paradigm shifts in quantum mechanics education. This transforms quantum mechanics teaching from passive learning to active collaborative learning, allowing learners to construct their understanding across different configurations. Indeed, this is supported by the competence-based curriculum that requires teachers to facilitate learning while learners directly involve themselves in creating their own learning experiences.

The Review synthesis and gaps

The merging of Conceptual Change Theory and Sociocultural theory proves that conceptual understanding of quantum mechanics is not tool-mediated and social process but solely the cognitive changes. While sociocultural theory describes how social discourse and technology artifacts facilitate such restructuring (Vygotsky, 1978), conceptual change theory describes the underlying cognitive mechanisms of restructuring past knowledge (Posner et al., 1982). The three CSCL pillars are not independent; when interactive technology affordances are included in structured instructional designs and applied through active peer collaboration, extreme conceptual gains are achieved.

Despite these promising findings, we identified three important research gaps in the synthesized literature. First, several studies involved where short term intervention trials; that means a longitudinal study is needed to evaluate whether the conceptual understanding of quantum mechanics through CSCL is sustained during extended academic careers. Second, there is no empirical studies synergized three CSCL pillars in quantum mechanics education simultaneously. Third, most of the studies we have synthesized are located in North American and European

institutions; that means more empirical studies are needed to determine the transferability and applicability of CSCL frameworks in low-resource educational settings.

Conclusion and Recommendations

In our systematic review, we synthesized 22 articles published between 2017 and 2025 on the impact of Computer-Supported Collaborative Learning (CSCL) pillars in quantum mechanics education. We identified how technological affordances enhance conceptual understanding of quantum mechanics, instructional design fosters critical thinking and problem-solving and collaborative modes promote knowledge construction in quantum mechanics. In response to the first research question, we find technological affordances such as interactive simulations, cloud-accessible quantum labs, and immersive VR environments work as cognitive and visual bridges. This minimizes cognitive strain and improves learners' understanding of abstract quantum mechanics concepts like wave functions, uncertainty, superposition, tunneling, and entanglement. In the second research question, we discovered that structured instructional designs, such as Quantum Interactive Learning Tutorials (QuILTs) and problem-based learning modules, promoted critical thinking and problem-solving by redirecting students' attention away from rote formula manipulation and toward adaptive reasoning and hypothesis testing. Finally, in response to the third research question, we discovered that a variety of collaborative interaction modes (synchronous peer dyads, small-group configurations, and asynchronous forums) could externalize mental models, and facilitate peer critique. These aid the establishment of Zones of Proximal Development, allowing for collaborative misconception resolution. We acknowledged that merging of these three pillars simultaneously shifts quantum mechanics education from rote equation memorization to collaborative, tool-mediated conceptual accommodation, resulting in conceptual comprehension, higher-order reasoning (critical thinking and problem-solving), and knowledge co-construction. Based on these findings, we offer a multitude of recommendations to stakeholders in the field of physics education.

i. Educators are encouraged to use digital technology in structured peer inquiry assignments and discussions while remembering that synchronous small-group interactions are useful for real-time problem- solving, whereas asynchronous interactions allow for more in-depth conceptual thinking.
ii. Curriculum developers should provide research-based instructional modules that reduce complex mathematical derivations and pose conceptual milestones to learners.
iii. Empirical research should be conducted by researchers to investigate the impact of the three CSCL pillars on students' comprehension of abstract physics concepts.

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