Review Article

Empirical insights into the effects of research-based teaching strategies in quantum education

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[This paper is part of the Focused Collection in Investigating and Improving Quantum Education through Research.] The present review intends to show the current state of teaching quantum-related content, to analyze and compare its learning efficiency, and to give a systemized overview of quantum-educational activities in the last years. We focus on teaching and learning elements, their innovative tools, and process-oriented studies that are empirically validated. In terms of content, we mainly concentrate on aspects of modern quantum technology. The final dataset for our analysis and synthesis included 50 studies published since 2017 and until the follow-up survey in February 2024. We have found that most of the teaching strategies described and investigated are in the field of quantum mechanics and are designed to provide an introduction to the rather broad and differentiated topic of quantum science. Studies specifically addressing mathematical concepts can exclusively be found for the target group of university students. Visualizing ideas or innovative social interventions to improve quantum learning is mainly found in schools while only a few approaches for further education show validated results. Tools most often examined in the studies reported were of digital nature, though some experiment-focused learning environments were also evaluated.

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I. INTRODUCTION

"The future is Quantum" [1]. This phrase encapsulates the European Union's vision for the Quantum Flagship project, which is aimed at advancing quantum technologies (QT) toward practical applications. These QTs, such as quantum computing, quantum communication, or quantum sensing, are poised to transform our technological landscape: "They hold the promise to affect dramatically our life overturning everything, from drug development, to cryptography, to data science and Artificial Intelligence" [2] (p. 2). In particular, these technologies will have profound societal implications, for example, in terms of privacy and equality [3]. In order for the next generation to be able to navigate these practical and societal implications of QTs, it seems imperative to provide awareness and a basic understanding of quantum physics (QP) concepts [4].

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Consequently, QP has been incorporated into secondary school curricula in many countries [4–6] and a variety of research-based teaching strategies have been developed to facilitate student learning of quantum physics and its applications (e.g., see Refs. [7–18]). In their 2017 literature review, Krijtenburg-Lewerissa *et al.* [19] identified a total of 74 articles concerned with the teaching and learning of quantum physics at the secondary and lower undergraduate levels published between 1997 and 2016. The articles included in the synthesis revealed learning difficulties frequently encountered by students, particularly in getting a grasp of wave-particle duality [20–22], photons [23,24], wave functions [25], spin [26], or atomic models [27,28]. According to previous research, these difficulties can often be traced back to a naive mix of classical and quantum thinking, with students having difficulty in (i) understanding the nondeterministic nature of quantum mechanics [19] and (ii) detaching from space-time notions when interpreting quantum phenomena (e.g., see Refs. [29,30]), among others. With regard to teaching strategies designed and evaluated for their learning effectiveness, the review emphasized the necessity of further empirical research to optimize these strategies for different educational levels. In particular, the review emphasized the necessity of improved and more comprehensive test instruments to evaluate students' understanding and, in turn, improving learning environments on quantum physics based on empirical evidence [31]. This latter need is further supported by the results of a bibliometric analysis reported in Ref. [32]. Since the publication of literature review by Krijtenburg-Lewerissa *et al.* in 2017 [19], quantum education has witnessed a significant advancement on a global scale: In Europe, two initiatives have been launched with the objective of promoting and coordinating quantum education and training projects within the European Quantum Flagship: QTEdu (Coordination and Support Action for Quantum Technology Education, 2019–2022 [33]) and QUCATS (Coordination and Support Action of the Quantum Flagship, 2022–2025 [34]). Similarly, in the United States, the National Q-12 Education Partnership has the objective of establishing a quantum learning environment with the aim of equipping the "next generation workforce with the tools to succeed in the industries of the future" [35]. Concurrently, quantum technologies have progressed from fundamental laboratory research to the development of prototypes and real-world applications [36]. These technologies now provide novel contexts for the teaching and learning of QP, enabling students to get a grasp of the far-reaching technological impact of quantum physics and its applications (e.g., see Refs. [37,38]). Hence, given the dynamic nature of the fields, both QT research and quantum education research, there is a need to update the current state of educational research on teaching and learning quantum physics.

This is where this paper comes in: We report a systematic literature review of QP education research published from 2017 to the present extending the review by Krijtenburg-Lewerissa *et al.* [19] in a twofold sense:

1. In terms of content, we provide an updated overview of empirically evaluated teaching strategies aimed at schools, universities, and further education with particular attention to recent developments in quantum technology as outlined in the Competence Framework for Quantum Technologies [39]. In this context, we also explore which innovative tools (e.g., augmented reality, virtual reality, applications, games, .) have been found to be conducive to the learning of quantum science.
2. Compared to the 2017 review, the present work reports on a systematic literature review that strictly follows the recognized PRISMA guidelines, which are described below. Thus, our review reflects the state of the literature on the basis of a methodologically rigorous approach.

In the next section, we provide an overview of the research questions, the search strings, and the paper selection process, before the findings of this review are reported in Sec. IV. In Sec. V, we contextualize the findings and identify research gaps for potential future work.

II. RESEARCH QUESTIONS

In line with the 2017 review by Krijteburg-Lewerissa *et al.* [19], we investigate teaching strategies designed and evaluated to promote student learning of quantum topics. In this context, we follow Ref. [40], in which a teaching strategy is defined as a "plan, method or series of activities to achieve [a] particular educational goal" (p. 332). In the literature, teaching strategies are also designated as teaching concepts [41], teaching-learning sequences [42], or educational paths [43]. A major focus of our systematic literature review lays in uncovering the efforts that have been made to integrate quantum technology topics into educational settings and to identify their effect on student learning. The conception and realization of a teaching strategy are automatically formed by the target group it is aimed at. Accordingly, this target group of learners is included as a subaspect in the formulation of the research questions. In the specification of this target group of learners, we are aligned with the studies themselves, which mostly describe a grouping in terms of age, in schools of grades, or in university teaching strategies for a particular study program. The methods used to play an equally influential role in shaping a teaching strategy. Our research questions focus on innovative technological tools. Therefore, our first research question (RQ) is:

RQ 1: Which teaching strategies

(a) with which thematic foci
(b) aimed at which target groups of learners have been designed and evaluated, and
(c) to what extent do they support learning quantum science and technology concepts?

Within the quantum physics teaching strategies developed and evaluated, a variety of different tools are used to facilitate student learning. Therefore, our second research question is

RQ 2: Which innovative tools have been found to be conducive to learning quantum science?

In this context, the "term 'innovation' conjures up images of new ideas, tools, and ways of doing things" (see *European School Education Platform* [44]). Therefore, we understand the term innovative tools to include but not be limited to digital tools.

III. METHODOLOGY

For the conceptualization of this systematic review, we followed the guidelines of the PRISMA framework (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [45]. This framework ensures a standardized approach to the development of systematic reviews and provides the authors with guidelines that help them achieve qualitative standards by successively following the predefined sequence of steps. The selection procedure, documentation, and criteria described there are presented below.

A. Eligibility criteria

Within the selection of our final dataset, we restricted our search to peer-reviewed journal articles. Studies were included for the review if they met the criteria we defined based on the structuring of the research questions:

1. Investigation scope relates to quantum science education research
2. Investigation scope relates to empirical research
   - 2.a Conceptual work (development of learning environments)
   - 2.b Teaching strategies
   - 2.c Innovative learning and teaching tools
3. Abstract and paper are available in English
4. Publications from 2017 onward
5. The reported paper has been peer reviewed

Articles on misconceptions, experiments, or individual learning tools were only considered if they aimed at the development of a teaching strategy and if this strategy was also presented in the same article and analyzed with regard to its effects. In principle, other reviews, papers that did not focus on the topic of quantum science or merely conceptual and nonevidence-based articles were excluded. Historical key experiments, methodological aspects, and preparatory fundamentals of classical physics were also not considered. Articles to which none of the participating authors or their universities had access to the full-text version were also not included in the review.

B. Information sources and search

The databases ERIC, SCOPUS, Web of Science, and PsychINFO were utilized for our review. In order to be able to include the most recent papers, there was a final follow-up survey in February 2024. For the databases ERIC and PsychInfo, the search results were automatically limited to peer-reviewed literature. As SCOPUS does not provide this opportunity, all studies without peer review were excluded later on during data extraction. As PsycInfo provides the filter "methodology: empirical study" and "population group: human," these were used for prescreening. Restrictions on the publication period (from 2017) and language have been placed on the database search.

TABLE I. Search string constructed by PI(C)O framework.

Category	Terms
Population	teach, learner, student, pupil, participant, expert, novice, people, graduate, adult, no machine teacher
Intervention	lesson, course, test, concept, assessment, evaluation, empirical, validation, instruction
Outcome	learning

The search string was constructed based on the PICO (**P**opulation **I**ntervention **C**omparison **O**utcome) framework. Within a search component (e.g., "Population"), the terms were connected by the Boolean operator "OR", whereas search components were linked with the Boolean operator "AND". Table I illustrates the structure of our search string: for the search query of the terms within a cell are connected with OR and the different rows with AND. As the search component "comparison" is traditionally used in the medical field to describe the, e.g., control group for a medication, there is no comparison row in our search query table.

This resulting search strings for the different databases, as well as the database specific, applied filters can be found in the Appendix.

C. Study selection

The exported records have been saved, managed, and duplicated in *Rayyan*—a free web tool designed for researchers working on systematic reviews and other knowledge synthesis projects which helps streamline the screening and selection process and make it more transparent for all collaborators. After the first database search, $n = 4876$ were uploaded into Rayyan. After applying the Rayyan "possible duplicates" algorithm, removing suggested duplicates by hand and carrying out a title-abstract-screening, $n = 291$ records remained. With the follow-up survey in February 2024, $n = 116$ were added to the full-text screening. To ensure that the most important papers were not skipped at any stage, *AS Review* was additionally implemented. *AS Review* is a basic and applied research project investigating the application of AI in the field of systematic reviews, validated by the scientific community [46]. This tool gave a ranking list of 100 articles out of the uploaded records, resulting from respective training performed with *AS Review* by indicating articles for exclusion and inclusion. The *AS Review* training was done by three reviewers.

In view of the wide range of topics, we considered articles that actually focused on a teaching strategy. This meant that studies on assessment tools or the mere analyses of misconceptions were no longer included. This reduced the number of articles for the full-text screening to $n = 119$. The whole selecting process is illustrated in Fig. 1. During the full-text screening, some studies were excluded since the full text did not show the evaluations announced in the abstract or they turned out as a side artifact of something else. In the end, 50 studies were included in the final dataset.

In addition to the eligibility criteria, the subsequent manual full-text screening was based on a protocol that analyzed the articles according to the research questions. This coding of the articles on the variables of interest for the research questions was done by four reviewers. The thematic areas were based on the research questions and thus deductively created, though the coding scheme was produced by inductive coding. The whole articles were screened to pinpoint and extract the information relevant to the thematic areas and categories were applied throughout the full texts of the paper to ensure the coding not missing out on crucial information. Categories were created by the four reviewers who analyzed roughly equal parts of the samples. Afterward, codes were compared and discussed until an agreement was reached in the sense of consensual validation [47]. If an author or authorship published several papers on the same content, the paper with the highest information load and the most recent results was chosen for the review.

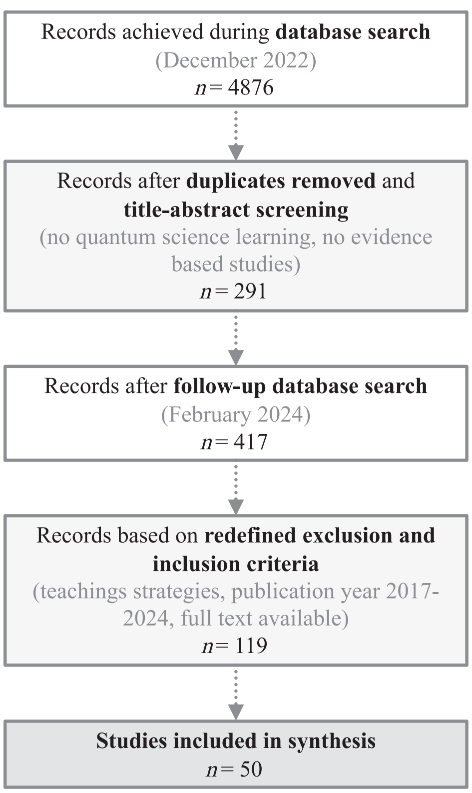

FIG. 1. Flowchart: Selecting process for the systematic review.

D. Data collection process

Data extraction using the protocols was done manually. In case of doubts regarding the exclusion during the full-text screening, controversial articles were discussed by a panel of four experts. An interrater rating was already carried out in the context of using AS Review, the results of which are provided in the Appendix. In this process, it is verified and illustrated whether the different raters evaluate the papers in a similar way and sort them out accordingly.

The protocols extract and structure information on the sample, study design, content focus, innovative tools used, measured variables and, in particular, the type of teaching. In order to compare and categorize the individual studies in the sense of a systematic review, the teaching strategies described in the articles were categorized according to the competence they aimed to achieve. The *competence framework* [48] was used as a categorization guide and logical structuring tool.

IV. RESULTS

A. Descriptive overview

In total, 21 different countries published studies on teaching strategies in quantum science within our dataset since 2017. As Fig. 2 illustrates, most of the studies included in our synthesis came from the United States, followed by Italy, Germany, and the Netherlands. United Kingdom, Norway, and Indonesia each provided two publications. Sweden, Slovenia, Finland, Chile, Switzerland, Spain, Uganda, and Rwanda, Russia, Turkey, Japan, Ukraine, Australia, and Denmark each published one study. In our final dataset, all studies from Germany [12,49–52] and the Netherlands [53–56] are aimed at schools, while all the studies from the United States [57–71] are targeted at university students. As the country with the second most publications in our dataset, Italy‘s approaches are aimed at both universities [72,73] and schools [74–76]. Looking at the dataset in relation to the type of study, Fig. 3 shows that most studies were conducted quantitatively, followed by mixed methods, and the rest qualitatively. There were no significant findings or correlations between the target group of teaching strategies and the chosen type of study. Among the quantitative studies, there is only a slight majority of teaching strategies for universities. The term “school” is differentiated by the tables and their column “educational level (grade).” As the meaning of school designations varies widely across the international context with regard to the integrated grades,

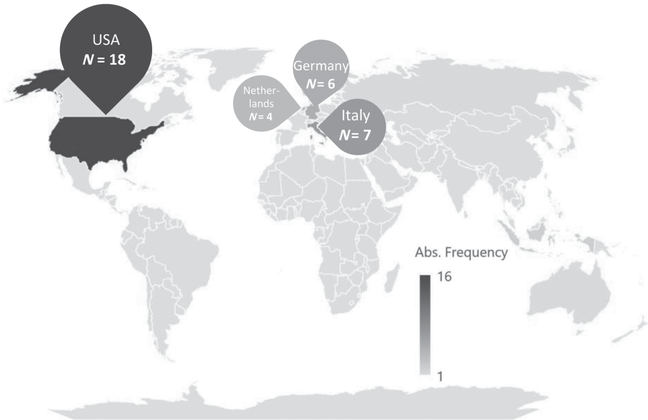

FIG. 2. Countries of publication with the highest number of studies in our dataset.

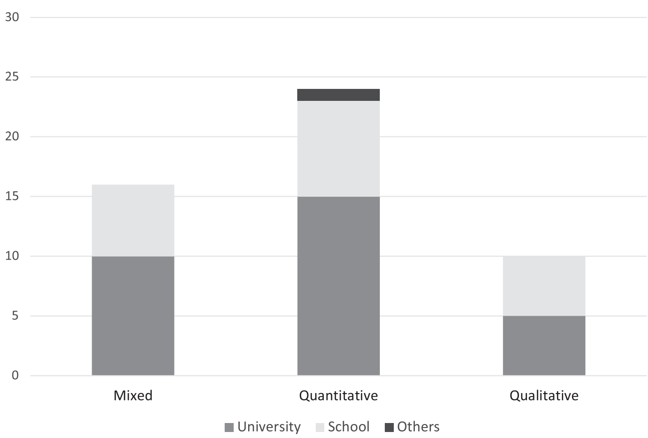

FIG. 3. Methods of the studies and the respective target groups (RQ1b).

the respective target groups of the individual teaching initiatives have been defined as precisely as possible in the tables.

B. Results regarding RQ1

In line with RQ1, the individual studies were analyzed for the teaching strategies described (RQ1a), for which learner group (RQ1b) they were designed, and how they attempted to achieve the intended learning outcome (RQ1c). Tables II–XIV show the most important key facts regarding RQ1(a)–(c) for each study of the final dataset. The columns of the table each cover a subsection (a) to (c) of RQ1. The studies were also analyzed with regard to the thematic focus of the respective teaching strategy and subsequently categorized and sorted. Given the great diversity, not too many structural overlaps emerged, whereas the individual studies within a thematic focus could be clustered according to their thematic content. A more detailed categorization is based on the competence framework [48]. In Tables II–XIV, the studies are additionally classified within the following areas, with the corresponding assigned number referring to the latest available version of the competence framework from April 2024:

1: *Quantum backround: Concepts and foundations*
- 1.1: *Basic quantum concepts: Entanglement, Bell inequalities, nonlocality, quantum measurement, probabilistic nature of quantum physics, superposition, interference, two-state systems, stationary states, energy quantisation, wells, measurement dynamics, qubits/state representation, visualization*
- 1.2: *Mathematical formalism and information theory: Linear algebra, functional analysis, state space, Dirac notation*

2: *Quantum background: Physical foundations of quantum technologies*
- 2.1: *Atomic physics*
- 2.2: *Quantum optics and electrodynamics: Quantum optical experiments, interferometry, microscopy, and spectroscopy*

5: *Quantum computing and simulation*
- 5.1: *Basics*

7: *Quantum communication and networks*
- 7.1: *Conventional and postquantum cryptography, combined cryptography approaches, classical and quantum and nonlinear optics, polarization degrees of freedom*
- 7.2: *Secure keys, e.g., for quantum key distribution*

Listed here are only those domains and subdomains that were also covered by the studies of our final dataset. In the following, the studies are therefore categorized according to the respective thematic focus of the teaching strategies. As an example, a study presenting a teaching strategy to improve the use of Dirac notation serves the thematic area **1.2** of the competence framework and is also categorized as "mathematical focus" if corresponding learner variables are analyzed. Figure 4 shows the overall distribution of the dataset across the various areas of quantum science. In addition to the focus categorization, the diagram illustrates which studies are aimed at target group of learners at school, universities, or others.

1. Quantum mechanics

Quantum mechanics records a total of ten studies ([57,58,60,72–75,77–79]). With only three exceptions [74,75,78], all of these approaches are dedicated to the target group of university students. Two exceptions addressed to schools originate from Italy and one from Slovenia and differ fundamentally in their idea and conception. Faletič [78] describes an introductory course including a double-well simulation and thereby studied the conceptual and experimenting students' skills. In this case, the experimental competence of students describes the ability to develop models and hypotheses and to test

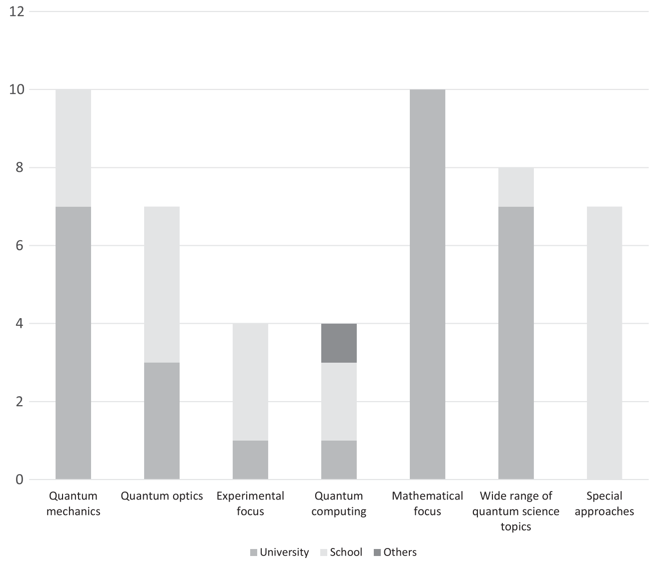

FIG. 4. Categorization of the dataset with regard to specific areas of focus (RQ1a).

them in experimental settings. di Uccio [75] used the levels of a construct map for designing a teaching-learning sequence with multiple-choice questionnaire and noted a development of students' abilities according to the structure of this construct map. Montagnani's [74] experimental program for high-school students includes real and simulated experiments and a quantum game. In addition to the improvement in cognitive skills, the study identified problems with highly mathematized representations. Two further articles on the field of quantum mechanics originate from Italy—both by Testa. The study published in 2020 [72] analyzes the effect of an innovative guided inquiry teaching-learning sequence. Compared to the control group, which was taught via textbooks, Testa recorded significantly higher accuracy and better confidence calibration with the experimental group. In contrast, the study from 2018 [73] compares three types of instruction regarding quantum mechanical learning progression. The comparison of different teaching methods and the respective effects on learners was also the focus of the article by Danielsson *et al.* [77]. This case study from Sweden investigated innovation attributes and metacognitive skills and found a correlation between the acceptance of a teaching method and the subjective rating of this method with regard to the future profession. Three approaches from the field of quantum mechanics are based on innovative tools [57,58,61]. Sayer *et al.* [57] and Marshman *et al.* [61] present a Quantum interactive learning tool (QuILT). Sayer's QuILT is combined with an interactive simulation and focuses on the double-slit experiment, whereas Marshman's QuILT intends to support as a self-paced learning tool a correct perception of expectations values. Both studies showed the improvement of conceptual skills. Kohnle and Passante [58] investigated the spontaneous use of representations within the combination of simulation and tutorial focusing on first-order energy corrections. Two studies [60,79] are based on innovative social interactions or activational techniques. Thus, Porter and Heckler [60] report on the use of guided group work and record significantly better conceptual and calculational performances. Palmgren *et al.* [79] introduce the concept of "prime-time learning" based on weekly students-instructor meetings, small group discussions, and assessment activities. Here, self-efficacy was additionally studied and an improvement was identified through the "prime-time" approach.

2. Quantum optics

A total of seven papers in our final dataset can be assigned to the field of quantum optics. The majority of studies [41,51,52,64,65], which focus on quantum optics, could also have been listed under the category "experimental focus." At the same time, these quantum optical approaches never involve just one experiment but rather the introduction to quantum physics using the manipulation of single photons in several experiments. Since 2017 educational research on quantum optical approaches and teaching ideas has been conducted and published either in Germany [41,50–52] or the United States [62,64,65]. The German contributions to teaching quantum optics content were conceptualized for use in schools and provided a quantum optics introduction to the broad field of quantum science. Quantum optics therefore serves as a starting point for the development of further concepts. The corresponding studies investigated how teachers evaluated the materials provided and how students processed a quantum physics curriculum based on (the model of) the photon and its manipulation in experiments. In contrast, the approaches from the United States in our dataset are aimed exclusively at university students. Consequently, they concentrate on quantum optics experiments in labs [64,65] or on interactive learning tutorials on the interference of single photons in the Mach-Zehnder interferometer. Here, the thematic field of quantum optics is not overstepped, with the studies focusing on the interventions' influence on conceptual skills [62,65] and motivational components or the valuation of technological importance [64].

3. Experimental focus

This section contains teaching approaches that are either based on a more specific thematic area of an experiment or develop further learning content starting from experiments. Four papers in our dataset belong to this category. Aehle *et al.* [12] follow the idea of using analogy experiments as a starting point for teaching quantum physics in schools. Also, Carreño *et al.* [80] focuses on students in schools as a target group for his teaching approach to quantum technologies with a demonstration of the Bell test. In addition to positive effects on the interest of the students, both studies [12,80] registered an improvement in conceptual skills. Maries' [66] approach, instead, is aimed at university students and follows the idea of experimental transfer learning from the Mach-Zehnder interferometer to the double-slit experiment. Here the study found positive transfer learning despite the lack of indication between the correspondences of the two experiments. The approach of Waitzmann *et al.* [49] is designed for use in schools but was evaluated with university students due to the pandemic situation. It focuses on the development of conceptual skills and students' reasoning during a learning unit with a quantum key experiment. Conclusions are drawn on the basis of concrete experimental components: The beam-splitter seemed to foster classical reasoning while the idea of superposition was not understood.

4. Quantum computing

Four papers [67,76,81,82] of our dataset could be related to the field of quantum computing. No tendency can be identified among these studies with respect to the target learner group. They are aimed at schools [67,76], universities [81], and further education [82]. The structures of the individual teaching approaches are also fundamentally different. The learning units for schools strive to integrate activating tools [76] or techniques that adapt to different levels of complexity [67] in order to maximize learning results and students' interest. Bungum and Selstø [81] start the approach for information technology students one step earlier and identify key topics for a quantum computing course. The conceptual problems evaluated in this context largely matched the known outcomes from physics education research. Combarro‘s [82] investigations on CERN‘s lecture series set out to prepare the field of quantum computing for a wide range of backrounds and with minimum prerequisites. The majority of these different backrounds turned out to be computer scientists, with the study finding a significantly increased conceptual knowledge. Among this group of papers on teaching approaches in the field of quantum computing, the years of publication are striking: they were all published in either 2022 [67,76,81] or 2021 [82].

5. Mathematical focus

All of the ten educational research studies with a mathematical focus in our dataset originated from the United States [59,61,62,68–71,83,84] or in cooperation with the United States [85]. In addition, all of these teaching approaches are aimed at university students. The target group of learners is not surprising when considering the complexity of the problems being addressed. Thus, the studies are focusing on very specific mathematical concepts such as inner products and quantum probabilities. Wan *et al.* [69] therefore present design guidelines for learning units to facilitate the use of Dirac notation, which have proven their effectiveness in a qualitative analysis. Also, Marshman‘s QuILT [63], dedicated to providing support in the handling of probability distributions of measurement outcomes, improved the students' performance with Dirac notation. Emigh *et al.* [70] developed three tutorials, including lectures, group activities, and worksheets focusing on the topic of wave function and their time evolution. The corresponding evaluation of these tutorials showed significantly improved performances among the students compared to traditional instructions, with small-to-medium effect sizes. Ahmed‘s visualization tool [85] "Quantum Composer" supports students' cognitive skills, whereas additional support is required for reasoning. Karakok‘s approach [68], in contrast, also showed the role and influence of prior learning experiences on the process of students' reasoning. Like in [66], Karakok also uses the transfer learning idea, in this case using well-known strategies from linear algebra for handling eigenvalues and eigenvectors. The instructional tutorial by Schermerhorn *et al.* [71] centers on the change of basis in quantum mechanics through the analogy between a Cartesian coordinate system and quantum states. The study recorded an effective support of the students in making sense of carrying out a change of basis. Hu *et al.* [59,83,84] implemented multiple-choice question sequences for learning assessment and recorded the reduction of students' prevalent difficulties regardless of the teacher-chosen course structure. Those multiple-choice questions sequences as a mathematical learning aid are presented for the topics of the change of basis [59], measurement uncertainty [84], the time-development of two-state quantum systems [83].

6. Wide range of quantum science topics

Eight studies [53,86–92] presented courses or teaching units covering a wide range of different topics in quantum physics. Therefore, they could not be assigned to a specific subtopic. In most cases, the teaching units described are modules that are offered as thematically broad courses at universities. The only exception in our dataset was Bouchée [53], who compares student-centred and teacher-driven quantum physics teaching approaches in schools. The study emphasizes the central role of teachers in the understanding process and mentions the positive effect of the digital materials provided on students' conceptual understanding. Like Bouchée, most of the studies [86,87,89,91,92] in this thematic category focus on digital quantum physics learning content and its effects. The individual educational research approaches differ only in the structure of these digital learning environments and with regard to the variables analyzed. The e-learning system described by Yusuf [89], includes videos, animations, and virtual experiment simulations, provided an improvement in students higher order thinking skills capabilities. Korsun‘s study [92], for its part, uses a Moodle environment and found an increase in the level of students' cognitive activity in this context. Denisova *et al.* [87] combine a Moodle environment in the sense of blended learning with in-person learning and also show the increase of cognitive activity levels. In the web-based learning approach "ReleQuant" [91], language plays a central role in the learning process. The study of students' experiences showed that the handling and perception of an innovative teaching strategy strongly depend on the type of teaching strategy one was socialized with. Socialization regarding multimedia and its use in the context of quantum physics teaching was investigated across Rwanda and Uganda by Nyirahabimana *et al.* [86]. Although an improvement in learning was also observed here, a lack of experience in dealing with multimedia tools among lecturers was nevertheless noted. This led to a reduced implementation of multimedia, especially in the field of quantum physics. The two studies by Abdurrahman *et al.* [90] and Dökme and Ünlu [88] also consider metacognitive skills in addition to conceptual understanding. Dökme noted positive influence of self-metacognitive questioning on the affective component of students' attitudes toward a quantum physics course. Abdurrahman uses differentiated feedback constantly given during a quantum physics course and thus recorded significant better learning outcomes.

7. Specials

All the studies described below are aimed at learners in schools. Those approaches [54–56,93–96] did not fit into the thematic structure of the previously grouped categories and took on a special position with their innovative strategy or thematic content. These exceptions include Stadermann's [54] buffet-style teaching resources, made available to high school teachers. The thematic focus of this approach is on linking the nature of science ideas with quantum physics and the investigation of reasoning about teaching this nature of science (NOS) idea. Krijtenburg-Lewerissa *et al.* [55] use a teaching module on classical energy diagrams as a sort of preparatory course for the introduction to quantum mechanics. The reported correlation between the understanding of potential energy diagrams and quantum mechanics attributes a bridging function to potential energy. The role of quantum science in society is the focus of the study by Moraga-Calderon *et al.* [56]. Here, the relevance and interest attributed to quantum mechanics by secondary school students during their visit of the "Quantum Rules!"-lab are investigated. The key statement "important, but not for me" [56] (p. 32) describes the observed tendency that social relevance of quantum physics is recognized but does not include an awareness of the need to learn it. Similarly, Bondani *et al.* [95] analyze the views about quantum technologies within an extracurricular course including interactive lectures on quantum technologies applications and reported an improvement in conceptual skills. Choudhary *et al.* [94] describe the special relationship between gravitational waves and quantum physics within an one-day learning unit and found next to a need for long interventions, which neither prior knowledge nor age had a significant influence on the measured conceptual skills. Malgieri *et al.* [93] use Feynman's sum over path approach as a starting for introducing quantum physics to high-school students and reports a supporting effect for students' creation of consistent and integrated mental models. For the evaluation of the analogy between musical instruments and quantum physics [96], Andreotti merely had a small sample but recognized the tendency toward a more quantum interpretation of the term "wave" and the appreciation of the preservice teachers for the inspiration on the use of various teaching tools.

C. Results regarding RQ2

Regarding the tools used in the teaching units, several broader categories have been found. First, with 20 studies the majority have been found to report on the use of digital tools such as Phet simulations, digital learning platforms, or videos. Second, there have been six studies that examined the effects of real-world tools such as experiments or flashcards or structured worksheets. Finally, four studies have been reporting on using social tools in learning environments, namely self-questioning and guided group work. Additionally to these studies, four have been found reporting on a mix of real, digital, and social tools.

1. Digital tools

For the digital tools (refer Table XV), several significant effects have been reported: Digital experiments in secondary classrooms have been shown to produce less classical influences in conceptions ($d = 0.27$ properties and behavior of quantum objects, probability interpretation $d = 0.38$, [51]). Also, on the entry university level, an E-Learning system about the basics of quantum mechanics did show a high N-gain ($g = 0.7$, [89]). Likewise, a Michelson-interferometer simulation significantly reduced learning difficulties [61], and videos on basic quantum principles statistically improved self-efficacy [79]. Also, the use of energy diagrams fosters better understanding of basic quantum mechanics [55]. A plethora of qualitative conclusions have also been drawn from digital tools implemented in secondary education: While content wise, most studies did focus on more basic quantum physics, some more advanced topics have also been examined (e.g., tunneling [55] or quantum computing [67]). Though some implementations did have only marginal effects (the symbolic math tool "geogebra" use of Ref. [93]), positive effects were reported: more differentiated knowledge of quantum computing in tandem with digital worksheets [67]. A variety of digital tools used for teaching quantum physics basics (simulations, Phet, Composer) was shown to improve understanding, interest, and engagement [95]. At the university level, the digital tool Composer was shown to support student reasoning and visualization of imaginary wave function components [85]. Also, an interactive simulation on energy corrections caused a higher use of representations in the students it was used by [58]. In general, multimedia usage has been shown to be different among countries and that mathematics used in conditions with them is not a consistent prerequisite for understanding quantum physics [86]. The digital environment Moodle has been shown to improve cognitive activity both alone [92] and implemented together with students' creation of explanatory gifs [87], both in the topic of blackbody radiation and general quantum basics, respectively. Furthermore, familiarity with quantum basics was shown to be improved with computer exercises [81] and learning about "which path information" with virtual experiments [66]. On the university level, interactive simulations have been shown to improve nonclassical understanding [57] and thus are roughly in line with the previously presented results for high schools. Finally, the usage of a mix of multimedia in university was reported to make quantum physics easier and the included visualization makes it more interesting [86]. An open lecture format on quantum computing for the broader public via digital broadcast did further increase the knowledge according to the participants' perception [82].

For the real tools, studies did not report on quantitative effects but qualitative results from the implementation of the studies. Of the three studies implemented on the secondary school level, [12] reported of a 3D-printed artifact that was accepted by students, [96] reported on facilitating progress toward a quantum physical view and [72] indicated that compared to textbooks, a guided inquiry approach facilitates less overconfidence in quantum physics. On the university level, real experiments have been shown to improve readiness for quantum interpretations [49] and to enable knowledge transfer from one experiment to another without explicit instruction on the matter [66]. Additionally, using flashcards was reported to facilitate better learning outcomes compared to a control group [90] and structured worksheets in the context of an additional tutorial for students help them succeed in exams [70].

V. DISCUSSION

With regard to the target group of learners, it is obvious that learners in further education are clearly underrepresented in the studies analyzed in comparison to those attending school or university. Further education addresses learners already working in fixed jobs, whose field of work is differentiating and facing new requirements not prepared for at university. Although the initial database search revealed some ideas on approaches for teaching quantum science to working professionals, these were excluded from the dataset due to a lack of evaluation. With 27 out of 50 studies, the large majority are focused on university students. Thematically, quantum mechanics in particular is represented here, alongside broader courses that cover several quantum science topics. Teaching strategies with a mathematical focus were presented exclusively for university use. About 19 studies describe teaching approaches for use in schools. These are mainly studies from the field of quantum optics or with another experimental focus. A large number of studies concentrates on social or special metacognitive tools in the context of quantum science education.

Regardless of the respective target group, the majority of efforts within our final dataset can be found in the field of quantum mechanics. In most cases, introductory courses were presented and enriched with simulations or innovative guided inquiry teaching-learning sequences. Alternatively, simulations and tutorials based on text-based teaching were combined and their effects were investigated. One exception, which focuses on the effect of social forms in the field of quantum mechanics, is described by Porter *et al.* [60]. In most cases, the studies concentrating on social forms and their impact in the context of quantum physics are aimed at schools and explore very specific subareas, which were presented under "Specials." As shown in Fig. 5, most of the studies examined the development of conceptual skills within the respective teaching approach, regardless of whether the studies aimed at schools, universities, or further education. Since all approaches with a mathematical focus were aimed at university learners, it is not surprising that the measurement of mathematical skills was carried out exclusively among studies with a university target group.

In the sense of a distinction between the first and second quantum revolution, different aims, approaches, and explanatory paths can be identified in the studies analyzed. While for the first quantum revolution, "wave functions in potential wells" are an important topic for teaching, in second quantum revolution, "qubits" are in focus. The wavefunction approach finds its scope, e.g., in the field of

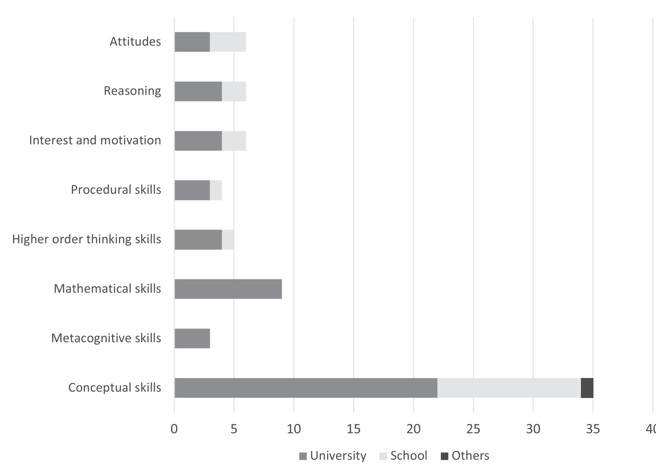

FIG. 5. Most frequently measured variables and the assignment to the respective target group.

tunneling or energy spectra, whereas quantum computer concepts like “programming” only come in the language of qubits. In our final database, 47% of the teaching strategies [53–58,60,65,70,72,73,75,77–79,83,86–90,92,96] operated in the sense of the first quantum revolution. The remaining database [12,41,49–52,61–64,66–69,71,74,76,80–82,84,91, 93–95] is based on or prepares with a specific methodology of the qubit idea.

The classification with regard to the competence framework clearly shows that, with a total number of 40 studies, the vast majority can be assigned to the subdomain “*1.1: Basic quantum concepts*”. Since many of the papers analyzed present interventions within introductory courses, it is not surprising that the basics are taught first before moving on to more complex content. The second most frequently thematized subdomain “*1.2: Mathematical formalism and information theory*”, with eight studies, belongs to the basics of quantum background as well. Several studies on quantum optics help the field of “*2.2: Quantum optics and electrodynamics*” to third position in the ranking of the most addressed subdomains of the competence framework. And finally, four studies relating to quantum computing belong to the subdomain *“Quantum computing and simulation: basics*”. Four broad domains, each with a wide thematic spectrum of subdomains, were not addressed by any of the studies within our final dataset. These include the domain “*3: Enabling technologies and techniques*,” which describes aspects such as laboratory techniques or optical and control technologies. The thematic areas around “*4: Quantum hardware*” and “*6: Quantum sensors and imaging systems*" are also not addressed in any study. Since only one study in our final set is aimed at further education anyhow, it is not surprising that the very specialized domain “*Valorisation*" with subdomains such as “*8.2: Business strategy, entrepreneurship, and management*" or “*8.4: Responsibility*" were not served either.

Though a large number of different tools, real, digital, and social, have been devised and implemented in universities and in secondary classrooms, quantitative statements about the exact effects these tools had were rarely reported. Most of the tools had shown positive effects in various educational quantum physics environments, ranging from being accepted to facilitating knowledge or attitudes, but in the end, comparing them is inconclusive based on the little quantitative data.

VI. CONCLUSION

Looking at the structure of teaching strategies, it is noticeable that approaches based on innovative social structures of activation strategies are exclusively aimed at schools. This automatically raises the question of why social structures and their effects on learning are not taken into account in university courses or further education in the context of quantum science. When the learning of complex content works for school students within innovative social learning environments, this can also have positive effects on university students or professionals. It could therefore be interesting for educational research to replicate the social innovations of these studies and test them in the context of university courses or further education.

Conversely, studies with a focus on highly mathematical content were dedicated only to university students. As soon as quantum physics is taught in schools, the focus is on demathematizing rather than tackling mathematical problems. Quantum physics teaching strategies for schools concentrate on visualizing, reducing, and illustrating. This leaves the impression that teaching strategies for schools want to bypass quantum mathematics instead of optimizing mathematics educationally in the context of quantum science or developing adequate, target group-adapted approaches. There are thus open topics and potential for educational quantum physics research to support students in mathematical processes through systematic teaching strategies for schools. In this respect, it would be desirable to observe how school students deal with the corresponding mathematical formalism and develop appropriate learning strategies. Avoiding mathematics solves problems for the moment but provides no sustainable basis for solving similar structures. The development of these mathematical learning strategies can also be derived from corresponding studies with the target group of university students. Recently, initial approaches [15] have been developed to address this issue.

Evaluated teaching strategies for the further education of professionals are clearly underrepresented. In this young field of research, the skills needed by the quantum workforce are currently being defined and renewed [39], but the learning effects of specific teaching interventions have not yet been widely published. In the ideal scenario, schools and universities prepare for this thematically with their respective teaching strategies. Several tools have already been implemented in digital, real, and social settings and all appeared to at least facilitate positive outcomes of teaching, though most studies did not report the effect sizes, which could be a task for further research in this direction. While the development and implementation of an actualized school curriculum is certainly slow, universities could react more spontaneously to the skills actually required by this quantum workforce with their lectures. This has not yet occurred in an evaluated manner for four thematically broad domains of the competence framework.

APPENDIX A: SEARCH QUERY

Search string for ERIC and web of science:

(teach* OR learner OR student OR pupil OR participant OR expert OR novice OR people OR graduate OR adult) AND (lesson OR course OR assignment OR “problem solving” OR learning OR test OR concept OR idea OR analysis OR qualitative OR quantitative OR assessment OR evaluation OR empirical OR validation OR instruction) AND quantum -“machine teacher” pubyearmin:2000 pubyearmax:2022

Additional filter “Web of Science”: Time interval; Peer-reviewed only.

Additional filter “ERIC”: Peer-reviewed only.

Search string for Psychinfo:

PY 2000-2022 AND TI-AB-KW (teach* OR learner OR student OR pupil OR participant OR expert OR novice OR people OR graduate OR adult) AND (lesson OR course OR assignment OR “problem solving” OR learning OR test OR concept OR idea OR analysis OR qualitative OR quantitative OR assessment OR evaluation OR empirical OR validation OR instruction) AND quantum NOT “machine teacher”

Additional filter “PsycInfo”: Peer-reviewed only.

Search string for SCOPUS:

((((PUBYEAR>1999 AND PUBYEAR < 2023) AND TITLE-ABS-KEY(teach* OR learner OR student OR pupil OR participant OR expert OR novice OR people OR graduate OR adult) AND TITLE-ABS-KEY(lesson OR course OR assignment OR “problem solving” OR learning OR test OR concept OR idea OR analysis OR qualitative OR quantitative OR assessment OR evaluation OR empirical OR validation OR instruction) AND TITLE-ABS-KEY (quantum) AND NOT “machine teacher”))) AND (LIMIT-TO(DOCTYPE,“ar”) OR LIMIT-TO(DOCTYPE,“cp”)) AND(EXCLUDE(SUBJAREA, “MEDI”) OR EXCLUDE (SUBJAREA,“COMP”) OR EXCLUDE(SUBJAREA, “ENGI”) OR EXCLUDE (SUBJAREA,“BIOC”) OR EXCLUDE (SUBJAREA,“MATH”) OR EXCLUDE (SUBJAREA,“MATE”) OR EXCLUDE(SUBJAREA, “PHAR”))

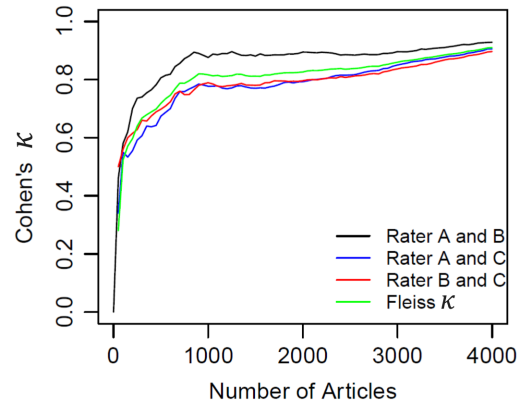

FIG. 6. Interrater reliability of three different raters.

APPENDIX B: INTERRATER RELIABILITY

Figure 6 shows the results of an interrater rating carried out in the context of using AS Review for the verification of evaluating the papers in a similar way.

APPENDIX C: TABLES RQ1

TABLE II. Results regarding research question 1.

		Teaching strategy		Empirical investigation			
Ref.	Quantum competence framework area	Thematic focus	Description	Study design	Educational level (grade)	Sample size	Main findings/effect
Montagnani *et al.* [74], 2023 Italy	1.1 and 1.2	Quantum mechanics polarization	Experimental program for high-school students based on real and simulated experiments in the context of light polarization including a quantum game.	Process data; tutorials, stimulating questions, online questionnaire	Final-year high-school students (18–19 years)	49	Variables measured: conceptual skills. The study identified a significant learning improvement on the concept of state and on appropriating the formalism meaning. Iconic representations as a bridge between the interpretation of phenomena and the mathematical formalism plays an important role: highly mathematised representations of the quantum state and superpositions seem to be more problematic for some students.
Palmgren *et al.* [79], 2022 Finland	1.1	Quantum mechanics two-state systems	Investigation of an introductory quantum mechanics course based on the spin first approach and including the "prime-time learning" idea, which is characterized by weekly students-instructor meetings, small group discussions, and assessment activities.	Self-efficacy questions, post-test (MC)	Junior-and students of physics	222	Variables measured: conceptual skills & self-efficacy Students' self-efficacy was negatively affected by the transition from a position first to the spin first instructional approach. The teaching method "prime-time" improved students' self-efficacy and remained remarkably stable during pandemic caused remote teaching.
Danielsson *et al.* [77], 2021 Sweden	1.1	Quantum mechanics	Quantum mechanics introduction course in which the teaching approaches on teachers and the impact on students were analyzed.	Case study: Observations, informal and semistructured interviews	University teachers ($N = 2$) and students in major physics, partly student teachers ($N = 30$)	32	Variables measured: Innovation attributes, metacognitive skills. The acceptance of a method of teaching/learning and active participation depends on the subjective rating of this method in the future profession.

TABLE III. Results regarding research question 1.

Ref.	Quantum competence framework area	Teaching strategy: Thematic focus	Teaching strategy: Description	Empirical investigation: Study design	Empirical investigation: Educational level (grade)	Sample size	Main findings/effect
Scotti di Uccio *et al.* [75], 2020 Italy	1.1	Quantum mechanics	Teaching-learning sequence and multiple-choice questionnaire were designed in strict relation with the levels of a construct map addressing introductory quantum mechanics topics at high-school level.	Quasiexperimental study on class level; designed questionnaire	High-school students (17–18 years); teaching-learning-sequence EG = 200; textbook instruction CG = 208	408	Variables measured: Students' reasoning. Students exposed to the teaching-learning sequence more likely moved toward upper levels of the construct map. The study confirmed the increase of students' abilities according to the construct map after the instruction.
Testa *et al.* [72], 2020 Italy	1.1	Quantum mechanics	During an introductory course on quantum mechanics, students join an innovative guided inquiry teaching-learning sequence (TLS).	Quasiexperimental study on class level	TLS supported EG = 182; textbook-based instructions CG = 201	408	Variables measured: Conceptual skills and overconfidence bias. The EG achieved a significantly higher accuracy and a better confidence calibration than the textbook-based CG.
Faletić [78], 2020 Slovenia	1.1	Quantum mechanics	Introductory course with double-well simulation for teaching the basic concepts of quantum mechanics.	Quasirandomized study on class level; worksheets and observations	High-school students (12th grade: $N = 64$ (17–18 yrs); 10th–13th grade: $N = 17$; 13th grade: $N = 30$) and physics teachers ($N = 20$)	131	Variables measured: conceptual & experimenting skills. Considering the low level of support required from the instructor, working with the simulation is considered appropriate for the self-directed elaboration of learning content.
Porter *et al.* [60], 2020 USA	1.1	Quantum mechanics	Guided group work in a quantum mechanics course.	Descriptive study; pre-post-test	Graduate students	133	Variables measured: Conceptual and calculational skills. Statistically significant effect of the group work attendance on the post-test gains. Especially the 60-min group work intervention improved the performance on related post-test.

TABLE IV. Results regarding research question 1.

		Teaching strategy		Empirical investigation			
Ref.	Quantum competence framework area	Thematic focus	Description	Study design	Educational level (grade)	Sample size	Main findings/effect
Testa *et al.* [73], 2018 Italy	1.1	Quantum mechanics measurement atoms and electrons wave function	Three ways of instruction are compared regarding quantum mechanical learning progression: No course, introductory course, and an introductory and upper-level course. For investigation, the influence of backround on 43 nonphysics students attending an introductory QM were included additionally.	Randomized controlled trial	G1 = first-year undergraduates, no previous QM courses. ($N = 76$); G2 = second-year undergraduates, attended first QM course ($N = 130$); G3 = third-year undergraduates, attended two QM courses ($N = 38$); CG = students with bachelor degree in mathematics ($N = 43$)	287	Variables measured: Conceptual skills. The study identified no significant differences between the students attending two quantum mechanics courses (introductory + upper level) and students who have only attended the introductory course. There were also no significant differences between the maths students and the physics students without any quantum mechanics course.
Sayer *et al.* [57], 2017 USA	1.1	Quantum mechanics double-slit experiment	Quantum interactive learning tutorial (QuILT) with an interactive simulation of the double-slit experiment.	Quasiexperimental study on class level; pre-post-test	Upper-level undergraduate ($N = 46$) and first-years physics graduate students ($N = 45$)	91	Variables measured: Conceptual skills. In the double-slit context, QuILT supported students to develop a robust understanding of foundational concepts.
Kohnle *et al.* [58], 2017 USA and United Kingdom	1.1	Quantum mechanics	The combination of simulation and tutorial on first-order energy corrections within the quantum mechanical time-independent perturbation theory.	Quasiexperimental study on class level; pre-mid-post-test	Junior and senior-level students	116	Variables measured: Spontaneous use of representations. The importance for supporting students in finding the meaning of representations, an increase in the number of representations used by students and a shift from perceptual to semantic use of representations were identified.

TABLE V. Results regarding research question 1.

		Teaching strategy		Empirical investigation			
Ref.	Quantum competence framework area	Thematic focus	Description	Study design	Educational level (grade)	Sample size	Main findings/effect
Borish *et al.* [64], 2023 USA	2.2	Quantum optics experiments	The study focuses on students learning that can be achieved while working with experiments.	Case study; Semistructured interviews	Instructors ($N = 14$) and students ($N = 14$)	28	Variables measured: Familiarity, excitement, and motivation, conceptual understanding, technological importance. The single-photon experiments were effective in making students feel like they observed quantum effects and achieve other related learning goals.
Ubben *et al.* [50], 2023 Germany	1.1	Quantum optics models and technologies	Online course including activities to foster students' functional thinking about models for learning quantum physics.	One group pre-post-test	High-school students (16–18 years)	59	Variables measured: Conceptual skills and functional thinking. Students improved their quantum physical thinking about photon and slightly improved their general understanding of physics models.
Lukishova [65], 2022 USA	1.1	Quantum optics experiments	"3-h mini labs": teaching approach including quantum optics lab experiments for different learning groups (freshman to senior and graduate student levels)	Pre-mid-post-test; Quizzes'questions	Undergraduate and graduate students	63	Variables measured: Conceptual skills and students' attitude and functional thinking. Visualizations and simulations enhance student learning. The experimental intervention had positive effects on the self-efficacy and the notion of a quantum optics/information career.
Bitzenbauer [51], 2021 Germany	1.1 and 2.2	Quantum optics	New curriculum based on quantum optics with single photon experiments including interactive screen experiments and worksheets.	Field trial quasirandomized on class level	Secondary school (12th grade) EG = 150 CG = 130	280	Variables measured: Conceptual skills and functional thinking. The influence of classical mechanics and deterministics on the EG is significantly less than on the CG.
Bitzenbauer [52], 2021 Germany	1.1 and 2.2	Quantum optics	New teaching material for a secondary school teaching sequence on quantum optics combining hands-on experience in real and virtual formats.	Questionnaire with open-ended and closed questions	Teachers	10	Variables measured: Ascribed relevance and engagement. The teachers welcomed the close reference to current research and the experiments while concerns regarding the mathematical requirements were expressed.

TABLE VI. Results regarding research question 1.

Ref.	Quantum competence framework area	Teaching strategy: Thematic focus	Teaching strategy: Description	Empirical investigation: Study design	Empirical investigation: Educational level (grade)	Sample size	Main findings/effect
Bitzenbauer [41], 2020 Germany	1.1 and 2.2	Quantum optics	New teaching concept on quantum optics for secondary school students developed around making use of interactive screen experiments with single photons.	Acceptance survey	Secondary school students (12th grade)	13	Variables measured: Acceptance, quality of paraphrasing. The concept was well accepted and the students were able to cope with quantum optics concepts.
Marshman et al. [62], 2021 USA	1.1 and 2.2	Quantum optics	Quantum interactive tutorial (QuILT) using the quantum optics context to teach foundational quantum mechanics concepts.	Pre-post-test	Upper level undergraduate ($N = 38$) and graduate students ($N = 45$)	83	Variables measured: Conceptual skills. The study identified the QuILT on the Mach-Zehnder interferometer with single photons as an effective tool for helping the participating students learn about foundation topics in quantum mechanics.
Waitzmann et al. [49], 2022 Germany	1.1 and 7.1	Experiments	Learning unit with a quantum key experiment based that can only be explained by using basic components of quantum physical reasoning.	Randomized controlled lab study; semistructured interviews ($N = 36$); pre-post-test	Physics students (first term)	80	Variables measured: Conceptual skills and students reasoning. The beamsplitter component of the key experiment seemed to foster classical reasoning while the idea of superposition was not understood.
Aehle et al. [12], 2022 Germany	2.2 and 7.1	Experiments analog experiments	Students visit a laboratory where they work with analog experiments for the polarization of single photons and near-field communication.	Lab study; pre-post-test	Secondary school	11	Variables measured: Conceptual skills. Increase of correct answers after intervention with analog experiments.
Maries et al. [66], 2020 USA	1.1 and 2.2	Experiments MZI and double slit	Learning transfer of the "which-path" concept from the context of the Mach Zehnder interferometer to the new context of double-slit experiment.	Lab study; think-aloud interviews and expert ratings, pre-post-test	Upper-level undergraduate ($N = 46$) and graduate ($N = 59$) students	105	Variables measured: Conceptual and experimenting skills; reasoning. Despite the lack of guidance in recognizing the similarities between the two contexts, a positive transfer of learning was found, especially in the expertise of the advanced physics students.

TABLE VII. Results regarding research question 1.

		Teaching strategy		Empirical investigation			
Ref.	Quantum competence framework area	Thematic focus	Description	Study design	Educational level (grade)	Sample size	Main findings/effect
Carreño *et al.* [80], 2019 Chile	1.1 and 7.2	Experiments Quantum key distribution	Imbedded in a lecture on quantum technologies: low cost 20 min demonstration of the Bell test (entanglement between two particles), used in quantum key distribution protocols.	Pre-post-test	High-school students (14–18 years)	220	Variables measured: conceptual skills. Students developed quantum-related concepts throughout the activity. The demonstration positively impacts the students' interest in physics and the role of quantum mechanics in modern industry.
Bungum *et al.* [81], 2022 Norway	1.1 and 5.1	Quantum computing	The study identifies key topics for a quantum physics and quantum computing course for information technology students.	Digital questionnaires and group interviews	Information technology students	9	Variables measured: conceptual skills, interest and backround. Apart from the mathematical formalisms, information technology students share common conceptual problems known from physics education research.
Satanassi *et al.* [76], 2022 Italy	1.1 and 5.1	Quantum computing	Educational approach to quantum computing module for secondary schools including an activity on quantum teleportation.	Convenience sampling; questionnaire with closed and open-ended questions	Secondary school students (volunteer students!)	14	Variables measured: Students' engagement and inclusiveness, reactions on the structure of the intervention, conceptual and epistemological skills. Preliminary study results show that students feel encouraged to use and combine several registers to elaborate personal descriptions of the phenomenon.
Hughes *et al.* [67], 2022 USA	5.1	Quantum computing	Quantum computing module for high-school students, including text- and active learning techniques with adaptive levels of complexity.	Field trial quasirandomized on class level; pre-post-test	High-school students	54	Variables measured: Conceptual skills, importance, and interest. Quantum mechanics and quantum computing knowledge significantly improved with the teaching module.

TABLE VIII. Results regarding research question 1.

Ref.	Quantum competence framework area	Teaching strategy: Thematic focus	Teaching strategy: Description	Empirical investigation: Study design	Empirical investigation: Educational level (grade)	Sample size	Main findings/effect
Combarro *et al.* [82], 2021 Spain and Switzerland	5.1	Quantum computing	Series of online lectures on quantum computing, focused on hands-on and practical aspects for minimizing prerequisite knowledge.	Convenience sampling; descriptive study	Viewers of different ages with different backrounds	184	Variables measured: Conceptual skills and backround. The viewers—mainly computer scientists—showed a significantly increased conceptual knowledge, which recommends the teaching approach for an introduction of quantum computing to a mixed population of practitioners.
Hu *et al.* [59], 2023 USA	1.1 and 1.2	Mathematics 2-state systems and Dirac notation	The use of multiple-choice question sequences for learning assessment is analyzed in online and in-person learning environments including traditional lecture-based instructions.	Pre-post-test and think-aloud interviews	Junior- and senior-level students	81	Variables measured: Conceptual and mathematical skills. Regardless of an online in person learning environment or the course structure chosen by the teacher: Clicker question sequences were helpful in reducing students' prevalent difficulties. Students consistently demonstrated notable enhancements in their understanding of problematic topics such as the depiction of outer products in matrix form and the process of basis alteration, ranging from moderate to significant improvements.
Hu *et al.* [84], 2023 USA	1.1 and 1.2	Mathematics 2-state systems anduncertainty	The use of multiple-choice question sequences for learning assessment is analyzed within two modes of instruction.	Pre-post-test and think-aloud interviews	Junior- and senior-level students	50	Variables measured: Conceptual and mathematical skills. Students performed about equally well on the post-test for both administrations, given that the online learning environment had greatly reduced opportunity for peers to discuss their responses with each other.

TABLE IX. Results regarding research question 1.

Ref.	Quantum competence framework area	Teaching strategy: Thematic focus	Teaching strategy: Description	Empirical investigation: Study design	Empirical investigation: Educational level (grade)	Sample size	Main findings/effect
Hu*et al.* [83], 2022 USA	1.1 and 1.2	Mathematics 2-state systems andtime-development	The implementation of a clicker-question sequences (CQS) on the topic of time-development of two-state quantum systems.	Pre-post-test & interviews	Upper-level students	54	Variables measured: Conceptual and mathematical skills. The CQS was effective in enhancing students performance and facilitated a better understanding and retention of the time evolution of quantum states. Improvement was noted in virtual and in-person classes.
Ahmed *et al.* [85], 2022 Denmark and United Kingdom and USA	1.1 and 1.2	Mathematics Statistic and dynamics of quantum states	Description and evaluation of the visualization tool “quantum composer” as a 1D quantum simulation.	Think-aloud interviews	Second-year undergraduate students	5	Variables measured: Cognitive skills and reasoning. The QC supports students in generating correct answers, although additional support is required to reason these answers.
Schermerhorn *et al.* [71], 2022 USA	1.1 and 1.2	Mathematics change of basis	Instructional tutorial for supporting the understanding of change of basis in quantum mechanics through the analogy between spin $\frac{1}{2}$ states and a Cartesian coordinate system.	Matched study; interviews ($N = 6$), observations, pre-post-test	Upper-division students	126	Variables measured: Conceptual and mathematical skills. The tutorial effectively supports students making sense of and carrying out a change of basis in quantum mechanics by using the analogy between quantum state and 2D Cartesian vectors.
Karakok [68], 2019 USA	1.2	Mathematics Eigenvectors and eigenvalues	Guided use for knowledge transfer: Applying insights from linear algebra to the handling of eigenvalues and eigenvectors in quantum physics	Task-based interviews, observations, pre-and-post-quizzes	Undergraduate students with initial learning experiences of linear algebra	2	Variables measured: Transfer ability, mathematical, conceptual, and procedural skills. Prior learning experiences influence the process of students’ reasoning.

TABLE X. Results regarding research question 1.

Ref.	Quantum competence framework area	Teaching strategy: Thematic focus	Teaching strategy: Description	Empirical investigation: Study design	Empirical investigation: Educational level (grade)	Sample size	Main findings/effect
Wan *et al.* [69], 2019 USA	1.1 and 1.2	Mathematics inner products and quantum probabilities	The study formulates guidelines for the design of teaching units that support learning in the handling of Dirac notation.	Qualitative analysis of student written responses and interviews ($N = 6$)	Junior-level students; number varies with task	121	Variables measured: Mathematical and procedural skills. Dirac notation used as a template supports students sensemaking of inner products between the state vector and eigenstates.
Emigh *et al.* [70], 2018 USA	1.1	Mathematics wave function and their time evolution	A set of three tutorials on time evolution and measurements was developed, including traditional lectures, small group sections, and structured worksheets with the instructional approaches "elicit-confront-resolve" and "model building."	Convenience sampling; pretest ($N = 237$) final exam = post-test ($N = 71$)	Undergraduate-level students	71	Variables measured: Mathematical and conceptual skills. Student‘s performance improved significantly with the tutorial compared to a traditional instruction with small-to-moderate effect sizes. Students' struggles with the correct use of the terms "stationary state" and "time dependence" were identified. Effect sizes:0.11-0.21.
Marshman *et al.* [61], 2017 USA	1.1	Mathematics expectation values of observables	Quantum interactive tutorial to support students in developing a good conception of the expectation value, also usable as a self-paced learning tool.	Written surveys, individual interviews	Upper-level undergraduate ($N = 184$) and Ph.D. students ($N = 97$)	281	Variables measured: Conceptual and procedural skills. All participating students performed significantly better on the post-tests after working on the QuILT, compared to the pretest after a traditional instruction. Students themselves consider QuILT to be very effective in helping them learn concepts.
Marshman *et al.* [63], 2017 USA	1.1 and 1.2	Mathematics probability distributions for measuring physical observables	Quantum interactive learning tutorial (QuILT) for supporting the development of proper conceptions for probability distributions of measurement outcomes.	Quasiexperimental study on class level;pre-post-tests	Upper-level undergraduate ($N = 62$) & Ph.D. students ($N = 66$)	128	Variables measured: Conceptual skills. Students working with QuILT showed better performance with Dirac notation and position representation in the context of probability distributions for measurement outcomes.

TABLE XI. Results regarding Research Question 1.

Ref.	Quantum competence framework area	Teaching strategy: Thematic focus	Teaching strategy: Description	Empirical investigation: Study design	Empirical investigation: Educational level (grade)	Sample size	Main findings/effect
Nyirahabimana *et al.* [86], 2022 Rwanda and Uganda	1.1	Wide range of quantum science topics	The study analyzes the given teaching situation in university quantum physics in Rwanda and Uganda and tries to identify characteristic aspects and their effects.	Nonexperimental descriptive study	Lecturers ($N = 10$) and students ($N = 300$)	310	Variables measured: Lecturers‘and students’ perceptions. Although the use of multimedia improves learning, teachers lack the experience to implement it. In Rwanda in particular, this results in the rare use of multimedia and even less in the context of quantum physics, which remains perceived as challenging due to the traditional way of teaching.
Denisova *et al.* [87], 2021 Russia	1.1	Wide range of quantum science topics	Combination of Moodle online environment with in-person learning (blended learning) in the context of quantum physics.	Open-ended questions; preliminary & final test	Technical university students EG = 91 CG = 92	183	Variables measured: Cognitive activity: motivational, content, and emotional components. An increase of cognitive activity levels is shown by students who worked with educational materials in Moodle.
Bouchée *et al.* [53], 2021 Netherlands	1.1	Wide range of quantum science topics	A teacher-driven and a student-centred teaching approach are compared in the context of quantum physics school lessons.	Case study with cross-case analysis; semistructured individual and focus group interviews	Teachers ($N = 3$) and their students ($N = 15$)	18	Variables measured: Teachers‘ and students’ experiences. While the study assigns a central role to teachers and the use of examples and applications in the understanding process of quantum physics, the teachers themselves struggled to convince their students of the subjects‘ relevance. The freely available digital materials could improve conceptual understanding.

TABLE XII. Results regarding research question 1.

Ref.	Quantum competence framework area	Teaching strategy: Thematic focus	Teaching strategy: Description	Empirical investigation: Study design	Empirical investigation: Educational level (grade)	Sample size	Main findings/effect
Dökme *et al.* [88], 2019 Turkey	**1**	Wide range of quantum science topics	Influence of self-metacognitive questioning for nonroutine quantum physics problems on preservice science teachers‘ attitudes toward a quantum physics course.	Quasiexperimental field trial; “attitude scale of quantum physics course” pre-post-test	Preservice teachers guided by self-metacognitive questioning EG = 27 CG = 30	57	Variables measured: Attitudes. Self-metacognitive training positively impacts the affective component of attitude (significant difference in favor of the EG). Regardless of the group. However, there was no change in the cognitive component of the attitude related to the importance of quantum physics course in everyday life in any group.
Yusuf *et al.* [89], 2018 Indonesia	1.1	Wide range of quantum science topics	Quantum physics course based on an e-learning system, including videos, animations, and virtual experiment simulations.	Quasiexperimental study; pre-post-test	Students of a quantum physics program	10	Variables measured: Higher order thinking skills. E-learning course improves students higher order thinking skills capabilities.
Abdurrahman *et al.* [90], 2018 Indonesia and Japan	**1.1**	Wide range of quantum science topics	During the course, the EG is constantly given differentiated feedback in the form of flashcards, correction and reinforcement. The CG receives traditional feedback through correction.	Quasiexperimental study on nonequivalent pre-post-test CG ($N = 18$)	Student teachers	37	Variables measured: Conceptual and metacognitive skills. Students with feedback on metacognitive and social constructivism showed significant better learning outcomes than the CG.
Bøe *et al.* [91], 2017 Norway	**1.1**	Wide range of quantum science topics	“ReleQuant” as a web-based learning approach used in physics classrooms, including activities focused on the role of language within the learning process.	Design-based research; classroom trial; interviews and observations	Senior upper secondary physics classes	58	Variables measured: Students’ experiences. Being socialized in traditional physics classroom influences future experiences with new teaching approaches. Tools of a new approach are recognized as helpful as long as they support the goals of traditional learning. However, if a new approach requires a deviation from familiar learning strategies, this leads to problems. The implementation of new learning approaches requires making implicit expectations explicit.

TABLE XIII. Results regarding research question 1.

		Teaching strategy		Empirical investigation			
Ref.	Quantum competence framework area	Thematic focus	Description	Study design	Educational level (grade)	Sample size	Main findings/effect
Korsun [92], 2017 Ukraine	1.1	Wide range of quantum science topics	E-learning of quantum physics in the Moodle environment.	Open-ended questionnaire, pre-post-test	Physics students EG = 91 CG = 92	183	Variables measured: Cognitive activity (motivational, content, emotional components). E-learning as a component of teaching quantum physics increased the level of students' cognitive activity.
Andreotti *et al.* [96], 2023 Belgium	1.1	Special approaches Quantization, superposition and wave modes	Investigation of the pedagogical potential of the analogy between musical instruments and quantum physics.	Open-ended questionnaire	Physics teacher students	6	Variables measured: Conceptual skills. Due to the small sample size, only cautious tendencies can be recognized: for example, a progress to a more quantum interpretation by the interpretation of the term "wave." Students valued the course for the inspiration on the use of various teaching tools in quantum physics lessons.
Krijtenburg-Lewerissa *et al.* [55], 2022 Netherlands	2.1	Special approaches Potential energy, energy wall and tunneling	A teaching module on classical energy diagrams is held for students (EG) before introduced to quantum mechanics.	Quasi-experimental study on class level; pre-post-tests	Secondary school students EG = 234 CG = 157	391	Variables measured: Conceptual skills. A significant correlation between the understanding of potential energy diagrams and the understanding of quantum mechanics was identified, which suggests emphasis on potential energy as a bridge for the gap between students' prior knowledge and quantum mechanics.
Bondani *et al.* [95], 2022 Italy	1.1 and 1.2	Special approaches Quantum physics concepts and technological applications	Design and implementation of an extracurricular course with eight interactive lectures on quantum physics concepts and quantum technologies applications for high school.	Questionnaire "Quantum Technologies Inventory" ($N = 176$) and pre-post-test "Views about Quantum Technologies"	High-school students (12th and 13th grade)	279	Variables measured: Conceptual skills and views about quantum technologies Designed activities improved students' knowledge of fundamental aspects of quantum mechanics and made them familiar with quantum technologies.

TABLE XIV. Results regarding research question 1.

Ref.	Quantum competence framework area	Teaching strategy: Thematic focus	Teaching strategy: Description	Empirical investigation: Study design	Empirical investigation: Educational level (grade)	Sample size	Main findings/effect
Stadermann *et al.* [54], 2021 Netherlands	1.1	Special approaches NOS and quantum physics	NOS-infused and buffet-style teaching resources are made available to teachers covering all learning objectives from the Dutch quantum physics curriculum.	Interviews and observations	Experienced Dutch high-school teachers	10	Variables measured: Innovation attributes, reasoning about NOS. The main reason why teachers taught NOS aspects was to enhance students' understanding of quantum physics concepts. NOS was not communicated for its own sake but for the achievement of other goals.
Moraga-Calderón *et al.* [56], 2020 Netherlands	1.1	Special approaches Importance of quantum science for society	During the lab visit "Quantum Rules!", students experiment with 20 quantum experiments designed according to the Dutch school curriculum.	Randomized controlled lab study; pre-post-test, interviews, self-reported questionnaires	Secondary school students	45	Variables measured: Perception (of the relevance) of quantum mechanics, Interests. Perceived relevance and interest correlate: "important, but not for me"; the social relevance of quantum physics is recognized, but this does not include an awareness of the need to learn it.
Choudhary *et al.* [94], 2018 Australia	1.1	Special approaches Basic concepts of quantum physics and gravitational waves	A one-day learning unit uses the phenomenon of gravitational waves to introduce the fundamental concepts of quantum physics and gravitation. The approach includes role-playing, model demonstrations, and single photon interference.	Quasirandomized study on class level;pre-post-test	High-school students (7th–10th grade)	103	Variables measured: Conceptual skills and attitude Neither prior knowledge nor age have a significant influence on understanding the basic concepts. While students understand derived concepts in long interventions, short interventions cannot achieve this. Girls responded significantly more positive compared to boys.
Malgieri *et al.* [93], 2017 Italy	1.1	Special approaches Wave-particle duality and uncertainty principle	Teaching-learning sequence on introductory quantum physics based on Feynman's sum over path approach.	Case study, randomized on class level; audio recordings, final test for school grading, questionnaires, interviews	High-school students (13th grade)	14	Variables measured: Degree of integration and interconnectedness of students' acquired knowledge. Feynman's approach supports students to create consistent, detailed, and integrated mental models.

TABLE XV. Results regarding research question 2: Digital tools used.

Digital tool(s) used	Learning environment	Thematic focus	Resulting learning support	Ref.
Clicker question sequences	University level (entry)	Quantum mechanics	Improvements in understanding in problematic topics like outer products	[59]
Clicker question sequences	University level	Mathematics 2-state systems and uncertainty	Conceptual knowledge improved	[84]
Clicker question sequences	University level (upper undergraduate)	Mathematics2-state systems and Dirac notation	Clicker improves performance and retention	[83]
Composer, (Phet) simulations	Secondary school level	Special approaches Quantum physics concepts and technological applications	Digital improved understanding, interest, engagement	[95]
Computer exercises	University	Quantum computing	Familiarity increased	[81]
E-learning system	University level (entry)	Wide range of quantum science topics	HOTS showed high N-gain ($g = 0.7$)	[89]
Energy diagrams	Secondary school level	Special approaches Potential energy, energy wall and tunneling	PE diagrams and QM understanding correlate	[55]
Geogebra, simulations	Secondary school level (high-school students)	Special approaches Wave-particle duality and uncertainty principle	Only marginally better than traditional in terms of conceptual knowledge	[93]
Interactive simulation	University level	Quantum mechanics	Increased representations used, students showed need in making sense of representations	[58]
Interactive simulations, worksheets	Secondary school (high school)	Quantum computing	More differentiated basic knowledge about QC	[67]
Lecture transmission	Open lecture	Quantum computing	Knowledge increase (perceived)	[82]
Moodle	University level	Wide range of quantum science topics	Cognitive activity improved	[92]
Moodle, GIF-creation software	University level	Wide range of quantum science topics	Cognitive activity level improved	[87]
Multimedia tools	University level	Wide range of quantum science topics	Different countries use different amount of mm-tools, mathematics is inconsistent for understanding qp	[86]
MZI simulation	University level (upper undergraduate, graduate)	Mathematics Probability distributions for measuring physical observables	Learning difficulties reduced significantly	[62]
Quantum optics experiments	Secondary school education	Quantum optics	Less classical influence in conceptions. ($d = 0.27$ properties and behavior of QO, probability interpretation $d = 0.38$)	[51]
QUILT	University level (upper undergraduate)	Mathematics expectation values of observables	QUILT was said to be helpful	[61]
QUILT, interactive simulation	University level	Quantum mechanics Double-slit experiment	Improving nonclassical understanding	[57]
Videos	University (undergraduate)	Quantum mechanics 2-state systems	Self-efficacy was statistically improved	[79]
YouTube, (Phet) simulations	University level (undergraduate)	Wide range of quantum science topics	Multimedia leads to perceiving QM as easier, visualizations make it more interesting	[86]

APPENDIX D: TABLES RQ2

1. Real tools

As for the real tools used (see Table XVI), experimental setups were the most used tools. In secondary schools, using an experiment in the context of deBroglie was found to progress the student's view toward a quantum physical view [96]. In the university context, experiments have been shown to facilitate improved readiness for quantum interpretations [49] and positive learning and transfer abilities [66]. Using structured worksheets in university tutorials on the time evolution of wave functions proved helpful for exam success [70] and flashcards facilitated better learning outcomes when compared to a control group [90]. Another artifact tested in secondary schools was 3D-printed black box models that were accepted by the students [12] and guided inquiry approaches that led to less overconfidence when compared to textbooks [72].

2. Social tools

Furthermore, self-questioning as a social tool used in quantum physics courses on the university level (see Table XVII) tackling basic topics has been shown to foster positive attitudes [88] and guided-group work to improve long-term performance [60]. The implementation of industry partners in quantum courses was also found to be perceived as helpful [63].

3. Mixed tools

As for methods that use a variety of real, digital, or social tools (see Table XVIII) in quantum physics education, positive effects have been reported both on the secondary school level. A mix of experiments, explanatory videos, and analogies was shown to enable learning of central concepts in quantum optics [41]. A combination of the digital tool H5P and social teaching strategies was seen as helpful for the visualization of quantum phenomena [91]. Mixed-methods approaches and use of different tools have also been indicated to enable an improved perception of relevance for quantum physics [56], and a combination of gamified real and digital experimental setups has made the teaching of vector representations more effective than algebraic representations [74]. A mix of role-play and digital media regarding analogies in quantum mechanics has been shown to have the same positive effects in both a lesson sequence taught across a long period and a condensed, short period [94].

TABLE XVI. Results regarding research question 2: Real-world tools used.

Real-world tool(s) used	Learning environment	Thematic focus	Resulting learning support	Ref.
Flashcards	University level	Wide range of quantum science topics	Learning outcomes improved in experimental group	[90]
Guided inquiry, textbooks	Secondary school level	Quantum mechanics	Textbooks lead to overconfidence, guided inquiry to less	[72]
Experiments	University (first semester)	Experiments	True experiment was used to facilitate improved readiness for quantum interpretations	[49]
Experiment	Secondary school	Special approaches Quantization, superposition and wave modes	Progress toward quantum physical view	[96]
Structured worksheets	University level	Mathematics Wave function and their time evolution	Tutorials help with exams	[70]
Experiments	University level (grad and undergrad)	Experiments MZI and double slit	Transfer from MZI to DSE occurred despite no explicit instruction, MZI tutorial provided positive learning	[66]

TABLE XVII. Results regarding research question 2: Social strategies used.

Social strategies used	Learning environment	Thematic focus	Resulting learning support	Ref.
Self-questioning	University level	Wide range of quantum science topics	Fosters positive attitudes	[88]
Guided group work	University level (graduate)	Quantum mechanics	Performance on a related post-test item increased by 6.4%, administered 2–10 weeks after the session.	[60]

TABLE XVIII. Results regarding research question 2: Mixed tools used.

Tools used	Learning environment	Thematic focus	Resulting learning support	Ref.
Social, digital (H5P)	Secondary school level	Wide range of quantum science topics	Visualizations seen as helpful	[91]
Real, digital (mixed methods, experiments, interactive simulations, lectures, etc.)	Secondary level (not in school)	Special approaches Importance of quantum science for society	Improved relevance perception of quantum physics	[56]
Digital (experiments), real (experiments), other (gamification)	Secondary school (high school)	Quantum mechanics Polarization	More vector representations managed to be taught than algebraic	[74]
Digital (videos and images), social (role-play) and one-day block lesson	Secondary school (year 9)	Special approaches Basic concepts of quantum physics and gravitational waves	No difference between 20 lessons	[94]

APPENDIX E: PAPER PROTOCOL

The form shown in Fig. 7 was used by the authors to extract the information relevant in terms of the RQs. According to the mainly addressed question, listed up and formulated in the gray box, the authors noted rough paraphrases and key points that summarize the full texts.

PAPER PROTOCOL

PAPER EXCLUDED:
- ☐ Not evaluated
- ☐ Off topic
- ☐ Others:______________________________

☐ **PAPER IS INCLUDED…**

FULLTEXT SCREENING QUESTIONS

1. Which **teaching strategies** are **studied** in educational research of quantum science technology?
   a. What are the **learners` conceptions** and learning **difficulties**?
   b. Which **methods** are used to identify learners` conceptions and learning difficulties?
   c. Which assessment instruments are empirically validated to assess conceptions?
2. Which **instructional methods** are implemented in schools and universities?
3. Which **quantum science topics** (defined by school and university curricula; previous reviews) are addressed in empirical research?

GENERAL:

Publication (Year): ____________

Institution: ______________________________

Sample:
- ☐ School students; Age/Grade:_________________
- ☐ University students; Age/Grade:_____________; Study program:_______________
- ☐ Further education; Professional backround:________________________

Type of instruction:
- ☐ Course (University)
- ☐ School
- ☐ Out-of-school LAB
- ☐ Further Education
- ☐ Others: ________________________

Mainly addressed question:
- ☐ 1a)
- ☐ 1b)
- ☐ 1c)
- ☐ 2
- ☐ 3

FIG. 7. Paper protocol page 1.

[1] https://qt.eu
[2] C. Foti, D. Anttila, S. Maniscalco, and M. L. Chiofalo, Quantum physics literacy aimed at K12 and the general public, Universe **7**, 86 (2021).
[3] R. De Wolf, The potential impact of quantum computers on society, Ethics Inf. Technol. **19**, 271 (2017).
[4] H. Stadermann, E. van den Berg, and M. Goedhart, Analysis of secondary school quantum physics curricula of 15 different countries: Different perspectives on a challenging topic, Phys. Rev. Phys. Educ. Res. **15**, 010130 (2019).
[5] E. K. Henriksen, B. Bungum, C. Angell, C. W. Tellefsen, T. Frågåt, and M. V. Bøe, Relativity, quantum physics and philosophy in the upper secondary curriculum: Challenges, opportunities and proposed approaches, Phys. Educ. **49**, 678 (2014).
[6] R. V. Olsen, Introducing quantum mechanics in the upper secondary school: A study in Norway, Int. J. Sci. Educ. **24**, 565 (2002).
[7] G. Pospiech, Teaching the EPR paradox at high school?, Phys. Educ. **34**, 311 (1999).
[8] G. Pospiech, Uncertainty and complementarity: The heart of quantum physics, Phys. Educ. **35**, 393 (2000).
[9] G. Pospiech, Quantum cryptography as an approach for teaching quantum physics, in *Teaching-Learning Contemporary Physics: From Research to Practice*, edited by B. Jarosievitz and C. Sükösd (Springer, Cham, 2021).
[10] M. Michelini, R. Ragazzon, L. Santi, and A. Stefanel, Proposal for quantum physics in secondary school, Phys. Educ. **35**, 406 (2000).
[11] P. Bitzenbauer and T. Zenger, Online course on quantum physics: Reading primary sources with secondary school students, Phys. Teach. **60**, 572 (2022).
[12] S. Aehle, P. Scheiger, and H. Cartarius, An approach to quantum physics teaching through analog experiments, Physics **4**, 1241 (2022).
[13] M. Malgieri and P. Onorato, Recent progress on the sum over paths approach in quantum mechanics education, Physics **4**, 1012 (2022).
[14] E. Y. Weissman, A. Merzel, N. Katz, and I. Galili, Phenomena and principles: Presenting quantum physics in a high school curriculum, Physics **4**, 1299 (2022).
[15] F. Hennig, K. Tóth, M. Förster, and P. Bitzenbauer, A new teaching-learning sequence to promote secondary school students' learning of quantum physics using Dirac notation, Phys. Educ. **59**, 045007 (2024).
[16] K. Tóth, M. Michelini, and P. Bitzenbauer, From light polarization to quantum physics: Supporting lower secondary school students' transition from gestalt to functional thinking, Eurasia J. Math. Sci. Technol. Educ. **20**, em2449 (2024).
[17] P. P. Angara, U. Stege, A. MacLean, H. A. Müller, and T. Markham, Teaching quantum computing to high-school-aged youth: A hands-on approach, IEEE Trans. Quantum Eng. **3**, 1 (2021).
[18] L. V. Rodriguez, J. T. van der Veen, A. Anjewierden, E. van den Berg, and T. de Jong, Designing inquiry-based learning environments for quantum physics education in secondary schools, Phys. Educ. **55**, 065026 (2020).
[19] K. Krijtenburg-Lewerissa, H. J. Pol, A. Brinkman, and W. Van Joolingen, Insights into teaching quantum mechanics in secondary and lower undergraduate education, Phys. Rev. Phys. Educ. Res. **13**, 010109 (2017).
[20] M. Ayene, J. Kriek, and B. Damtie, Wave-particle duality and uncertainty principle: Phenomenographic categories of description of tertiary physics students' depictions, Phys. Rev. Phys. Educ. Res. **7**, 020113 (2011).
[21] E. K. Henriksen, C. Angell, A. I. Vistnes, and B. Bungum, What is light? Students' reflections on the wave-particle duality of light and the nature of physics, Sci. Educ. **27**, 81 (2018).
[22] M. Nousiainen and I. T. Koponen, Pre-service teachers' declarative knowledge of wave-particle dualism of electrons and photons: Finding lexicons by using network analysis, Educ. Sci. **10**, 76 (2020).
[23] P. Bitzenbauer and J.-P. Meyn, Toward types of students' conceptions about photons: Results of an interview study, in *Physics Teacher Education: What Matters?* (Springer, New York, 2022), pp. 175–187.
[24] M. Ayene, J. Krick, B. Damitie, A. Ingerman, and B. Thacker, A holistic picture of physics student conceptions of energy quantization, the photon concept, and light quanta interference, , Int. J. Sci. Math. Educ. **17**, 1049 (2019).
[25] Ö. Özcan, Pre-service physics teachers' comprehension of wave function and operator concepts in quantum mechanics, Int. J. Phys. Sci. **6**, 2768 (2011).
[26] Ö. Özcan, Investigation of mental models of turkish pre-service physics students for the concept of "spin", Eurasian J. Educ. Res. **52**, 21 (2013).
[27] J. Petri and H. Niedderer, A learning pathway in high-school level quantum atomic physics, Int. J. Sci. Educ. **20**, 1075 (1998).
[28] K. S. Taber, Learning quanta: Barriers to stimulating transitions in student understanding of orbital ideas, Sci. Educ. **89**, 94 (2005).
[29] M. S. Ubben and P. Bitzenbauer, Two cognitive dimensions of students' mental models in science: Fidelity of gestalt and functional fidelity, Educ. Sci. **12**, 163 (2022).
[30] M. Ubben and P. Bitzenbauer, Exploring the relationship between students' conceptual understanding and model thinking in quantum optics, Front. Quantum Sci. Technol. **2**, 1207619 (2023).
[31] S. Faletic, P. Bitzenbauer, M. Bondani, M. Chiofalo, S. Goorney, K. Krijtenburg-Lewerissa, O. Mishina, R. Muller, G. Pospiech, I. Ercan *et al.*, Contributions from pilot projects in quantum technology education as support action to quantum flagship, arXiv:2303.07055.
[32] P. Bitzenbauer, Quantum physics education research over the last two decades: A bibliometric analysis, Educ. Sci. **11**, 699 (2021).
[33] https://qtedu.eu/
[34] https://cordis.europa.eu/project/id/101070193
[35] https://q12education.org/about
[36] A. Acín, I. Bloch, H. Buhrman, T. Calarco, C. Eichler, J. Eisert, D. Esteve, N. Gisin, S. J. Glaser, F. Jelezko *et al.*, The quantum technologies roadmap: A European community view, New J. Phys. **20**, 080201 (2018).

[37] R. Müller and S. Heusler, Quantentechnologien unterrichten? Schulische Zugänge mit den Wesenszügen der Quantenphysik und didak1sche Potenziale, Unterr. Phys. **2023**, 2 (2023).
[38] A. Merzel, P. Bitzenbauer, K. Krijtenburg-Lewerissa, K. Stadermann, E. Andreotti, D. Anttila, M. Bondani, M. L. M. Chiofalo, S. Faletič, R. Frans *et al.*, The core of secondary level quantum education: A multi-stakeholder perspective, Eur. Phys. J. Quantum Technol. **11**, 27 (2024).
[39] F. Greinert, R. Müller, P. Bitzenbauer, M. S. Ubben, and K.-A. Weber, Future quantum workforce: Competences, requirements, and forecasts, Phys. Rev. Phys. Educ. Res. **19**, 010137 (2023).
[40] A. R. Hayati, Z. L. Afriani, and A. Akbarjono, Teacher's teaching strategies in EFL class, Jadila **1**, 330 (2021).
[41] P. Bitzenbauer and J.-P. Meyn, A new teaching concept on quantum physics in secondary schools, Phys. Educ. **55**, 055031 (2020).
[42] K. Tóth, M. Michelini, and P. Bitzenbauer, Exploring the effect of a phenomenological teaching-learning sequence on lower secondary school students' views of light polarisation, Phys. Educ. **59**, 035009 (2024).
[43] M. Michelini and A. Stefanel, A path to build basic quantum mechanics ideas in the context of light polarization and learning outcomes of secondary students, J. Phys. Conf. Ser. **1929**, 012052 (2021).
[44] https://tinyurl.com/ye24923s
[45] D. D. Moher, A. Liberati, J. Tetzlaff, and D. Altmann, Preferred reportin items for systematic reviews and meta-analyses: The prisma statement, PLoS Med. **6**, e1000097 (2009).
[46] R. van de Schoot, J. de Bruin, and R. Schram *et al.*, An open source machine learning framework for efficient and transparent systematic reviews, Nat. Mach. Intell. **3**, 125 (2021).
[47] C. E. Hill, B. J. Thompson, and E. N. Williams, A guide to conducting consensual qualitative research, Couns. Psychol. Q. **25**, 517 (1997).
[48] F. Greinert and R. Müller, European competence framework for quantum technologies Zenodo, 10.5281/zenodo.6834598 (2024).
[49] M. Waitzmann, K.-A. Weber, S. Wessnigk, and R. Scholz, Key experiment and quantum reasoning, Physics **4**, 1202 (2022).
[50] M. S. Ubben, J. M. Veith, A. Merzel, and P. Bitzenbauer, Quantum science in a nutshell: Fostering students' functional understanding of models, Front. Educ. **8**, 1192708 (2023).
[51] P. Bitzenbauer, Effect of an introductory quantum physics course using experiments with heralded photons on pre-university students' conceptions about quantum physics, Phys. Rev. Phys. Educ. Res. **17**, 020103 (2021).
[52] P. Bitzenbauer, Practitioners' views on new teaching material for introducing quantum optics in secondary schools, Phys. Educ. **56**, 055008 (2021).
[53] Z. Bouchée, M. Thurlings, L. de Putter-Smits, and B. Pepin, Investigating teachers' and students' experiences of quantum physics lessons: Opportunities and challenges, Res. Sci. Technol. Educ. **41**, 777 (2021).
[54] H. K. E. Stadermann and M. J. Goedhart, Why and how teachers use nature of science in teaching quantum physics: Research on the use of an ecological teaching intervention in upper secondary schools, Phys. Rev. Phys. Educ. Res. **17**, 020132 (2021).
[55] K. Krijtenburg-Lewerissa, H. Pol, A. Brinkman, and W. von Joolingen, Prior knowledge of potential energy and the understanding of quantum mechanics, Phys. Educ. **57**, 025012 (2022).
[56] T. S. Moraga-Calderón, H. Buisman, and J. Cramer, The relevance of learning quantum physics from the perspective of the secondary school student: A case study, Eur. J. Sci. Math. Educ. **8**, 32 (2020).
[57] R. Sayer, A. Maries, and C. Singh, Quantum interactive learning tutorial on the double-slit experiment to improve student understanding of quantum mechanics, Phys. Rev. Phys. Educ. Res. **13**, 010123 (2017).
[58] A. Kohnle and G. Passante, Characterizing representational learning: A combined simulation and tutorial on perturbation theory, Phys. Rev. Phys. Educ. Res. **13**, 020131 (2017).
[59] P. Hu, Y. Li, and C. Singh, Challenges in addressing student difficulties with basics and change of basis for two-state quantum systems using a multiple-choice question sequence in online and in-person classes, Eur. J. Phys. **44**, 065703 (2023).
[60] C. D. Porter and A. F. Heckler, Effectiveness of guided group work in graduate level quantum mechanics, Phys. Rev. Phys. Educ. Res. **16**, 020127 (2020).
[61] E. Marshman and C. Singh, Investigating and improving student understanding of the expectation values of observables in quantum mechanics, Eur. J. Phys. **38**, 045701 (2017).
[62] E. Marshman and C. Singh, Investigating and improving student understanding of quantum mechanics in the context of single photon interference, Phys. Rev. Phys. Educ. Res. **13**, 010117 (2017).
[63] E. Marshman and C. Singh, Investigating and improving student understanding of the probability distributions for measuring physical observables in quantum mechanics, Eur. J. Phys. **38**, 025705 (2017).
[64] V. Borish and H. J. Lewandowski, Seeing quantum effects in experiments, Phys. Rev. Phys. Educ. Res. **19**, 020144 (2023).
[65] S. Lukishova, Fifteen years of quantum optics, quantum information, and nano-optics educational facility at the institute of optics, University of Rochester, Opt. Eng. **61** (2022).
[66] A. Mariesa, R. Sayer, and C. Singh, Can students apply the concept of which-path information learned in the context of Mach–Zehnder interferometer to the double-slit experiment?, Am. J. Phys. **88**, 542 (2020).
[67] C. Hughes, J. Isaacson, A. Perry, R. Sun, and J. Turner, Teaching quantum computing to high school students, Phys. Teach. **60**, 187 (2022).
[68] G. Karakok, Making connections among representations of eigenvector: What sort of a beast is it?, ZDM Math. Educ. **51**, 1141 (2019).
[69] T. Wan, P. J. Emigh, and P. S. Shaffer, Investigating how students relate inner products and quantum probabilities, Phys. Rev. Phys. Educ. Res. **15**, 010117 (2019).
[70] P. J. Emigh, G. Passante, and P. S. Shaffer, Developing and assessing tutorials for quantum mechanics: Time

dependence and measurements, Phys. Rev. Phys. Educ. Res. **14**, 020128 (2018).

[71] B. Schermerhorn, G. Corsiglia, H. Sadaghiani, G. Passante, and S. Pollock, From Cartesian coordinates to Hilbert space: Supporting student understanding of basis in quantum mechanics, Phys. Rev. Phys. Educ. Res. **18**, 010145 (2022).

[72] I. Testa, A. Colantonio, S. Galano, I. Marzoli, F. Trani, and U. Scotti di Uccio, Effects of instruction on students' overconfidence in introductory quantum mechanics, Phys. Rev. Phys. Educ. Res. **16**, 010143 (2020).

[73] I. Testa, G. Capasso, A. Colantonio, S. Galano, I. Marzoli, U. S. di Uccio, F. Trani, and A. Zappia, Development and validation of a university students' progression in learning quantum mechanics through exploratory factor analysis and Rasch analysis, Int. J. Sci. Educ. **41**, 388 (2018).

[74] S. Montagnani, A. Stefanel, M. L. M. Chiofalo, L. Santi, and M. Michelini, An experiential program on the foundations of quantum mechanics for final-year high-school students, Phys. Educ. **58**, 035003 (2023).

[75] U. S. di Uccio, A. Colantonio, S. Galano, I. Marzoli, F. Trani, and I. Testa, Development of a construct map to describe students' reasoning about introductory quantum mechanics, Phys. Rev. Phys. Educ. Res. **16**, 010144 (2020).

[76] S. Satanassi, E. Ercolessi, and O. Levrini, Designing and implementing materials on quantum computing for secondary school students: The case of teleportation, Phys. Rev. Phys. Educ. Res. **18**, 010122 (2022).

[77] A. T. Danielsson, S. Engström, P. Norström, and K. Andersson, The making of contemporary physicist: Figured worlds in the university quantum mechanics classroom, Res. Sci. Educ. **51**, 1141 (2021).

[78] S. Faletić, A double well on-line simulation and activities for active learning of introductory quantum mechanics, Eur. J. Phys. **41**, 045706 (2020).

[79] E. Palmgren, K. Tuominen, and I. Kontro, Self-efficacy and conceptual knowledge in quantum mechanics during teaching reforms and the Covid-19 pandemics, Phys. Rev. Phys. Educ. Res. **18**, 020122 (2022).

[80] M. J. Carreño, J. Sepúlveda, S. Tecpan, C. Hernández, and F. Herrera, An instrument-free demonstration of quantum key distribution for high-school students, Phys. Educ. **54**, 065006 (2019).

[81] B. Bungum and S. Selstø, What do quantum computing students need to know about quantum physics?, Eur. J. Phys. **43**, 055706 (2022).

[82] E. F. Combarro, S. Vallecorsa, L. J. RodríguezMuñiz, A. AguilarGonzález, J. Ranilla, and A. D. Meglio, A report on teaching a series of online lectures on quantum computing from CERN, J. Supercomput. **77**, 14405 (2021).

[83] P. Hu, Y. Li, and C. Singh, Challenges in addressing student difficulties with time-development of two-state quantum systems using a multiple-choice question sequence in virtual and in-person classes, Eur. J. Phys. **43**, 025704 (2022).

[84] P. Hu, Y. Li, and C. Singh, Challenges in addressing student difficulties with measurement uncertainty of two-state quantum systems using a multiple-choice question sequence in online and in-person classes, Eur. J. Phys. **44**, 015702 (2023).

[85] S. Z. Ahmend, C. A. Weidner, J. H. M. Jensen, J. F. Sherson, and H. J. Lewandowski, Student use of a quantum simulation and visualization tool, Eur. J. Phys. **43**, 065703 (2022).

[86] P. Nyirahabimana, E. Minani, M. Nduwingoma, and I. Kemeza, Prime indicators of current teaching methodologies and students' perceptions in quantum physics, Int. J. Eval. Res. Educ. **11**, 1134 (2022).

[87] D. A. Denisova, N. G. Levanova, I. V. Evgrafova, and A. S. Verkhovod, Formation of cognitive activity of technical university students using elements of blended learning in the study of quantum physics, Rev. Tempos Espaços Educ. **14**, e15296 (2021).

[88] I. Dökme and Z. K. Ünlü, The challenge of quantum physics problems with self-metacognitive questioning, Res. Sci. Educ. **51**, 783 (2019).

[89] I. Yusuf, S. W. Widyaningsih, and S. R. B. Sebayang, Implementation of e-learning based-STEM on quantum physics subject to student HOTS ability, J. Turk. Sci. Educ. **15**, 67 (2018).

[90] Abdurrahman, A. Saregar, and R. Umam, The effect of feedback as soft scaffolding on ongoing assessment toward the quantum physics concept mastery, J. Pendidikan IPA Indonesia **7**, 41 (2018).

[91] M. V. Bøe, E. K. Henriksen, and C. Angell, Actual versus implied physics students: How students from traditional physics classrooms related to an innovative approach to quantum physics, Sci. Educ. **102**, 649 (2018).

[92] I. V. Korsun, How e-learning demonstrates the formation of students' cognitive activity in the teaching of quantum physics, Inf. Technol. Learn. Tools **61**, 127 (2017).

[93] M. Malgieri, P. Onorato, and A. D. Ambrosis, Test on the effectiveness of the sum over paths approach in favoring the construction of an integrated knowledge of quantum physics in high school, Phys. Rev. Phys. Educ. Res. **13**, 010101 (2017).

[94] R. K. Choudhary, A. Foppoli, T. Kaur, D. G. Blair, M. Zadnik, and R. Meagher, Can a short intervention focused on gravitational waves and quantum physics improve students' understanding and attitude?, Phys. Educ. **53**, 065020 (2018).

[95] M. Bondani, M. Chiofalo, E. Ercolessi, C. Macchiavello, M. Malgieri, M. Michelini, O. Mishina, P. Onorato, F. Pallotta, and Satanassi, Introducing quantum technologies at secondary school level: Challenges and potential impact of an online extracurricular course, Physics **4**, 1150 (2022).

[96] E. Andreotti and R. Frans, Teaching quantum physics in secondary schools using the analogy with the physics of musical instruments, Phys. Educ. **58**, 015008 (2023).