Expert perspectives on the future of quantum physics education at the secondary level

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As quantum technologies increasingly impact society and the workforce, there is a growing need to integrate quantum physics (QP) education into all levels of the curriculum, including secondary education. However, despite increasing interest, there is little consensus on which topics should be covered and to what depth. This study addresses this issue by exploring experts' perspectives on the future of QP education at the secondary school level. Using an adapted Delphi method, we conducted three rounds of surveys with a diverse panel of quantum physics and physics education experts. The study aimed to identify the most appropriate QP concepts for inclusion in secondary school curricula and the instructional level at which they should be taught. The findings show strong expert support for including foundational QP topics, such as quantum interference, superposition, and quantum measurement, taught at a conceptual rather than a mathematical level. More advanced topics related to quantum technologies were widely deemed unsuitable for the secondary school. These results are consistent with existing national curricula and provide valuable insights into current perspectives on QP education, reinforcing the importance of core quantum physics concepts in secondary education. These insights lay the groundwork for further research into the future direction of quantum education and support the integration of quantum technologies into secondary school curricula.

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I. INTRODUCTION

Although quantum principles underpin many everyday technologies—from laser pointers to smartphones—public awareness of quantum physics (QP) and its modern application in quantum technology (QT) remains limited [1,2]. While emerging QT advancements, including quantum computing, quantum sensing, and quantum communication, already affect the labor market, the growing demand for people with various levels of quantum expertise is developing beyond academia [3–5]. This requires a transformation of QP education at all levels, from secondary schools to universities. Although the emphasis in secondary education is pivotal in arousing student interest in future QT careers and promoting societal understanding of quantum concepts [6–10], developments at this level have lagged behind the more advanced progress seen in higher education.

At the higher education level, numerous national initiatives are already spearheading transformative changes, for example in the United States, India, and Canada. [11]. At the international level, the European Quantum Technologies Education Coordination and Support Action (QTEdu CSA) [12] brought together partners from 14 countries to coordinate efforts between academia and industry. The renewal of the quantum curricula is reflected in recent developments, such as the pan-European Open Master (QTOM) [13] and the European Competence Framework for Quantum Technologies [14], which provide a regularly updated, comprehensive mapping of competences and skills in quantum technologies. Meanwhile, projects such as Quantum Technology Education for Everyone [15] emphasize the broader societal need for quantum literacy.

In contrast, in secondary education, the introduction of QP concepts remains a topic of debate among educators, researchers, and curriculum developers. A growing body of physics education research shows that QP education can engage students with cutting-edge science [16–18], deepen their scientific literacy [19,20], and attract a more diverse student body to science, technology, engineering, and mathematics (STEM) fields [21–23]. However, the lack of consensus on what QP topics to include in secondary school curricula, how to teach them, and at what level of abstraction has resulted in a patchwork of fragmented implementations across different countries and educational systems [8,24–26].

To address this lack of consensus and inform future curriculum development, the QTEdu CSA community initiated the "QCI pilot": a collaborative effort to develop the Quantum Concept Inventory [27]. This project has two main objectives: to develop an assessment tool for evaluating secondary school students' understanding of QP and QT key concepts and to explore expert perspectives on the future QP curriculum. In this article, we focus on the latter, by exploring the perspectives of physics education and QP experts on an appropriate and desired secondary school QP curriculum and instruction. We aim to obtain a comprehensive and realistic picture of a potential future QP curriculum in secondary schools by incorporating input from QP experts, physics education researchers, and practicing teachers. This study, therefore, explores the possibilities and challenges of reforming QP education in secondary schools, which could contribute to a broader public understanding, including application-oriented QT and new approaches at several educational levels. In light of the above, we pose the following research questions (RQs):

1 RQ1: What topics and concepts should be included in a secondary school QP curriculum, according to physics education and QP experts?
2 RQ2: What levels of instruction for the identified topics are appropriate for secondary school students, as viewed by physics education and QP experts?

II. THEORETICAL CONSIDERATIONS

A. The European Competence Framework for Quantum Technologies

The European Competence Framework for Quantum Technologies (CFQT) is the "reference framework for planning, mapping and comparing QT-related educational activities, personal qualification and job requirements" [5,14,28] developed within the Quantum Flagship. It offers a structured collection of topics and concepts relevant to QT, with a focus on competences relevant to the emerging quantum industry, including recommendations for upskilling efforts and degree programs.

Although the QCI being developed is intended to address the needs in secondary education by outlining relevant content based on input from physics teachers, education researchers, and quantum experts, the domains defined in the CFQT [29,30] provide a useful framework for structuring this content. The CFQT distinguishes three relevant domains for secondary education: (i) domain 1—*Concepts of QP*, (ii) domain 2—*Physical Foundations for Quantum Technologies*, and (iii) domains 3–6 on quantum technologies, including enabling technologies, hardware, and the three main QT pillars computing, sensing, and communication.

B. Levels of understanding

The concepts of QP, as identified by the CFQT, are numerous. Not all can be covered in a secondary school course, nor does it make sense to cover all of them. Existing approaches to QP education differ not only in terms of the concepts they emphasize but also in the depth of understanding they aim to achieve, including the extent to which mathematical formalism is used. It is therefore important to understand on what level a specific concept should be learned by the students. Based on existing approaches and considerations from the quantum education community [31,32], we defined four levels:

- Mathematical—students are able to apply and/or explain the concept using mathematical calculations.

- Conceptual—students are able to apply and/or explain the concept using nonmathematical representations.
- Awareness—students are aware of the phenomenon or concept.
- Not needed—students do not need to learn this.

The proposed levels correspond to Vermunt's learning patterns [33]:

The mathematical level aligns with application-directed learning. Students at this level can apply QP concepts through calculations. This level does not necessarily require expert-level formalism. Alternative quantitative notations —such as those discussed in Refs. [34,35]—can be used. For example, students can calculate the probability that a vertically polarized photon passes through a series of polarizers without using Dirac notation.

The conceptual level aligns with meaning-directed learning. At this level, students can construct knowledge and see relations between different concepts. While mathematics can be part of this level, it is not required. Nonmathematical representations, as shown in Ref. [31], can be highly effective.

The awareness level aligns with reproduction-directed learning. While rote memorization is generally discouraged, a foundational level of awareness is necessary for some complex or specialized QP concepts (e.g., tunneling). Students should be aware of the existence and basic implications of such concepts, even if a deeper understanding is not feasible [9]. For example, a general overview of various quantum technologies, their importance, and potential impact is valuable, even without detailed technical explanations.

The not needed level was created explicitly to exclude topics that, in the view of instructors, students do not need to know.

The appropriate level for each concept depends on the specific learning goals, teaching methods, and overall approach. We anticipate variations in level assignments among different experts. Analyzing the distribution of suggested levels across various QP concepts will help identify areas of consensus, which can inform the development of general educational resources, such as textbooks and concept inventories.

III. METHODOLOGICAL CONSIDERATIONS

A. Delphi study

Our study followed an adapted Delphi approach.The Delphi method is a common method in physics education research to determine estimates and predictions of unclear needs and requirements [36–40]. For example, the Delphi method was also used in another QTEdu pilot project on key quantum concepts for QT outreach [15].

In general, the Delphi method is a technique for gaining expert consensus for decision making, including applications in curriculum development [41]. In a typical Delphi study, the same group of experts answers at least two questionnaires, where the latter one is based on the responses to the previous one. In this way, a larger group of experts can be surveyed than would be possible in a group discussion, and the answers are given independently and anonymously, thus reducing group effects. The method is not very strictly defined, allowing for a variety of objectives. However, the main characteristics include (i) feedback of views, (ii) assessment of views, (iii) opportunity to revise views or narrow them down, and (iv) anonymity [42]. The whole process is guided by researchers who prepare the questionnaires and evaluate the responses.

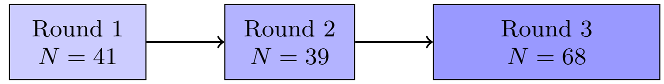


FIG. 1. Three rounds in our Delphi study with the number of participants N. Note that participants in each round do not necessarily overlap.

In this study, the research team consisted of the authors of this article plus further members of the former QCI project [27], a group of 26 researchers from 9 countries with expertise in physics and physics education research, several with secondary teaching experience. The first and last author designed the Delphi rounds, the team gave feedback on the questionnaires, validated the categories and items, and analyzed the responses.

This study consisted of three rounds, i.e., three questionnaires, visualized in Fig. 1. See Supplemental Material [43] for the complete questionnaires. Each questionnaire was designed and discussed in the monitoring panel, leading to decisions about which views from the previous round would be fed back and in what way. This was done in order to gain further assessments and to allow for anonymous revision of views from the previous round.

Each round of the survey had an individual focus. The first round was used for a qualitative elaboration of the experts' views and mainly included open-ended questions. Figures from the CFQT were provided to stimulate ideas and highlight possible topics. In the second round, a long list of topics was presented for selection by experts. Finally, the selected topics from round 2 had to be assessed to determine whether they are relevant for a secondary school curriculum and how they should be addressed, i.e., the desired level of instruction (mathematical, conceptual, or on awareness level). On this basis, we answer our research questions.

B. Expert panel

We recruited study participants through personal networking and professional contacts—sometimes translating the surveys into local languages—as well as more broadly via distribution through the QTEdu newsletter, which reaches all scholars subscribed to the QTEdu CSA mailing list. The respondents constituted the experts' panel. In contrast to traditional Delphi studies, we did not maintain a fixed panel of experts. Instead, we opened the subsequent questionnaires to participants who had not answered the previous questionnaire. With this approach, we gained a broader picture of opinions, especially in the final round of evaluations. In round 3, most of the participants indicated that they had not participated in previous rounds. Since our study did not aim for consensus in a preselected group of experts, but for a variety of perspectives and views, this change in the expert panel is appropriate for our approach.

Previous studies on QP secondary school curricula have typically focused on physics researchers who teach physics at the university level, as they are considered experts in the subject matter of QP [26,38,39,44–46]. However, some of these studies have found low variability in experts' opinions, potentially due to a narrow focus on what is feasible to teach in secondary school classrooms. To achieve a broader and more inclusive scope of opinions regarding the topics and conceptual levels that should be included in a secondary school QP curriculum, our expert panel was formed by engaging participants with diverse perspectives bringing extensive pedagogical content knowledge based on their experience and research in teaching QP. Some participants have multiple areas of expertise (e.g., both physicists and physics education researchers), offering them a broad perspective on teaching QP in secondary school. Details on the participants for each round are provided in the following sections.

IV. STUDY IN ROUND 1

A. Participants and methods

In the first round of the adapted Delphi study, we aimed to gather insights from the expert panel to identify possible topics of interest for QP education at the secondary level. A total of 41 participants from 12 different countries took part in the survey. The participants brought in expertise from various fields: 22 had a background in physics education research, 22 had a background in teaching physics at the university level, and 13 were teachers at secondary schools. The majority of respondents came from Italy (12) and Germany (9), but respondents also came from Austria (1), Belgium (2), Croatia (3), the Czech Republic (1), Denmark (2), Hungary (2), Israel (4), the Netherlands (3), Poland (1), and Slovenia (1). To guide the process, we presented the experts with three domains of the CFQT, which the monitoring panel identified as particularly relevant for secondary school students: *Concepts of QP*, *Physical Foundations of Quantum Technologies*, and *Quantum Technologies 2.0*. After presenting these domains, the experts were asked to reply to the following two tasks for each domain:

TABLE I. Expert-identified ($N = 41$) categories for secondary quantum physics education, categorized by three CFQT domains (round 1).

Domain	Category	No. of mentions
Concepts of QP	Superposition and interference	28
	Quantum measurement and quantum properties	26
	Entanglement and nonlocality	16
	Heisenberg principle and complementarity	13
	Quantization	13
	Mathematical formalism	11
	Wave-particle duality	9
	Qubits	8
	Schrödinger equation	8
	(Quantum) Optics	5
	Miscellaneous	4
	Mathematical foundations	3
Physical Foundations of Quantum Technologies	Solid state physics	24
	Atoms and atomic physics	21
	Quantum optics	18
	Material science and nanostructures	6
	Miscellaneous	2
Quantum Technologies 2.0	Quantum computing	34
	Quantum sensors and metrology	25
	Quantum communication	18
	Enabling technologies	14
	Hardware for quantum computers and sensors	9
	Miscellaneous	7

1. From your point of view, which concepts from this domain should secondary school students learn?
2. Illustrate these concepts by providing an example or a specific context.

B. Results

The concepts and illustrations mentioned by the expert panel were categorized by the authors, using the CFQT. As shown in Table I, 12 categories were mentioned for concepts of QP, five for Physical Foundations of Quantum Technologies, and six for Quantum Technologies 2.0. For *concepts of QP*, two categories were often mentioned: (1) superposition and interference, which include the topics quantum states (e.g., qubits and spin states) and interference experiments like the double-slit experiment and two-photon interference; (2) quantum measurement and quantum properties including, for example, the topics decoherence, the statistical nature of QP, and measurement dynamics. For *Physical Foundations of Quantum Technologies*, the highest scoring categories were as follows: (1) solid state physics, which includes the topics material properties, band structures, and superconductivity, and (2) atoms and atomic physics, covering the topics atomic models, spectroscopy, and semiconductor basics. For *Quantum Technologies 2.0*, the highest scoring categories were as follows: (1) quantum computing, focusing on topics such as qubit manipulation, quantum gates, and programming; (2) quantum sensors and metrology, which includes the topics atomic clocks and applications of quantum sensing and imaging. A detailed analysis of the perspectives of different stakeholders on the concepts and illustrations from round 1 was previously reported by Merzel *et al.* [8].

The topics and the experts illustrations collected in round 1 were used to create the survey of round 2 using the QCFT, netting 246 distinct topics.

V. STUDY IN ROUND 2

A. Participants and methods

In round 2, a total of $N = 39$ participants took part in the survey. They reported of being from several areas of expertise, multiple statements being allowed in the survey. Among the participants, most (17) had a background in research education, several were physicists working on QT (12), some were physics educators at a university (10), and some physics teachers at secondary schools (10). A small number were physicists in other fields (9) or other professions (consultant, general education researcher, self-employed, trainer). All participants were acquired from a range of countries, most from Germany (12) or Italy (12), but also from Belgium (3), Netherlands (3), Austria (2), France (2), Israel (2), Croatia (1), Finland (1), and Uruguay (1). About half of them (18) had participated in round 1.

All participants received an online survey of the 246 topics from round 1, where they had to assess whether the topics were relevant for inclusion in school curricula at mathematical, conceptual, or awareness levels, as described in Sec. II B. The scales used to measure the expert rating were ordinal (1—mathematical, 2—conceptual, 3—awareness, and 4—not at all). In this step, it was possible to select multiple levels (in case of 1–3) or option 4. The dataset was then evaluated with retrospect to agreement for each topic, meaning that all categories were extracted that had a 75% agreement to be included in any of the three levels.

B. Results

In the end, a total of 114 of 246 topics (the expert panel added two topics) were agreed to be important for curricula by more than 75% of respondents. Of those, 69 (about 74% of the given categories) belonged to the domain *concepts of QP*, 26 to the domain *Physical Foundations for QT* (about 29%), and 17 to the domain *Quantum Technologies 2.0* (about 35%). Because several of the 114 categories were very similar, they were merged into a final set of 105 distinct topics, which are listed in Tables III–V (as detailed in the Appendix).

C. Interim conclusion

From the results, several interim conclusions can be drawn. First, the thematic field that most people still agreed were somehow important to be integrated into school curricula was that of Basic Quantum Concepts. Only about a quarter of the topics from the Physical Foundations and about a third of the topics from Quantum Technologies were agreed upon to be of importance (albeit using a strict 75% inclusion agreement rule). As such, it stands to question which of the new topics indeed have a stable agreement and if there is a consensus on them. Therefore, a third round was prepared to better evaluate this aspect with a larger sample size and more focus on consensus formation.

VI. STUDY IN ROUND 3

A. Participants and methods

In round 3, a total of $N = 68$ participants contributed to the survey. They reported being from several areas of expertise, multiple statements being allowed in the survey. Of the participants, most (33) had a background in education research, some were physicists working on Quantum Technologies (16), a small number were physicists in other fields (9), and quite a few were physics teachers at high schools (29). This high percentage of teachers brings strong external validity to our findings, as they offer grounded perspectives on what is realistically teachable in the classroom, based both on their students' needs and their own confidence with the material. All participants were acquired from a range of countries, most coming from the Netherlands (23), but also Germany (11), Israel (7), Italy (7), Spain (4), Croatia (2), Denmark (2), Finland (2), Hungary (2). Single participants also came from Romania, Portugal, Belgium, Slovenia, France, Pakistan, and the United States. Most of them (51) did not participate in a previous round of this study.

All participants received an online survey, where they had to assess if they estimated the topics extracted from round 2 as relevant for inclusion into school curricula at mathematical, conceptual, or awareness levels. The scales used to measure the expert rating were the same as in round 2 (1—mathematical, 2—conceptual, 3—awareness, and 4—not at all). In this round, however, a measurement of consensus among the participants was also the aim, and therefore a statistical evaluation was conducted. This method allows the degree of consensus among respondents to be expressed statistically, taking into account both the distribution of ratings and their distance from the group's mean response, giving a more differentiated estimate. As the scales used to measure the expert rating were Likert-like, an entropy-based consensus measure for these types of scales was used, as proposed by Ref. [47]:

$$\mathrm{Cns}(X) = 1 + \sum_{i=1}^{n} p_i \log_2\left(1 - \frac{|X_i - \mu_X|}{d_X}\right), \qquad (1)$$

where p_i is the probability (relative frequency) of outcome X_i (which ranges from 1 to 4). Furthermore, μ_X is the mean of X and $d_X = X_{\mathrm{max}} - X_{\mathrm{min}}$ be the width of X. Finally, $|X_i - \mu_X|$ is the absolute deviation of X from the mean. Using this equation, a consensus of 0 is defined as total disagreement and 1 as total agreement [48]. For the purpose of the present study, two inclusion criteria were applied to evaluate which topics should be included at what level with consensus. A topic was included only if it satisfied both criteria:

1. We decided that a sufficient consensus is that the value of $\mathrm{Cns}(X) \geq 0.75$, since it suggests high consensus.
2. A category was included if at most 25% of experts deemed it as ”not needed” (i.e., answer option 4 in the rating scale), the same criterion as in round 2.

B. Results

Taking the ratings of all participants across all subjects into account, we derived the topics presented in Table II by applying our two established criteria. These final topics were both agreed upon by the expert panel to hold some level of importance for curricula and achieved a consensus level of above 0.75. In the domain of *concepts of QP*, ten categories met both criteria. Table III in Appendix displays all relevant values for the topics that satisfied both criteria.

In the domain of *Physical Foundations*, no topics met both criteria. Table IV in the Appendix provides the relevant values for the topics that satisfied only one of the criteria.

Similarly, in the domain of *Quantum Technologies*, no topics met both criteria either. Table V in the Appendix presents the relevant values for topics that fulfilled only one of the criteria. However, it should be noted that, in both domains, there was no consensus among the expert panel to exclude all corresponding topics.

The included topics are mainly advised to be taught conceptually, with only Schrödinger's cat and photons falling below a 50% inclusion (the latter barely). Only for the double-slit, quantum measurements, the statistical nature of measurements, probability amplitudes, and superpositions of quantum states more than 25% of the experts recommend a mathematical inclusion. The collapse of the wave function and Schrödinger's cat were also the only topics deemed important by more than 25% of experts on the awareness level.

C. Interim conclusion

From the gathered data, only the topics associated with the domain *quantum concepts* exhibited both sufficiently high consensus among experts and a recommendation to be included by more than 75% of the experts surveyed. In contrast, for both of the other domains, no single topic was recommended for inclusion in the curricula by a sufficient number of experts, nor was there a sufficiently high level of consensus supporting such recommendations. On the

TABLE II. Topics in the domain *concepts of QP* matching both inclusion criteria in study round 3 (for details, see body text). For each category *X*, the consensus measure Cns(X) is shown. Also, the advised level (mathematical = 1, conceptual = 2, and awareness = 3) of inclusion is also given. Note that the percentages may not sum to 100%, because experts could choose multiple levels or opt out.

Topic	Cns(X)	Mathematical (%)	Conceptual (%)	Awareness (%)	Not needed (%)
Collapse of the wave function	0.80	15	59	29	6
Probability amplitudes	0.76	34	56	16	4
Statistical nature of measurement	0.80	26	56	15	0
Superposition of quantum states	0.79	34	51	21	4
Wave interference	0.82	13	53	12	4
Quantum measurement	0.81	37	53	28	7
Double slit	0.76	37	51	15	1
Schrödingers cat	0.81	6	43	37	12
Atomic models	0.83	9	57	25	3
Photons	0.75	24	49	19	0

contrary, the only topics in these domains that reached a notable level of consensus were those for which there was agreement to exclude them from the curricula. Additionally, most participants agreed that conceptual understanding of the topics at hand is the most desired result from integrating them into curricula. In the end, only probability amplitudes, quantum measurements, the statistical nature of measurements, superposition of states, and the double-slit experiment are recommended (taking the rather strict criterion of agreement for the level being 75% or above as indicators) to be included at a mathematical level, meaning only the basic concepts are recommended to be introduced mathematically.

VII. DISCUSSION

A. Comparison with international curriculum documents of secondary school QP

In this study, we have investigated what experts and practitioners in physics education view as desirable topics for a secondary school quantum curriculum. To contextualize our findings, it is worth examining how these expert recommendations relate to actual curricula. For this purpose, we compare the results of our current study with the findings of the curriculum document analysis conducted by Stadermann *et al.* [24], which examined 23 secondary education curricula originating from 15 countries. Their study provides a valuable benchmark for assessing the relevance, novelty, and alignment to school reality of our expert recommendations.

In their curriculum analysis, the authors identified 17 quantum-related content items mentioned in the curriculum documents. Seven of these items appeared in the majority of the examined curricula:

- Discrete energy levels (line spectra).
- Interactions between light and matter.
- Wave-particle duality or complementarity.
- Matter waves, quantitative (de Broglie).
- Technical applications.
- Heisenberg's uncertainty principle.
- Probabilistic or statistical predictions.

The authors referred to these items as the international "core curriculum" for QP at the secondary school level.

The topics matching both inclusion criteria in the third round of our study do not identically match the names of the content items in the core curriculum [24]. However, our findings show several notable alignments with the topics currently present in the curricula. For example, the topic "discrete energy levels and line spectra" in the core curriculum relates to the category "atomic models" in our expert recommendations. Similarly, the item "wave-particle duality or complementarity" (curricula) is often explained through "photons" (experts) in the context of the "double-slit experiment" (experts), which demonstrates behavior comparable to "wave interference" (experts) [49–52]. Additionally, "probabilistic or statistical predictions" (curricula) are related to the expert-recommended concepts of "probability amplitudes," "collapse of the wave function," "statistical nature of measurement," and "quantum measurement" [53].

A comparison between Table II and the core curriculum shows consensus between our expert recommendations for desired QP curricula and the core topics frequently found in secondary school curricula. Notably, Schrödinger's cat is the only topic that does not appear in most of the curricula analyzed in 2019. In that analysis, Schrödinger's cat would likely fall under the common extension to the core curriculum labeled as "philosophical consequences." While the depth of mathematical content was not explicitly analyzed, examples from the curriculum documents, provided as Supplementary Material [43], suggest that—consistent with our experts' recommendations—secondary school students are expected to develop a conceptual understanding of QP [24].

To summarize the comparison, we can conclude that, with the exception of Schrödinger's cat, the quantum concepts recommended by our experts (see Table II) all happen to fall within the existing QP curricula implemented in many countries.

B. Comparison to the competence framework

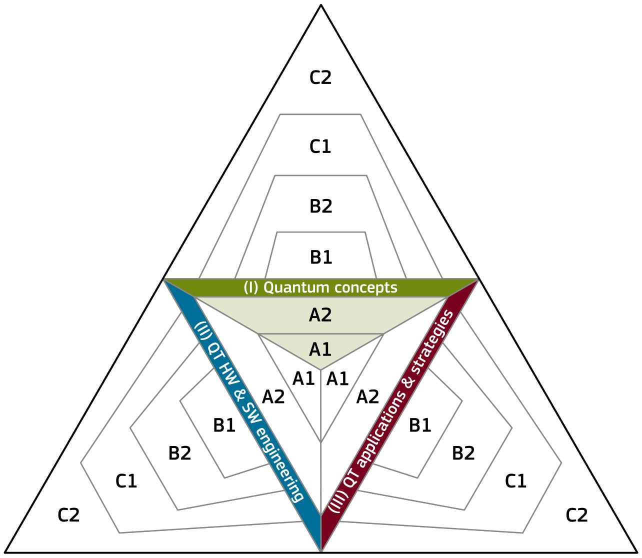
In the refined 2024 version, the CFQT distinguishes three domains—(1) *Quantum Concepts*, (2) *QT Hardware & Software Engineering*, and (3) *QT Applications & Strategies*—and also specifies proficiency levels. Level A represents beginners, level B corresponds to intermediate proficiency comparable to the bachelor level, and level C denotes advanced proficiency, reflecting greater experience at the master's or Ph.D. level [14].

The results of round 3 show consensus only for topics that belong to a specific part of domain 1, namely subdomain 1.1 *Basic Quantum Concepts*. These topics are not specific to QT but can be introduced in the context of QT and prepare for further education that may be specific to QT.

The Delphi study results further show consensus that the topics should be addressed at the conceptual level. This level corresponds to a position between the proficiency levels A1 (awareness) and A2 (literacy) of the CFQT. Level A1 focuses on general awareness, the ability to reproduce basic quantum concepts and terminology, while level A2 focuses on describing and relating quantum concepts, including elements of mathematical formalism. Figure 2 visualizes this proficiency levels in the proficiency triangle with the description of the proficiency level covered, specifying knowledge (K) and skills (S).

The monitoring panel, responsible for designing the study and guiding its development, held a meeting to discuss the results and their implications.

The main result of this study is the list of quantum concepts to teach to secondary school students. The panel



A2 Literacy: Describe fundamental quantum concepts with appropriate terminology, e.g., in conversations

K: Knowledge of fundamental quantum concepts with underlying mathematical formalism.

S: Ability to explain basic quantum concepts and describe them using basic mathematics and appropriate terminology, e.g., to communicate with quantum experts and novices.

A1 Awareness: Reproduce basic quantum concepts & terminology

K: Basic idea (phenomena-oriented) of elementary quantum concepts with the corresponding terminology.

S: Ability to identify basic quantum concepts and assign the appropriate term, e.g., to follow (media) conversations about quantum.

FIG. 2. Proficiency triangle coverage for A2 literacy in quantum concepts with proficiency level descriptions for A1 and A2, extracted from the CFQT [14].

considers this recommendation a necessary step toward fundamentally incorporating QP in secondary school teaching and curricula in different countries. It is also an important starting point for teachers to plan QP teaching within the limits of current curricula. Instead of waiting for curricula to change, the panel encourages teachers already now to build QP teaching within the given time limits by following the list of quantum concepts provided in this study. They propose a modular incorporation of quantum concepts: within shorter teaching hours to achieve an awareness level, with more time available (e.g., 6 h) to carry out conceptual teaching, and even deepen students' understanding on the mathematical level if teaching hours allow it (e.g., 20 h). Some inspiration on how to teach quantum concepts can be drawn from already existing secondary school teaching practices: for example, the use of quantum games and interactive tools [54] or teaching quantum concepts by linking them to nature of science [49].

However, the panel emphasizes that the results of this study should not be seen as the limitation to teach only basic quantum concepts to secondary school students in the future. Rather, these results reflect the current state of QP education development. Since didactic approaches on how to include quantum technologies in secondary school teaching are still largely unexplored, experts tend to choose familiar approaches to QP teaching. Therefore, the panel considers the results of this study as a call to bring to light why and how quantum technologies should be a part of secondary school curricula. Accordingly, the incorporation of mathematical QP in secondary school teaching should be further explored. To summarize, the results of this study should be applied to QP teaching in secondary schools within the current curricula, and for the future, we set the direction toward curricula incorporating quantum technologies and giving enough time for mathematical-level teaching.

C. Limitations

While our study provides valuable information on the development of a QP curriculum for secondary education, several limitations should be acknowledged:

- *Deviation from the traditional Delphi method*: Our study deviated from the traditional Delphi method in important ways. Although conventional Delphi studies usually maintain a fixed panel of experts throughout all rounds to promote consensus, we allowed new participants to join in later rounds and several experts left between rounds. This approach broadened the range of perspectives but may have weakened the consistency of feedback.
- *Control of participants and online survey format*: The online survey format limited our ability to control participants, in particular control over multiple participation. Although we aimed to recruit individuals with expertise in QP, physics education, and student learning, we could not ensure balanced representation or consistent participation in each round. The voluntary nature of our survey may have selectively attracted respondents with a specific interest in quantum education, potentially introducing further bias, which may limit the generalizability of our results.
- *Rapid evolution of the QT context*: QT is evolving rapidly, which may influence the perceived relevance of certain topics over time. Concepts perceived as less important at the time of this study may become central in the near future and vice versa. These temporal factors underscore the importance of periodically revisiting curriculum recommendations to maintain alignment with emerging technological and pedagogical developments. As our findings capture expert opinion at a particular point in time, follow-up research may be required to confirm their continuing relevance.
- *Consensus criteria and interpretation*: We use both percentage-based thresholds and entropy-based metrics to assess consensus on inclusion of quantum topics in secondary school curricula. However, the notion of "curriculum inclusion" can vary considerably depending on the experts' national education

systems, curriculum guidelines, and teaching experience. In addition, differences in the stringency of curriculum enforcement between countries may shape experts' priorities, further influencing the results.

- *Limitations on quality and stakeholder representation*: Although the first study round allowed for open-format responses, subsequent rounds included more quantitative assessments, potentially limiting the richness of qualitative insights. Although the expert panel included educators who understand student learning, secondary students themselves were not directly involved, despite being the primary beneficiaries of any future curriculum. Furthermore, since members of the monitoring panel were involved in the design of the questionnaires and data analysis, background may have unintentionally biased the direction and focus of the study.
- *Language and cultural considerations*: Given the international scope of this research, language barriers and cultural nuances in educational practices may have affected participants' interpretation of questions or their responses. These differences could limit the consistency and comparability of the data with future investigations in the same direction.

VIII. CONCLUSION

In conclusion, this study provides critical insights into the integration of QP into secondary school curricula. Drawing on the perspectives of both physics education and QP experts, it identifies which topics are most suitable for inclusion at this level and examines the appropriate depth and instructional level for each topic.

Using an adapted Delphi study design in three rounds, we gathered feedback from 41 experts in round 1, 39 in round 2, and 68 in round 3. Participants from various countries and backgrounds in QP and physics education provided insight into which QP topics they believe are essential for secondary school students. The study revealed that experts strongly supported the inclusion of foundational topics in the domain of *concepts of QP*, such as wave interference, superposition, quantum states, probability amplitudes, quantum measurement, and atomic models. In contrast, topics related to the Physical Foundations of Quantum Technologies were less favored, with many experts suggesting their exclusion or deeming them less relevant for secondary education. Regarding instructional levels, the study revealed a preference for a conceptual approach to teaching QP over a mathematical one. Experts emphasized that secondary school curricula should prioritize developing a conceptual understanding and awareness of QP, rather than focusing on a mathematical level.

A comparison of the outcomes of this study with Stadermann *et al.* [24], highlights a strong alignment between expert-endorsed topics and those already present in many national curricula. Core topics such as discrete energy levels, wave-particle duality, interactions between light and matter, and Heisenberg's uncertainty principle appear consistently in curricula. The study also aligns with the CFQT [14], showing that the recommended topics fit within the domain *concepts of QP*.

A key limitation of the study is that expert recommendations largely reflect the current state of QP education and their recommendations for topics to include are based on what they know about QP in education at this moment in time. As quantum education evolves, recommendations may change accordingly. This study therefore gives an overview of relevant topics to focus on in quantum education research but does not aim to limit them.

Given the growing impact of QT on society, a forward-looking approach is needed to prepare students for future technological and scientific developments in QT. Proactively integrating QT into the curriculum through a modular approach—introducing QP at different levels depending on the curriculum—could allow small-scale adoption of QT in secondary education. Further research into areas where consensus has not been reached—such as Dirac notation, the Schrödinger equation, quantum key distribution, and quantum teleportation—would be particularly valuable to guide these developments. Eventually, this will contribute to addressing the possibilities and challenges of reforming QP education in secondary schools, promoting broader public understanding of QT.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available because of legal restrictions preventing unrestricted public distribution. The data are available from the authors upon reasonable request.

APPENDIX

TABLE III. Round 3: Topics of quantum concepts for secondary school in sequence as given to the experts in the field of Quantum Concepts. In bold font, there are topics matching both inclusion criteria, in italic font, those that match one (consensus regarding levels), and in normal font, those that do not meet any.

Topic	Cns(X)	Include (%)
Eigenvectors, eigenvalues	0.46	46
Inner products	0.40	50
Matrix algebra	0.49	41
Dirac notation	0.47	44
Operators	0.58	47
Collapse of the wave function	**0.80**	**81**
Probability amplitudes	**0.76**	**78**
Statistical nature of measurement	**0.80**	**81**
Polarized light	*0.82*	69
Spin-1/2 particle (two level system)	*0.77*	74
Nondeterminism	*0.77*	68
Decoherence and coupling to the environment	*0.80*	57
Electron spin state (Stern-Gerlach)	*0.79*	63
Superposition of quantum states	**0.79**	**78**
Difference between classical and quantum superposition	*0.80*	74
Quantum eraser	*0.76*	37
Delayed-choice-experiments	*0.79*	37
Wave interference	**0.82**	**75**
Interference of very large molecules	*0.83*	47
Quantum versus classical probability	*0.82*	74
Quantum measurement	**0.81**	**75**
Wave packets	*0.82*	60
Interference of classical light	*0.81*	71
EPR paradox	*0.75*	51
Quantum teleportation	*0.87*	46
Historical development of QP	*0.84*	68
Entanglement	*0.75*	71
Quantum correlations	*0.72*	50
Hidden variables	*0.84*	35
Double slit	**0.76**	**78**
Mach-Zehnder interferometer	*0.72*	59
Photoelectric effect	*0.76*	69
Schrödingers cat	**0.81**	**75**
Matter wave interference	*0.80*	65
Interference with single quantum objects	*0.78*	62
Particle in a box (1D infinite potential well)	*0.81*	46
Measuring h	*0.81*	44
Colour	*0.72*	46
Quantization of energy	*0.76*	71
Spin	*0.81*	71
Electrons	*0.75*	72
Franck-Hertz experiment	*0,76*	40
Atomic models	**0.83**	**76**
Quantization of the radiation field	*0.84*	47
Stern-Gerlach experiment	*0.81*	53
Bound states	*0.74*	46
Double well	*0.81*	24
Quantum harmonic oscillator	*0.84*	28
Quantum tunnelling	*0.87*	60

(Table continued)

TABLE III. *(Continued)*

Topic	Cns(X)	Include (%)
Atomic orbitals	*0.87*	62
Photon statistics (differences classical vs quantum light)	*0.78*	40
Spontaneous and stimulated emission	*0.83*	54
Photons	**0.75**	**75**
Qubits	*0.77*	63
Bloch sphere	*0.80*	29
Complementarity	*0.76*	40
Uncertainty principle	*0.76*	66
Uncertainty of energy and time	*0.78*	57
Complementarity: double/single slit and Stern-Gerlach experiment	*0. 83*	44
The role of modeling in (quantum) physics	*0.75*	57
Paradigm change caused by QP	*0.80*	63
Many-world interpretation	*0.86*	37

TABLE IV. Round 3: Topics of quantum concepts for secondary school in sequence as given to the experts in the field of Physical Foundations. For none of these, no consensus was reached and all were chosen to be included by less than 75%.

Topic	Cns(X)	Include (%)
Excitation and emission in the Bohr model	0.67	53
Quantum numbers (n. l. m. s)	0.65	51
Hydrogen atom	0.71	60
Spectra of light/stars	0.73	59
Spectroscopy	0.68	56
Ions	0.65	51
Laser	0.74	65
Conductivity	0.66	51
Semiconductors	0.70	56
Photovoltaic solar cells	0.70	56
CCD camera	0.66	43
Electronic properties of materials	0.66	53
LED	0.72	56
NMR: magnetic fields	0.66	46
Band structure	0.64	46
Superconductivity (e.g., Meißner-Ochsenfeld-effect)	0.62	28
Atomic force microscope	0.67	32
Quantum dots	0.64	28
2D electron gas	0.65	16
Nanostructures	0.65	26
Nanowires	0.65	15
Carbon based nanostructures	0.65	19
Topological effects	0.64	9
Surface tension	0.63	19
Fermions/bosons	0.65	47
Pair production	0.62	38

TABLE V. Round 3: Topics of quantum concepts for secondary school in sequence as given to the experts in the field of Quantum Technolgies. For none of these, no consensus was reached and all were chosen to be included by less than 75%.

Topic	Cns(X)	Include (%)
Quantum gates (esp. H. Z. X. CX)	0.55	28
BB84 protocol and hardware	0.56	34
Quantum random number generators	0.58	37
Comparison to current cryptography technologies	0.63	40
Superconducting sensors	0.65	31
Spin-qubit based sensors	0.64	22
Atom interferometers	0.65	29
Definition of SI units	0.63	51
Imaging (e.g., living cells)	0.67	40
Quantum sensors versus classical sensors	0.66	44
Single photon sources	0.66	46
Entangled photon sources	0.64	43
Photon fibres	0.64	19
Single photon detectors	0.66	40
Microelectronics (Arduino. Raspberry)	0.62	28
Vacuum technology	0.67	21
Using tunneling for flash memory	0.65	25

[1] A. van de Merbel, J. Peer, S. J. Willems, and J. Cramer, Quantum technology will change my life. "Citizens" attitudes and knowledge of quantum science and technology, J. Phys. Commun. **8**, 075005 (2024).

[2] EPSRC, Quantum technologies public dialogue report, https://nqit.ox.ac.uk/sites/www.nqit.ox.ac.uk/files/2018-07/Quantum%20Technologies%20Public%20Dialogue%20Full%20Report_0.pdf (2017).

[3] C. D. Aiello *et al.*, Achieving a quantum smart workforce, Quantum Sci. Technol. **6**, 030501 (2021).

[4] 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).

[5] F. Greinert, R. Müller, S. Goorney, J. Sherson, and M. S. Ubben, Towards a quantum ready workforce: The updated European Competence Framework For Quantum Technologies, Front. Quantum Sci. Technol. **2**, 1 (2023).

[6] E. Barnes *et al.*, Outcomes from a workshop on a National Center for Quantum Education, arXiv:2410.23460.

[7] M. Darienzo, A. M. Kelly, D. Schneble, and T.-C. Wei, Student attitudes toward quantum information science and technology in a high school outreach program, Phys. Rev. Phys. Educ. Res. **20**, 020126 (2024).

[8] A. Merzel, P. Bitzenbauer, K. Krijtenburg-Lewerissa, H. K. E. 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).

[9] T. Roberson, Talking about responsible quantum: "Awareness is the absolute minimum that … we need to do", NanoEthics **17**, 2 (2023).

[10] G. Zuccarini, C. Sutrini, M. Bondani, C. Macchiavello, and M. Malgieri, Teaching quantum information science to secondary school students with photon polarization and which-path encoding, Eur. Phys. J. Quantum Technol. **11**, 74 (2024).

[11] M. Kaur and A. Venegas-Gomez, Defining the quantum workforce landscape: A review of global quantum education initiatives, Opt. Eng. (N.Y.) **61**, 081806 (2022).

[12] QTEdu CSA, QTEdu.eu: European open portal: Community and resources, https://qtedu.eu/ (2024).

[13] S. Goorney, M. Sarantinou, and J. Sherson, The quantum technology open master: Widening access to the quantum industry, Eur. Phys. J. Quantum Technol. **11**, 7 (2024).

[14] F. Greinert and R. Müller, *European Competence Framework for Quantum Technologies (CFQT)* (Publications Office of the European Union, Luxembourg, 2024), 10.2759/389764.

[15] Z. C. Seskir, S. R. Goorney, and M. L. Chiofalo, Educating to the "culture" of quantum technologies: A survey study on concepts for public awareness, Eur. J. STEM Educ. **9**, 03 (2024).

[16] M. L. M. Chiofalo, C. Foti, C. Lazzeroni, S. Maniscalco, Z. C. Seskir, J. Sherson, C. A. Weidner, and M. Michelini,

Games for quantum physics education, J. Phys. Conf. Ser. **2727**, 012010 (2024).

[17] A. Donhauser, P. Bitzenbauer, L. Qerimi, S. Heusler, S. Küchemann, J. Kuhn, and M. S. Ubben, Empirical insights into the effects of research-based teaching strategies in quantum education, Phys. Rev. Phys. Educ. Res. **20**, 020601 (2024).

[18] P. Kaushik, N. Vu, C. Yeung, N. Sorak, P. Khazaei, D. G. A. Cabral, B. C. Allen, V. Venkatesh, L. K. Boyle, V. S. Batista *et al.*, Impact of quantum mechanics-based workshops on developing high school students' interest and intuition in quantum information science, in *Proceedings of the 2024 IEEE Integrated STEM Education Conference (ISEC)* (IEEE, New York, NY, 2024), pp. 1–4.

[19] P. Onorato, M. Di Mauro, and M. Malgieri, Investigating the beliefs of experts on teaching quantum physics at secondary schools: Key concepts, topics, and fundamentals, Phys. Educ. **59**, 025006 (2024).

[20] 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).

[21] C. Foti, D. Anttila, S. Maniscalco, and M. L. Chiofalo, Quantum physics literacy aimed at K12 and the general public, Universe **7**, 86 (2021).

[22] 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).

[23] D. M. Silberman, Teaching quantum to high school students, in *Seventeenth Conference on Education and Training in Optics and Photonics: ETOP 2023*, edited by D. J. Hagan and M. McKee (SPIE, 2023), Vol. 12723, p. 127232R, 10.1117/12.2665916.

[24] H. K. E. Stadermann, E. van den Berg, andM. J. 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).

[25] 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).

[26] B. Winkler, P. Bitzenbauer, and J.-P. Meyn, Quantum physics≠ quantum physics. A survey of researchers' associations, Phys. Educ. **56**, 065031 (2021).

[27] QTEdu CSA, Community-based development of the Quantum Concept Inventory [QCI], https://qtedu.eu/project/community-based-development-quantum-concept-inventory (2024).

[28] F. Greinert, S. Goorney, D. Hilfert-Rüppell, M. S. Ubben, and R. Müller, Extending the European competence framework for quantum technologies: New proficiency triangle and qualification profiles, arXiv:2410.07692.

[29] F. Greinert and R. Müller, European Competence Framework for Quantum Technologies (v1.0), Zenodo, 2021, 10.5281/zenodo.6834599.

[30] F. Greinert and R. Müller, *Competence Framework for Quantum Technologies: Methodology and Version History* (Publications Office of the European Union, Luxembourg, 2021), 10.2759/130432.

[31] S. Faletič, M. Bondani, P. J. Emigh, K. Krijtenburg-Lewerissa, G. Pospiech, and M. Michelini, Symposium on teaching and learning quantum physics, in *Physics Education Today: Innovative Methodologies, Tools and Evaluation* (Springer, New York, 2024), pp. 55–72.

[32] M. Michelini and A. Stefanel, Approaches on T/L quantum physics from per literature, in *Teaching-Learning Contemporary Physics: From Research to Practice* (Springer, Cham, 2021), Vol. 3,10.1007/978-3-030-78720-2.

[33] J. D. Vermunt and Y. J. Vermetten, Patterns in student learning: Relationships between learning strategies, conceptions of learning, and learning orientations, Educ. Psychol. Rev. **16**, 359 (2004).

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

[35] M. Michelini, R. Ragazzon, L. Santi, and A. Stefanel, Proposal for quantum physics in secondary school, Phys. Educ. **35**, 406 (2000).

[36] P. Häußler, K. Frey, L. Hoffmann, J. Rost, and H. Spada, Physikalische Bildung: Eine curriculare Delphi-Studie Teil II, IPN-Arbeitsberichte 42, IPN Leibniz Institute for Science and Mathematics Education, Kiel, 1980.

[37] K.-A. Weber, Quantenoptik in der Lehrerfortbildung: Ein bedarfsgeprägtes fortbildungskonzept zum quantenobjekt "photon" mit realexperimenten, in *Studien Zum Physik- und Chemielernen* (Logos, Berlin, 2018), Vol. 269.

[38] K. Krijtenburg-Lewerissa, H. J. Pol, A. Brinkman, and W. R. van Joolingen, Key topics for quantum mechanics at secondary schools: A Delphi study into expert opinions, Int. J. Sci. Educ. **41**, 349 (2019).

[39] F. Gerke, R. Müller, P. Bitzenbauer, M. S. Ubben, and K.-A. Weber, Requirements for future quantum workforce—A Delphi study, J. Phys. Conf. Ser. **2297**, 012017 (2022).

[40] 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).

[41] M. J. Clayton, Delphi: A technique to harness expert opinion for critical decision-making tasks in education, Educ. Psychol. **17**, 373 (1997).

[42] H. A. Linstone and M. Turoff, Introduction, in *The Delphi Method: Techniques and Applications*, edited by H. A. Linstone and M. Turoff (Addison-Wesley, 1975), pp. 1–16.

[43] See Supplemental Material at http://link.aps.org/supplemental/10.1103/d1yx-kfsz for the three questionnaires that were used in this Delphi study.

[44] 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).

[45] S. Wuttiprom, M. D. Sharma, I. D. Johnston, R. Chitaree, and C. Soankwan, Development and use of a conceptual survey in introductory quantum physics, Int. J. Sci. Educ. **31**, 631 (2009).

[46] S. McKagan, K. Perkins, and C. Wieman, Design and validation of the quantum mechanics conceptual survey, Phys. Rev. ST Phys. Educ. Res. **6**, 020121 (2010).

[47] W. J. Tastle and M. J. Wierman, Consensus and dissention: A measure of ordinal dispersion, Int. J. Approx. Reason. **45**, 531 (2007).
[48] The authors of Ref. [47] illustrate the plausibility of the formula using example answer distributions to a rating-scale question. For instance, on a five-point scale (1 = strongly disagree, … , 5 = strongly agree), if 50% of respondents select strongly disagree and the other 50% select strongly agree, the consensus metric yields Cns = 0.00.
[49] H. K. E. Stadermann and M. J. Goedhart, "Why don't you just tell us what light really is?" Easy-to-implement teaching materials that link quantum physics to nature of science, Phys. Educ. **57**, 025014 (2021).
[50] M. Rabinowitz, Examination of wave-particle duality via two-slit interference, Mod. Phys. Lett. B **9**, 763 (1995).
[51] 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).
[52] P. Lautesse, A. Vila Valls, F. Ferlin, J.-L. Héraud, and H. Chabot, Teaching quantum physics in upper secondary school in France: "Quanton" versus "wave–particle" duality, two approaches of the problem of reference, Sci. Educ. **24**, 937 (2015).
[53] P. Bitzenbauer, S. Faletič, M. Michelini, K. Tóth, and G. Pospiech, Design and evaluation of a questionnaire to assess learners' understanding of quantum measurement in different two-state contexts: The context matters, Phys. Rev. Phys. Educ. Res. **20**, 020136 (2024).
[54] M. L. Chiofalo, C. Foti, M. Michelini, L. Santi, and A. Stefanel, Games for teaching/learning quantum mechanics: A pilot study with high-school students, Educ. Sci. **12**, 446 (2022).