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The core of secondary level quantum education: a multi-stakeholder perspective

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Abstract

Quantum physics (QP) education at the secondary school level is still in its infancy. Not only is there ongoing discussion about how to teach this subject, but there is also a lack of coherence in the selection of concepts to be taught, both across countries and over time. To contribute to this discussion, we investigated the perspectives of $N = 39$ high school teachers, university-level physics educators, and physics education researchers regarding the essential concepts in QP and the corresponding illustrations that should be introduced at the secondary school level. We examined the prominence of different key concepts and illustrations, as well as the level of consensus among the various professional groups. Our analysis revealed that certain key concepts are universally valued across all professional groups, while others are specific to particular groups. Additionally, we explored the relationships between these key concepts and their corresponding illustrations. Overall, our study offers valuable insights into the perspectives of different stakeholders, emphasizing the essential concepts and visualizations that should be considered when designing and implementing the teaching of QP at the secondary school level.

Keywords: Quantum physics; Secondary school level; Teaching; Consensus; Profession group

1 Introduction

There is growing interest in teaching quantum physics (QP) in high-schools (HS) although the design of teaching strategies aimed at introducing learners to the core of QP is still in its infancy [1]. Compared with electricity (cf. [2]), for example, the opinions about the pedagogy of secondary school QP are diverse (e.g., [1, 3, 4]). In the last few years, more and more initiatives have sprouted, connecting QP education researchers together (e.g., [5]), with QTEdu being one of them. QTEdu was launched in 2020 (https://qtedu.eu/) as a Quantum Flagship CSA on quantum technology (QT) education, supporting pilot programs like our study, and aiming to enrich knowledge and materials for teaching QP, specifically QT in Europe. Nevertheless, there is an on-going debate about what content aspects are at the core of teaching and learning quantum physics in HS and which illustrations (i.e., experiments, models, contexts etc.) of these topics are particularly conducive for learning QP in secondary education.

Various factors influence HS physics curricula, reflecting different learning objectives associated with advanced physics topics. However, these objectives may not necessarily align with one another [6–9]. For instance, some argue that HS physics, and particularly QP, should primarily serve as a foundation for subsequent education and ultimately a career in the QT industry. In contrast, others prioritize physics education for students' well-being and broader civic knowledge. Consequently, different actors within the educational landscape emphasize different aspects of QP learning in HS.

Supporters of the former perspective, typically physics researchers, emphasize cutting-edge scientific advancements as the focal point. Conversely, proponents of the latter viewpoint recognize additional factors that influence high school education [10], such as time constraints, availability of teaching materials, and the value of teaching topics that may not directly benefit students in their future studies. Both approaches require specific knowledge and understanding of QP concepts.

Therefore, the objective of this paper is to explore and present the key concepts of QP that different professional groups perceive as relevant to high school education, along with suitable illustrations. By doing so, we aim to shed light on the diverse perspectives and considerations surrounding QP education in the high school context.

2 Research background

Previous studies have shown that the way a QP curriculum is perceived and implemented in a particular teaching approach is contingent upon teaching objectives, and the main key concept deemed important varies depending on the perspective of the individual being asked. To mention some, McKagan et al. [11] and Wuttiprom et al. [12] interviewed university faculty physics researchers to validate concept tests for undergraduate level, and found high variability in the concepts that experts thought to be important for teaching. In a Delphi study, Krijtenburg-Lewerissa et al. [13] searched for the topics that experts consider to be important to teach at HS level and found consensus regarding duality, wave function and atoms. Stadermann et al. [3] analyzed HS QP curriculum documents from different countries and found shared items along with differences in focus of some countries. Winkler et al. [14] used mind maps to look at the differences between associations of physics researchers from different disciplines in physics as a source for no consensus of the key topics suitable for HS. They also found a high level of diversity regarding the opinions of what is at the core of QP. Gerke et al. [15] conducted a Delphi study also addressing a diverse population of physics experts aimed to identify knowledge and competences in the field of quantum technologies, to create a competence framework and thus a common language for quantum technology education, and likewise, a heterogeneous picture emerged. Weissman et al. [16] interviewed physics researchers to delineate the core ideas of QP, and exemplified the mixture way to treat concepts and phenomena found in QP textbooks intended for colleges or as service courses for engineering students (hence be more suitable for the high-school level). In the US, the National Q-12 Education Partnership is developing educational pathways to QP in middle and high schools. For this, a framework "for future expansion and adaptation for students at different levels in computer science, mathematics, physics, and chemistry courses" was created [17].

Table 1 Conceptual ways to organize KCs in QP. Rows were organized to underline similarities, but it does not imply common classification

Winkler et al., 2021 [14]	Stadermann et al., 2019 [3]	Gerke et al., 2022 [15]	Krijtenburg-Lewerissa et al., 2019 [13]	Weissman et al., 2022 [16]
Fundamental principles	Fundamental principles	Phenomena/ basic principles	Concepts	Nucleus
Phenomena and applications	Phenomena and applications	Applications	Applications	Body
About QP (philosophical; QP vs. CP)	Philosophical aspects	Physical background (including QP vs. CP)		Periphery
Atomic theory	Atomic theory			
Mathematical representations	Wave function or other mathematical representations	Mathematics		
Mathematical terms				
Experiments			Examples	
Associations (inc. fields of physics)				

The aforementioned studies that explored concepts or topics in QP used similar, but not identical themes to arrange these concepts into classes: Some more broad (e.g., "fundamental principles") and some more content-specific (e.g., "atomic theory"). Table 1 summarizes some of these thematic classifications. It seems agreeable that a classification of concepts in QP should differentiate between fundamental concepts (i.e., key concepts; KCs) and phenomena or applications, which exemplify these concepts (i.e., illustrations). In addition, it should have a class of philosophical aspects including a comparison between QP and classical physics and a class that refers to mathematical representations.

Previous studies have mainly focused on the views of physicists, as they are considered experts in QP. However, they may have a limited idea of what can be taught in the classroom. On the other hand, high school teachers and physics education researchers with expertise in QP might have pedagogical content knowledge (PCK) based on their experience and research. This knowledge could impact what they consider the appropriate topics, concepts, and examples that should be taught in high school physics. Examining the differences among these stakeholders- high school teachers (HT), Physics researchers and educators at the university level (PR), and Physics education researchers (PER)-could shed light on how advanced physics topics might be integrated into high school physics instruction. Although Greinert et al. [18] referred to some differences between professions, they only looked at higher education. Moreover, previous studies were focused on either QP concepts *or* QT, and therefore, we need one study that incorporates them both, including a distinction between the KCs and their illustrations.

3 Research questions

Therefore, the overarching research question tackled in this paper is the following: What are the differences between HS teachers (HT), Physics researchers and educators at the university level (PR), and Physics education researchers (PER) in the way they perceive key concepts (KC) of QP and the illustrations that they use for these KCs that are suitable for teaching in secondary education? This broad question consists of several questions:

1. a. In which respect do the participants' views of quantum KCs for secondary education differ depending on their profession?
   b. What is the focus of the different profession-groups in terms of KCs classes?

These differences might be mild or strong, therefore it brings forth the question,

2. To what extent are the opinions regarding the KCs across the different profession-groups homogeneous?

Teaching and learning QP requires suitable illustrations for KCs. Strict time constraints for teaching QP in HS suggest that illustrations should be comprehensive, in the sense that teachers could use one illustration to demonstrate more than one KC. The illustrations considered suitable to make students' get a grasp of the KCs could differ among the profession-groups. Therefore, the following questions arise:

3. According to the different profession-groups,
   a. which illustrations can be used comprehensively to make students get a grasp of the different quantum KCs in secondary education, and,
   b. for which of these illustrations can be found a consensus among the profession-groups?

4 Methods

4.1 Context of the study

The European Quantum Technology Flagship has focused on education, outreach, and training through the QTEdu Coordination and Support Action (CSA) until 2022 and has continued educational efforts within the Qucats CSA from then. Eleven pilot projects on education, outreach, and training were launched. One such initiative is the *Community-based development of the Quantum Concept Inventory* (*QCI*) project. This project brought together more than twenty researchers to create a modular Quantum Concept Inventory, the QCI, based on community input to allow for the assessment of students' understanding of quantum physics' key concepts in different QP contexts. To ensure content validity of the QCI in an early stage of development, a Delphi study is conducted involving various profession-groups (see Sect. 4.3 Sample, below). This study is part of it. Nonetheless, the questions asked here are not addressed in further Delphi rounds. In fact, since a Delphi study is an iterative process of several rounds of questionnaires, it aims at identifying an increased level of consensus among participants as it progresses [19]. So, examining the differences (and similarities) between profession-groups is most distinguishable in its initial rounds. Adhering to the Delphi method, the findings of this study can also inform the participants toward further rounds.

In this paper, we report findings from the analysis of the data from this Delphi which provides insights into participants' views on KCs and illustrations relevant for teaching QP at the secondary level with respect to their professional backgrounds in order to approach a clarification of the research questions posed in Sect. 3.

4.2 Study design and data collection

An online questionnaire survey was conducted. The study was launched in April 2021 and participants with specific experience in teaching quantum physics, either at the high school or university level, were invited to participate through the QTEdu newsmail and via dissemination among personal networks (for sample details, refer to Sect. 4.3). We intended to collect responses from participants of various countries, to ensure that the findings and their use in the development of the QCI would be more meaningful, although different origins add some noise to the study (for example, due to different curricula [3]).

The questionnaire was developed iteratively by the working group members (the authors) and was inspired by the questionnaires used in the course of the Delphi study as part of the development of the Competence Framework for Quantum Technologies [15].

The questionnaire asked the respondents (among other things, reported elsewhere):

(a) *From your point of view, which key concepts for quantum physics secondary school students should learn?*

(b) *Illustrate these quantum physics key foundations by providing an example or a specific context.*

We deliberately did not explain the terms 'key concepts' and 'illustrations' to leave it as open as possible for the participants' considerations.

The competence framework for quantum technologies [20] was presented to the participants as a means to achieve some degree of uniformity about what was meant as KC. However, this was not a hard constraint as they were not obliged to choose from it and they could add any KC or illustration that crossed their mind.

4.3 Sample

In total, 39 respondents from 12 different countries completed the entire questionnaire, and this data was used for analysis in this paper. We were unable to analyze the data based on the respondents' origins as, in most cases, we had too few participants from each specific country. Nevertheless, we conducted a more general analysis of the responses across countries. Based on the participants' responses regarding their profession (they could check all that applied for them), we divided them into five groups (see Fig. 1): (a) ten physics researchers and educators at the university level (PR), (b) six physics education researchers (PER), (c) eight physics teachers at the high school level (HT), and two groups of

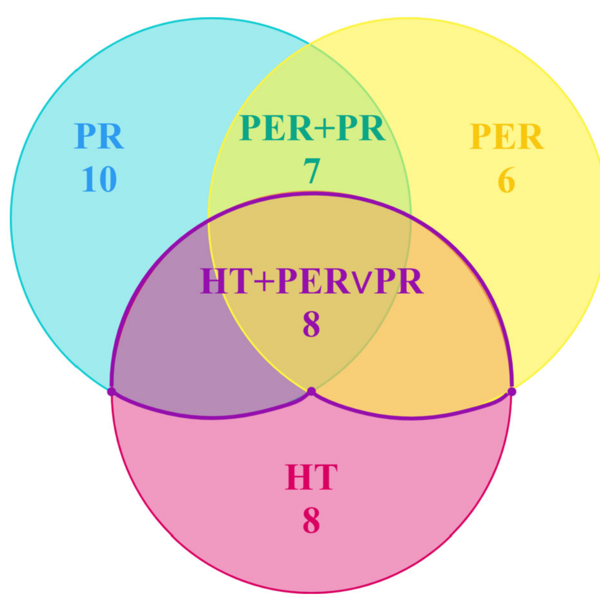

Figure 1 The way we set the profession-groups

combined professions: one group consists of seven physics education researchers that report also have subject specific background as physics researchers (referred to as PER+PR-group). The second group comprises eight high school teachers who indicate to also have experience in physics education research or subject specific background as physicists (referred to as HT+PER$\vee$PR-group).

4.4 Data analysis

4.4.1 Analysis carried out to answer research question 1*a*

In total, the 39 respondents provided 205 KCs crucial for QP education at the secondary level. We categorized all 205 KCs through peer validation in the following process: the first and last author discussed and categorized together the KCs. In order to keep the respondents' voice, we did not impose any top-down categorization. At first, only identical KCs were put into one category. Hence, responses like "Superposition" and "Superposition and interference" were categorized separately. It seems that some respondents understood the question as "What is important to teach in QP in HS", or mix concepts and phenomena (e.g., offering an experiment as a KC), which in teaching QP is not infrequent [16].

Independent of the first and last authors categorization, we gave the list of KCs to another peer (one of the authors) for categorization. Initial agreement was 72%, but full agreement was reached after discussion between all three authors. This process resulted in 42 categories of KCs. This large number of KC categories implies the non-congruent way of perceiving QP, and especially of teaching this subject in HS. Extracting meaningful insights from that many categories, while some have a very small number of entries (many categories had only 1 entry) is difficult and unrobust. Therefore, we clustered (similarly to the process of [13]) these categories in peer validation of the first and last authors, with initial agreement of 94% and full agreement after discussion. In the process, we excluded five entries, which fell under no category (e.g., "Topology"). This resulted in 19 categories (of the 200 KCs; see Table 2).

We quantified the occurrences of each category in each profession-group. The more entries it has in a profession-group, the more prominent this category is to that group. Hence, we could learn about the different profession-groups views regarding the most prominent KCs categories in QP.

4.4.2 Analysis carried out to answer research question 1*b*

Qualitative analysis of responses to open questions usually entails thematic categorization (e.g., [21]), especially when followed by quantitative analysis. With the goal to examine the different foci of the profession-groups, we followed the classification possibilities we mentioned above (see Table 1). Through peer validation of three of the authors (initial agreement: all three: 63.2%; each pair's agreement: 68-90%. After discussion: all three: 84%; each pair's agreement: 84-100%) we named each of the 19 categories of KCs to be one of either class: Fundamental concepts, Phenomena or applications, Mathematical representations and Philosophical aspects. In the three cases where there was no full agreement of all three, we named it like the two peers in agreement. Next, we summed the number of entries per group per class of category, divided by the number of respondents (see Table 5 and Fig. 2). This measure implies that a higher score of a class of categories in a profession-group represents a higher focus of that profession-group in that class of categories. Note, that this is a wide analysis overarching the specific KCs categories.

Table 2 Clustering the categories of the KCs

Category	Key Concepts (Exemplary)
Superposition	Superposition Interference
Quantum measurement	Quantum measurement
Quantization	Quantization Quantum state Energy quantization Quantum numbers Many-body-system
Entanglement	Entanglement
Heisenberg principle	Heisenberg uncertainty
Mathematical foundations	Mathematical foundations Dirac Notation Bloch sphere Operators
Qubit	Qubit Quantum computing
Statistical nature	Statistical nature Probability
Wave-Particle Duality	Wave-Particle Duality
Atomic models	Atomic models Band Structure Orbitals Pauli Exclusion principle Light emission
Time evolution	Unitary time evolution
Non-locality	Non-locality Non-determination (of trajectory)
Decoherence	Decoherence
Two-level system	Two-level system Spin
Classic vs. Quantum models	Classic vs. Quantum models Historical view
Tunneling The Schrödinger eq. Complementarity No cloning	Tunneling The Schrödinger eq. Complementarity No cloning theorem

4.4.3 Analysis carried out to answer research question 2

To measure the relative consensus about KC categories among profession-groups, we first normalized (per respondent) the number of entries per category, and calculated the variance among the profession-groups. The lower the variance, the higher homogeneous is the category among the profession-groups. This approach has been similarly used in previous studies (cf. [22]). However, this might cause a bias since a category might get attention only by some of the profession-groups, resulting in a low variance (high homogeneity). To mitigate this, we summed the normalized (per respondent) number of entries per category across all profession-groups.

$$KC_{Homogeneity} = -1 \cdot \left(VAR\left(\frac{\#\ entries\ for\ KC}{\#respondents} \right)_{profession\ groups} - Mean_{VAR} \right)$$

$$KC_{Prominence} = \sum_{Profession\ groups} \frac{\#\ entries\ for\ KC_{profession\ groups}}{\#respondents_{profession\ groups}} - Mean_{prominence}$$

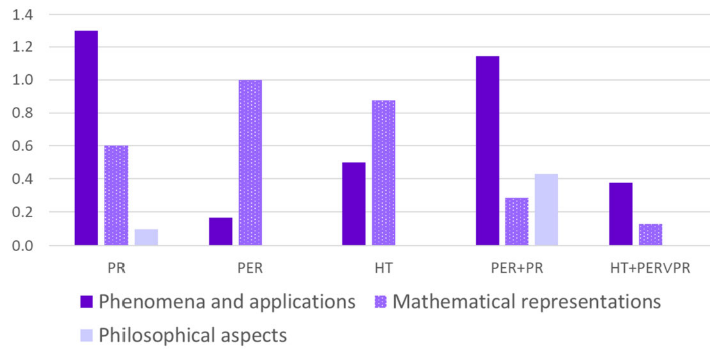

Figure 2 Classes of categories of KCs, normalized by the number of respondents. The class "Fundamental concepts" is excluded, since it masks the difference between the groups

Categories that were more frequently mentioned received higher values, providing an indication of their prominence.

We plotted both measures for prominence and homogeneity (the variance, reversed) on a coordinate system, setting the mean of each measure as the origin (see Fig. 3 in the Results section). This resulted in four distinct domains: KC categories that were deemed important by all profession-groups (positive homogeneity, positive prominence), KC categories that were deemed important by some profession-groups but not by others (positive prominence, negative homogeneity), KC categories that received little attention from all profession-groups, but some deemed them more important than others (negative prominence, negative homogeneity), and KC categories that received little attention from all groups (positive homogeneity, negative prominence). KC categories for which there is consensus among profession-groups regarding their importance (whether high or low) are located in the 1st and 4th quadrants.

4.4.4 Analysis carried out to answer research question 3

We categorized the illustrations according to the categories of the KCs they were offered to illustrate (e.g., if someone offered the Double slits experiment as an illustration for the KC Superposition, we counted that as an illustration for the Superposition category), by a similar process of peer validation. We counted the number of illustrations per category by profession-group (see Table 6; organized from the highest total number of KCs to the lowest; including cases in which the same illustration is connected more than once to a KC category). Some of the illustrations were general in nature and some very specific with many details, so some were counted to more than one category of KCs. We also mapped (quantitatively) for each illustration, to which KC categories it was offered and by which profession-group. Of the 104 different illustrations offered in 284 entries, we focus on the illustrations that were mentioned at least 6 times and were offered for at least 4 KC categories. Although this cut-off on 6 entries might seem arbitrary, we consider these illustrations to be comprehensive since it addresses more than a fifth (21%) of the KCs categories. That is, we do not elaborate on illustrations with low prominence (i.e., those illustrations that were mentioned less than 6 times or offered as illustration for less than 4 KC categories). To measure prominence and homogeneity of these illustrations we used the same measures as mentioned in the previous section (see Fig. 4). Additionally, we examined how many and which profession-groups offered an illustration for a specific KC category.

Another justification for emphasizing the illustrations of prominent KC categories is to examine the correlation between the prominence of KC categories and the variety of illustrations available for them. A strong correlation would indicate that prominent KCs have a wide range of illustrations.

5 Results

In the analysis we focus first on the KCs categories, then we incorporate into the analysis the illustrations that the participants mentioned as suitable for these KCs categories.

5.1 Results regarding RQ 1: differences regarding KCs categories between profession-groups

5.1.1 Description of the data – key concepts

As mentioned in Sect. 4.4.1, we categorized the 200 entries of KCs into 19 categories (see Table 2). These categories are the basis for the analysis presented in the following sections.

We counted the number of entries per category and per profession group, i.e., we counted how many respondents per profession-group mentioned a KC that is related to that category (see Table 3 for the average number of KCs per participant and Table 6 for the distribution of entries per KC category). Note that it is possible to have more entries than respondents since a category might include more than one KC.

5.1.2 Similarities and differences regarding KCs categories among profession-groups

In the following, we summarize the most notable KC categories – i.e., the ones that have been mentioned by at least three respondents – per profession-groups. We arranged them by the number of entries for each profession-group in Table 4.[1] This table stresses the common KC categories between profession-groups and the relative importance of the KC category within each profession-group. Note, that different number of respondents might cause a bias if a comparison between-groups is made. We overcome this bias in Sect. 5.2.

The KC categories that all profession-groups gave 3 or more entries are Superposition, Quantum measurement and Quantization. Entanglement and the Heisenberg principle were notable by four profession-groups, and Mathematical foundations by three. However, the differences between the groups are interesting: While Qubit has the highest number of entries in the PR group, it has few (if any) entries in any other group. This shows the importance of applications of QT for this group, which is more oriented towards the uses of QP for technology applications. Other differences between the profession-groups are KC

Table 3 Respondents and KCs categories by profession

Profession-group	# Respondents	# Entries of KCs provided	Average number of KCs per participant
Physics researchers and educators at the university level (PR)	10	50	5.00
Physics education researcher (PER)	6	34	5.67
Physics high school teacher (HT)	8	44	5.50
PER+PR	7	40	5.71
HT+PER∨PR	8	32	4.00
Total	39	200	5.13

[1] We give the full information about *all* KC categories and their illustrations in Table 6. We use Table 4 to highlight similarities and differences about KC categories.

Table 4 Most notable KCs categories by profession [# of entries]; Colored font represents a KC category that more than one profession group mentioned. Black font denotes KCs that other profession-groups mentioned less than 3 times, if at all

	PR (n=10)	PER (n=6)	HT (n=8)	PER+PR (n=7)	HT+PER∨PR (n=8)
1	Qubit [8]	Superposition [7]	Superposition [7]	Quantization [7]	Superposition [6]
2	Superposition [7]	Quantization [5]	Quantum measurement [6]; Heisenberg principle [6]	Superposition [5]	Quantum measurement [5]
3	Quantum measurement [6]	Quantum measurement [4]; Mathematical foundations [4]	Mathematical foundations [4]	Quantum measurement [4]; Wave-Particle Duality [4]; Atomic models [4]	Quantization [4]; Heisenberg principle [4]; Entanglement [4]
4	Entanglement [5]	Entanglement [3] Heisenberg principle [3]	Entanglement [3]; Quantization [3]; Decoherence [3]	Heisenberg principle [3]; Classic vs. Quantum models [3]	Non-locality [3]
5	Mathematical foundations [4]				
6	Quantization [3]; Wave-Particle Duality [3]; Statistical nature [3]				

Table 5 Foci of profession-groups: Categories of KCs (Table 2) sorted to classes of Fundamental concepts, Phenomena and applications, Mathematical representations and Philosophical aspects. The values in the table are the sum of entries per profession-group per class of categories, normalized by the number of respondents (for the number of entries of KCs to each category see Table 6)

Categories' Classification [# of KCs entries, all profession groups] {KCs categories included}	PR	PER	HT	PER+PR	HT+PER∨PR
Fundamental concepts [145] {Superposition; Quantum measurement; Quantization, Heisenberg principle; Entanglement, Statistical nature; Wave-Particle duality; Non-locality; Decoherence; Complementarity}	3.00	4.50	4.13	3.86	3.50
Phenomena and applications [29] {Qubit; Atomic models; Two-level system; Tunneling; No cloning}	1.30	0.17	0.50	1.14	0.38
Mathematical representations [22] {Mathematical foundation; Time evolution; The Schrödinger eq.}	0.60	1.00	0.88	0.29	0.13
Philosophical aspects [4] {Classic vs. Quantum models}	0.10	0.00	0.00	0.43	0.00

categories that are notable only in one group: The Statistical nature of QP, Decoherence, Atomic model, Classic vs. Quantum models and Non-locality. Along with the absence of Wave-Particle duality from three groups (PER, HT and the HT+PER∨PR) this finding is somewhat surprising, since these concepts (except Decoherence and Non-locality) gets relatively high attention in many curricula [3].

Regarding the foci of KCs categories for each profession-groups, Table 5 pronounces that all are focused mainly on the Fundamental concepts, although the PR group is less focused on it than the other groups. However, this group is more focused on Phenomena and applications. To better highlight the differences between the profession-groups, we draw a graph of the classification of categories by profession-group. We excluded the Fundamental concepts class from the graphical representation since it masked the differences between the professions (see Fig. 2).

In Fig. 2, we see that the PER and the HT groups are similar to each other, and emphasize more the mathematical representation. Similarly, the PR and the PER+PR groups give more emphasis on KCs related to phenomena and applications. Although HT+PER∨PR offered, on average, fewer KCs, it seems that this group is similar to PR and PER+PR, focusing on phenomena and application and less on mathematical representations.

5.2 Results regarding RQ 2: consensus about KCs among profession groups

We plotted the KC categories on a homogeneity and prominence axes as described in the methodology section (Sect. 4.4.3). Two of the KC categories got relatively high prominence and are in consensus, as they appear in the 1st quadrant of the graph in Fig. 3. These are Quantum measurement and Entanglement. The KC categories of Superposition, Quantization, Heisenberg principle, Mathematical foundations and Qubit appear in the 2nd quadrant, meaning they displayed rather high prominence but with rather high variance. For example, the sum of normalized number of entries of Quantization ranged from low prominence among the group of physicists ($Prominence_{\mathrm{PR}} = 0.30$) to rather high prominence among physics education researchers with background in physics research ($Prominence_{\mathrm{PER+PR}} = 1.00$). Nonetheless, there seems to be a big difference between Superposition, which is rather close to the 1st quadrant with the highest prominence, and Qubit, which is just a thread from belonging to the 3rd quadrant, with low prominence and lowest homogeneity. The 4th quadrant is characterized by positive homogeneity, but with relatively low prominence. For example, the category of No cloning has rather high homogeneity since only one group did not ignore it altogether ($Prominence_{\mathrm{PER+PR}} = 0.14$).[2]

It is worth noting that this visualization is relative, since we set the origin of the axes to be the average of our measures. By doing that, we condemned at least some KCs categories

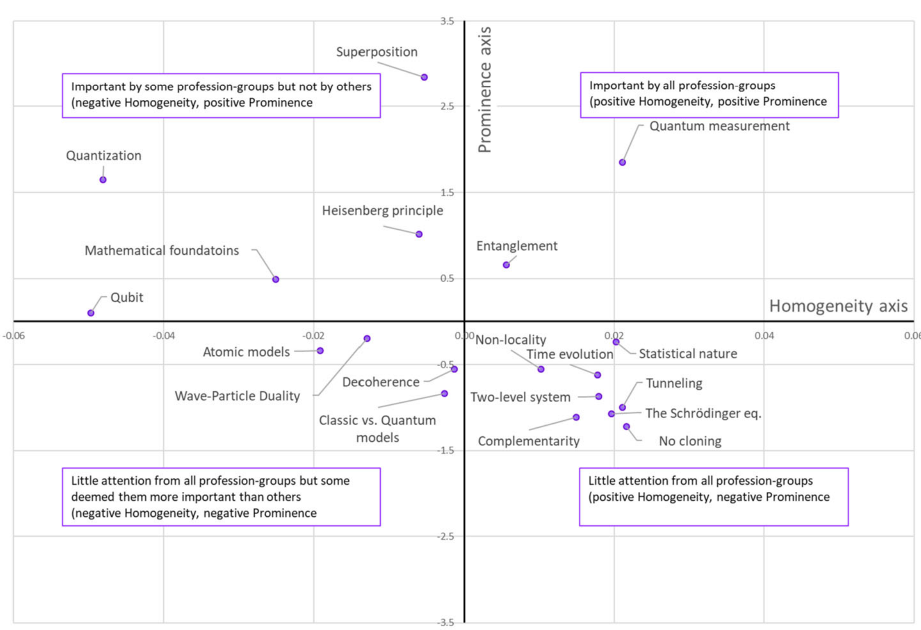

Figure 3 Consensus measure of KC categories: The Prominence axis represents the sum of normalized number of entries per KC category and the Homogeneity axis represents the variance (*reversed*) *among profession-groups*

[2]The prominence values per specific profession-group are the absolute values (and not the aggregated values, which were adjusted to set the mean as the origin of the axis in Fig. 3).

to be on the negative sides of the axes. Therefore, our results are not to contradict previous studies that clearly show that the Wave-Particle Duality, the Statistical nature and the Heisenberg principle are prominent concepts [3, 13–16]. Rather, our results imply which KCs categories have higher consensus among the profession-groups.

5.3 Results regarding RQ 3: illustrations offered for KCs and consensus among profession-groups about illustrations

5.3.1 Description of the data – illustrations

We counted the number of entries of KCs and the illustrations per category by profession-group (see Table 6; organized from the highest total number of KCs to the lowest; including cases in which the same illustration is connected to a KC category more than once).

Table 6 Categories of KCs and their illustrations (Ils) by profession-group [# of respondents]. The rightmost column presents the total number of different illustrations offered per KC category

Categories of KCs and the number of illustrations (Ils) by profession	PR [10]		PER [6]		HT [8]		PER+PR [7]		HT+PERVPR [8]		Total [39]		
	KCs	Ils	KCs	Ils	KCs	Ils	KCs	Ils	KCs	Ils	KCs	Ils	Different Ils
Superposition	7	9	7	15	7	12	5	9	6	12	32	57	21
Quantum measurement	6	8	4	8	6	4	4	4	5	8	25	32	14
Quantization	3	4	5	14	3	2	7	7	4	9	22	36	20
Heisenberg principle	2	2	3	7	6	5	3	2	4	4	18	20	13
Entanglement	5	6	3	5	3	2	1	0	4	6	16	19	12
Mathematical foundations	4	4	4	7	4	3	2	5	0	0	14	19	13
Qubit	8	10	0	0	2	0	2	3	1	5	13	18	16
Statistical nature	3	4	1	5	1	1	2	3	2	3	9	16	13
Wave-Particle Duality	3	5	1	1	0	1	4	2	0	0	9	8	5
Atomic models	2	2	0	0	0	0	4	4	2	3	8	9	9
Time evolution	2	1	1	1	2	5	0	0	1	2	6	9	9
Non-locality	0	0	1	8	1	0	1	3	3	4	6	15	13
Decoherence	1	2	2	1	3	2	0	0	0	0	6	5	5
Two-level system	2	2	1	2	1	2	0	0	0	0	4	6	6
Classic vs. Quantum models	1	1	0	0	0	0	3	7	0	0	4	8	8
Tunneling	1	1	0	0	1	2	1	1	0	0	3	4	4
The Schrödinger eq.	0	0	1	1	1	0	0	0	0	0	2	1	1
Complementarity	0	0	0	0	2	0	0	0	0	0	2	0	0
No cloning	0	0	0	0	0	0	1	2	0	0	1	2	2
Total	50	61	34	75	44	40	40	52	32	56	200	284	184

Reminding that this was an open question, some of the illustrations were general in nature and some very specific with many details. Detailed illustrations were sometimes divided to represent different illustrations (e.g., an illustration given to the KC Entanglement was: "Polarization and spin: from entanglement of modes of 1 particle (position + spin) to the entanglement of more particles". We counted it as three illustrations: Polarization, Spin and Entanglement of many particles). This represents the voice of our respondents better, since a detailed description represents a more elaborate knowledge, or teaching options.

Examining the average number of *different* illustrations per KC category per profession-group we noticed that those who pursue physics education (i.e., PER) offer much more illustrations per KC category ($M_{\mathrm{PER}} = 0.57$) and the HT group offers somewhat less illustrations ($M_{\mathrm{HT}} = 0.24$) than all the other profession-groups ($M_{\mathrm{PR}} = 0.29$; $M_{\mathrm{PER+PR}} = 0.36$; $M_{\mathrm{HT+PER\vee PR}} = 0.34$).

5.3.2 *Illustrations provided for KCs and consensus among profession-groups about them*

The respondents offered 284 illustrations for the KCs; 104 of them were *different* illustrations. Among these illustrations, the most prominent are those mentioned at least 6 times (see Sect. 4.4.4). These 8 illustrations are the Double-slit experiment, Polarization, the Stern-Gerlach experiment, Qubit, the Mach-Zehnder interferometer, Spin, Matter waves and the Double-well. Each is offered as an illustration for at least 4 categories of KCs, suggesting these might be comprehensive for teaching, allowing teachers to illustrate several KCs through a small number of illustrations. For example, the Double slit experiment was offered 29 times for 9 KCs categories (see Table 7a below. For the other prominent illustrations see Tables 7a-7h in Appendix A).

Since our participants were free to interpret the terms 'KCs' and 'illustrations', we will not analyze the illustrations that were offered less than 6 times. Nonetheless, it is worth mentioning that the participants considered some terms to be both KCs and illustrations (for example, 'Qubit', 'Two level systems', 'Tunneling'), which might suggest some indeterminacy about the role of these terms in QP education (cf. [16, 23]).

To examine consensus about these illustrations, we plotted them on Prominence and Homogeneity axes, in a similar way to the KCs categories in Sect. 5.2 (see Fig. 4). The

Table 7a KCs categories to which participants offered the Double-slit experiment as an illustration ($n = 29$; 9 KCs categories); Common KCs categories are shaded {# times the illustrations are mentioned in a profession-group}; [# times the illustration is linked to a KC category within the profession-group]. For the other 7 prominent illustrations and the KCs categories they were offered to, see Appendix A

The Double-slit experiment as an illustration				
PR {4}	PER {9}	HT {4}	PER+PR {6}	HT+PERVPR {6}
Superposition	Superposition [3]	Superposition [2]	Superposition [3]	Superposition
Quantum measurement	Quantum measurement			Quantum measurement [2]
WP duality [2]	WP duality		WP duality	
	Heisenberg principle	Heisenberg principle	Heisenberg principle	
	Non-locality		Non-locality	Non-locality
	Statistical nature and probability			Statistical nature and probability
	Quantization	Decoherence		Entanglement

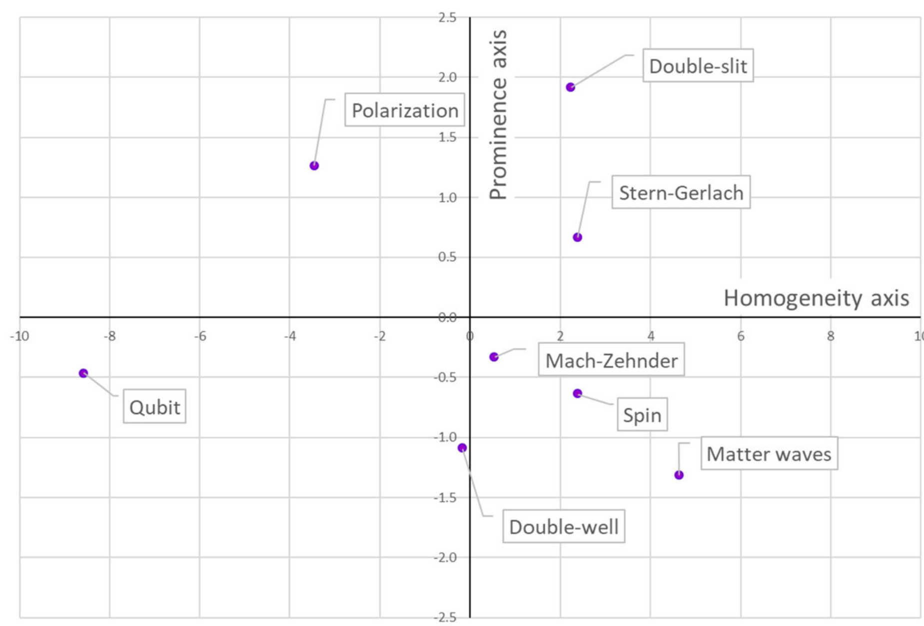

Figure 4 Consensus measure for illustrations: The Prominence Axis, which is represented by the sum of normalized number of entries of KCs and the Homogeneity axis, which is represented by the variance (*reversed*) *among profession-groups. The quantities' meaning is as in Fig.* 3

Double-slit and the Stern-Gerlach experiments, as illustrations, fall in the 1st quadrant, which means there is higher consensus about their prominence. Polarization, in the 2nd quadrant has fairly high prominence but with certain variance, as the normalized mean ranged from low prominence among the group of physicists ($Prominence_{\mathrm{PR}}$ = 0.10) to rather high prominence among physics education researchers ($Prominence_{\mathrm{PER}}$ = 1.67). Qubit and Double-well are both at the 3rd quadrant, which represents relatively low prominence and low homogeneity. Yet, they seem to be different from each other, as the Double-well was addressed only by one profession-group ($Prominence_{\mathrm{PER}}$ = 1.67), and Qubit had more profession-groups that mentioned it (as an illustration), but with relatively high variance.

To establish the connection between KC categories and the illustrations offered for them, we examined the correlation between KC category prominence and the number of different illustrations. The results revealed a significant positive correlation (Pearson's $r = 0.85$, $p < 0.001$), indicating that more prominent KC categories are associated with a greater variety of illustrations. This is crucial for facilitating versatile teaching approaches, as it grants teachers the freedom to select illustrations that best demonstrate the KC categories.

Some illustrations were offered by all profession-groups, while others were offered by one profession-group only. Some were offered more than once for a specific KC category. For example, among the illustrations for the KC category of Superposition (see Table 8a), the illustration of the Double-slit experiment was offered by all profession-groups. It was offered by physics education researchers (PER) 3 times and twice by teachers (HT). Michelson interferometer, however, was offered only once, by physicists at the university level (PR).

Table 8a The illustrations offered for the KC category Superposition. {# KCs entries per profession-group}; [# repetition of illustration in a specific profession-group]; Illustrations offered by more than one profession-group are shaded. Illustrations offered to other KCs categories are shown in Tables 8a-8i in Appendix B

PR {7}	PER {7}	HT {7}	PER+PR {5}	HT+PERVPR {6}
Double-slit exp.	Double-slit exp. [3]	Double-slit exp. [2]	Double-slit exp. [3]	Double-slit exp.
	Polarization [3]	Polarization [2]	Polarization	Polarization
Spin states	Spin states [2]		Spin states	Spin states
	Stern-Gerlach	Stern-Gerlach		Stern-Gerlach
Mach-Zehnder	Mach-Zehnder			Mach-Zehnder
Qubit [2]	Qubit			Qubit
Matter waves		Matter waves		Matter waves
		Light interference		Light interference [2]
		Wave interference	Wave interference	
	Classical vs. quantum		Classical vs. quantum	
Single photon interferometry				Single photon interferometry
Two photon interference	Birefringent crystals	Diffraction of light [2]	Quantum eraser	Not like statistical probability
Michelson interferometer	Double well		Delayed-choice exp.	Schrödinger's cat

Table 9a Illustrations with high consensus (at least 4 profession-groups mentioned this illustration as suitable for a specific KC category)

Illustration	Offered for KC category	PR	PER	HT	PR+PER	HT+PER∨PR
Polarization	Quantum measurement	V	V	V	V	V
Double-slit exp.	Superposition	V	V	V	V	V
Stern-Gerlach	Quantum measurement	V	V	V		V
Polarization	Superposition		V	V	V	V
Spin states	Superposition	V	V		V	V

In Tables 8a-8i in Appendix B we bring the illustrations offered for the 9 most prominent KCs categories: Superposition, Quantum measurement, Quantization, Heisenberg principle, Entanglement, Mathematical foundations, Qubit, Statistical nature and Wave-particle duality (see Tables 8a-8i).

Looking at specific connections between KC categories, their offered illustrations and the profession groups, we see that four illustrations are in high consensus for two KCs categories: All profession-groups agree that Polarization is an illustration for Quantum measurement, and that the Double slit experiment is an illustration of Superposition. Polarization is also agreed by four profession-groups as an illustration of Superposition, as well as Spin states. Similarly, the Stern-Gerlach experiment is agreed by four groups as an illustration of Quantum measurement (see Table 9a).

There is a medium consensus about 14 illustrations. That is, they are offered (for a specific KC category) by three profession-groups (see Table 9b). The rest of the illustrations (per KC category) were offered only by two or one group, therefore considered as illustrations with low consensus for those KC categories.

Table 9b Illustrations with medium consensus. Three profession-groups linked that specific illustration to a specific KC category

Illustration	Offered for KC category	PR	PER	HT	PR+PER	HT+PER∨PR
Double-slit exp.	Quantum measurement	V	V			V
Double-slit exp.	Wave-Particle duality	V	V		V	
Double-slit exp.	Heisenberg principle		V	V	V	
Double-slit exp.	Non-locality		V		V	V
Stern-Gerlach	Superposition		V	V		V
Stern-Gerlach	Quantization	V	V			V
Stern-Gerlach	Qubit	V			V	V
Mach-Zehnder	Quantum measurement	V	V			V
Mach-Zehnder	Superposition	V	V			V
Qubit	Superposition	V	V			V
Wave function collapse	Quantum measurement	V	V			V
Position and momentum	Heisenberg principle		V	V	V	
Matter waves	Superposition	V		V		V
EPR exp.	Entanglement	V	V	V		

Table 9b reveals that although the similarity between PER and HT profession-groups mentioned above about their foci (see Fig. 2), little they agree about the illustrations for these KCs. This could not be explained only by the low rate of illustrations the teachers offered, since they could propose similar illustrations. The same goes for PR and PR+PER groups. That is, even if there is some agreement between the profession-groups about the KCs categories and their foci, what they consider as illustrations for these KCs in HS classes is less in consensus.

To sum up our findings, we constructed Figures 5a and 5b. Figure 5a represents the 9 most prominent KCs categories and their connections to the 8 most prominent illustrations, by profession-group. The KCs categories and the illustrations are arranged by their prominence. Figure 5b represents the connections across profession-groups. The width of the connecting lines represents the number of profession-groups that mentioned these connections.

6 Discussion and conclusion

This report is the result of the first round of a wide Delphi study, in which 39 participants of different professions answered open questions about key concepts (KCs) in QP and their illustrations for high school (HS). This study focuses on the differences between five profession-groups: Physics researchers at the university level (PR), Physics education researchers (PER), High school teachers (HT), PERs which are also PRs (PER+PR) and HTs which are also PERs or PRs (HT+PER∨PR).

6.1 General findings

We found 19 KC categories, and classifying them according to the literature (see Table 1) to classes of Fundamental concepts, Phenomena and applications, Mathematical representations and Philosophical aspects revealed similarities and differences among the foci of the profession-groups. PER and HT were similar in their foci (see Table 5 and Fig. 2), which is plausible, since both profession-groups are usually involved with HS students and could be aware of similar aspects of teaching. The profession-groups of PR and PR+PER also presented similar foci. We attribute this similarity to their main focus in higher education or *doing* physics, rather than on *teaching* it (especially not to HS students), hence the

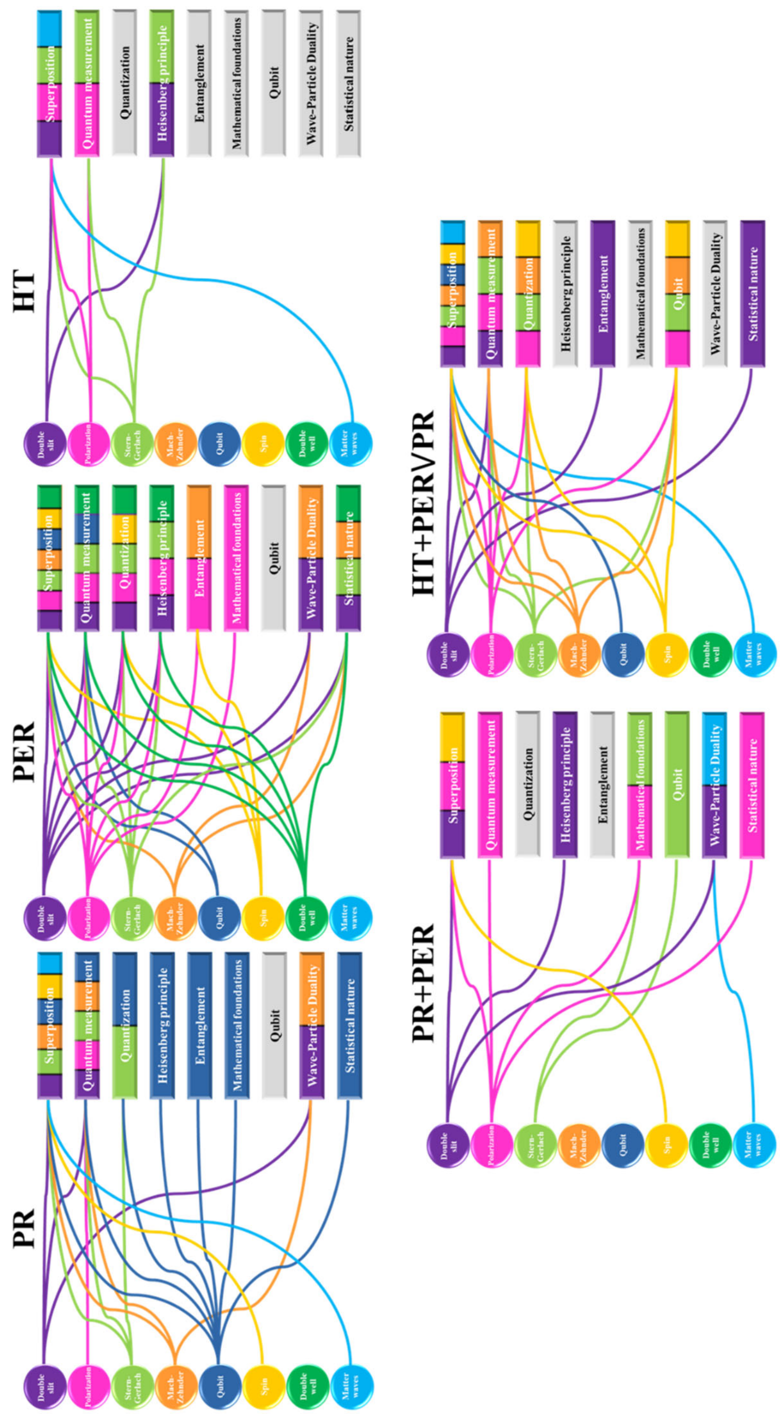

Figure 5a The connections between the 9 most prominent KCs categories (*on the right side of each diagram*) *and the 8 most prominent illustrations* (*on the left side of each diagram*), *by profession-group*

focus on phenomena and applications. It is common knowledge that the level of mathematics is higher in upper education, hence the focus of PER and HT on mathematical aspects is somewhat surprising. Another intriguing finding is that neither the PER group

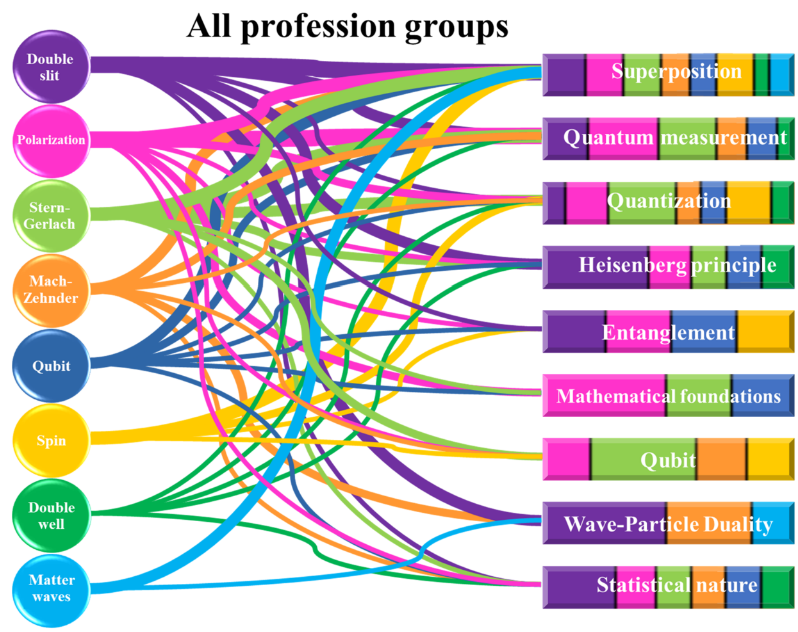

Figure 5b The connections between the 9 most prominent KCs categories (*right*) *and the 8 most prominent illustrations* (*left*), *across all profession-groups. The width of the connecting lines represents the number of profession-groups that mentioned these connections*

nor the teachers give any weight to philosophical aspects, while aspects of the nature of science frequently rise in learning QP [24].

The KC categories that are the most conspicuous and agreed upon by all or most of the profession-groups are Superposition, Quantum measurement, Quantization, the Heisenberg principle, Entanglement, and Mathematical foundations. However, not all of these KC categories gained high homogeneity among the different profession-groups (see Fig. 3). The most eminent illustrations were Polarization, the Double slit experiment and the Stern-Gerlach experiment, for the KC categories of Quantum measurement, Superposition and Spin states (see Tables 9a and 9b, and Tables 8a-8i in Appendix B). These illustrations were also the most connected to other KCs clusters (see Figures 5a and 5b and Table 7a-7h in Appendix A). Other frequently offered illustrations are the Mach-Zehnder interferometer, Qubit, Wave function collapse, Matter waves and the EPR experiment.

6.2 Mixture of KCs and illustration

It is worth noting that there is some mixture of KCs and illustrations, as some items are offered as both (most prominent example: Qubit). This mixture was observed in all profession-groups. Although this is likely due to our decision to allow participants to interpret the exact meaning of these terms, it reflects the ambiguous nature of the subject matter when it comes to teaching – namely, which concepts are considered key and how they should be illustrated. This blending of KCs and illustrations aligns with the non-rigorous utilization of principles and phenomena often encountered in QP education [16]. Furthermore, it may indicate a confluence of teaching goals in QP. The first is to ultimately foster a deeper conceptual understanding. Consequently, educators employ illustrations to facilitate comprehension of the key concepts. The other objective is more trivial: ensuring that high school students are familiar with the quantum illustrations themselves, as literate citizens of the modern era. While the first goal encompasses the second, these two approaches might lead to different teaching emphases. In this study, we implicitly assume that our participants are primarily focused on the first goal, while achieving the second objective along the way, although it is possible that not all participants share this perspective. Further research could dive into goals of teaching QP in HS among the different profession-groups.

6.3 Scrutinizing KCs and illustrations

Other studies have also attempted to scrutinize the key topics or nucleus, or system categories of QP [13, 14, 16]. Common to these studies and our own, are the key concepts of the Heisenberg principle, Wave-Particle duality, and the Statistical nature of QP. The relatively large number of respondents to our Delpi study enhances the credibility of these findings, although none of these concepts were specified by all profession-groups. Some items, such as the Double slit experiment, the Stern-Gerlach experiment and the Potential well, were offered previously as key topics, whereas our participants found them to be illustrations of the key concepts. This differentiation might be due to the explicit request to distinguish between the two types of concepts in the context of teaching QP in HS, or to the aforementioned difference in approaches.

However, Superposition, Quantum measurement, and Entanglement, which we found to be highly prominent and in consensus, were mentioned only by some of these studies. Specifically, these KCs are noted to be yet uncovered by common research tools [1], so future research should look into these KCs to better characterize the way they should be incorporated into HS teaching, for example, by utilizing them in QT outreach activities [25].

6.4 Curricular implications

Comparing the prominent KC categories to curricula from different countries, shows some misalignments. Whereas Superposition was unanimously the most prominent KC, it is mentioned in one curriculum [4] and absent from the content item mentioned in curricular documents of many countries [3]. Although it is unlikely that teachers ignore this KC, it is not explicitly mentioned. The same is for Quantum measurement. In addition, Mathematical foundations and Entanglement get little attention in those curricula. In contrast, aspects of Quantization, and the Heisenberg principle get relatively high attention, as well as aspects of Atomic models, Wave-Particle duality and the Statistical nature of QP. Under the assumption that each profession-group expresses its most important issues, our findings suggest that decision-makers or curricula designers should consider some revisions to curriculum in order to adhere to what most of the profession-groups think is important. Our findings also offer a way to implement it: for example, if Superposition is to be included in a curriculum more explicitly, it could be illustrated in various ways (see Table 8a), acceptable by many stakeholders. However, HT should be trained toward such changes, since it seems that they are less aware of the opportunities some of the illustrations might yield in this respect. To continue with the current example, teachers seem to be unaware of using the Mach-Zehnder interferometer, Qubit or Spin states to illustrate Superposition.

Connecting each illustration to several KCs could assist in constructing curricula suitable for the short time usually allocated for teaching QP in HS. It also may help to present the students a more coherent picture of QP. Of course, teachers should adjust their teaching so as not to burden the students' cognitive load. Such could be a spiral teaching that starts from experimental results, which could lead to a conceptual understanding and goes into more abstract representations and to problem solving (e.g., [26]).

Quantum technologies (QT) are currently receiving significant attention (e.g., [18, 25, 27]). Examining the key concepts (KCs) and illustrations provided by the participants through the lens of the Competence Framework for Quantum Technologies [20], we found that the participants mention aspects of QT, not only those that fit in the Theoretical Background section, which includes concepts and foundations (e.g., Qubit, Mathematical formalism), but also aspects that could fit in the Quantum Technology section, encompassing quantum computing and communication. Naturally, QT was utilized as an illustrative tool. One proposal for combining KC with QT (quantum cryptography) for teaching in high school is offered in [28]. Mostly, the respondents offered quantum gates as an illustration of Quantization, and quantum cryptography (e.g., BB84, Ekert91) as an illustration of the KCs of Entanglement, Heisenberg's principle, and No cloning. However, these illustrations were sparse, accounting for less than 8% (22 of 284) of the total. This observation suggests that our participants may prefer focusing on the fundamental concepts and foundations of quantum physics during HS, leaving QT topics for higher education. Alternatively, it highlights the need for dedicated efforts to enhance the accessibility of QT at the HS level. This could be done by outreach activities that incorporate KCs with high agreement (like Superposition, Quantum measurement and Entanglement), which were identified as such by recent studies [25]. Additionally, it is worth noting that half of these illustrations (11 illustrations) were provided by PRs, while only 3 were from the HTs, further emphasizing the difference between the profession-groups.

6.5 Difference between profession groups

Our study examines the perspectives of different profession-groups involved in QP education, ranging from high school teachers to subject-specific experts. Our findings reveal some notable differences between these groups.

Different profession-groups hold somewhat different perspectives on quantum physics, which is not surprising considering that even among physicists, there are differences regarding this topic [14]. Additionally, the answers of PER+PR are neither the sum nor the average of the PR and the PER groups, and the same is for the HT+PER$\vee$PR (see Fig. 2). Rather, the pattern of answers resembles those of the PR profession-group. This might suggest that there might be an underlying variable, or that a background in practicing physics research per se, overshadows other perspectives. Moreover, Physics Education Researchers (PERs) tend to offer more illustrations and connect them to more KCs. In contrast, High School Teachers (HTs) gave fewer KCs and offered less illustrations. We could also identify 50% a higher rate of HTs opting out of our questionnaire after only filling in their profession and country (comparing profession-groups). This is possibly due to feelings of incompetence or a lack of awareness of connections between KCs and their possible illustrations. This is in line with teachers' report of insufficient content knowledge in QP [29, 30]. Nonetheless, teachers have much to contribute to curriculum design since they are immersed in their students' difficulties, aware of system constraints, and ultimately responsible for executing any planned curriculum in class [31].

To ensure that the voices of HTs are better represented, there is a need to conduct focus groups or interviews with teachers. Such procedures are expected in the next step of the QCI Delphi study. We also recommend special training programs for teachers (e.g., [30, 32]).

We must exercise caution when generalizing our findings, but we believe that collaboration among these profession-groups is necessary. Previous studies have shown that collaborations between HTs, PERs, and subject-specific experts in QP are important, especially for HTs [30]. By learning from each other's strengths and perspectives, these groups can bridge gaps in their knowledge and teaching approaches, and ultimately improve the quality of QP education.

QP and QT education may have various target populations with different mathematical backgrounds. These may include those who intend to become part of the QT workforce, those directed to study physics in higher education, and those who are not destined for physics but aim to become literate citizens capable of making informed decisions regarding QP and QT-related societal issues. This diversity necessitates the development of customized curricula and assessment tools. As we have demonstrated, it is plausible that certain key concepts and illustrations will appear in all curricula, as they are homogeneously more prominent than others (i.e., frequent KCs; illustrations connected to many KCs). The engagement of different professional groups, which we have shown to have different foci, may assist in constructing these tailored curricula.

Appendix A

The 8 most frequent illustrations (mentioned more than 6 times) and the KCs categories they were offered for, by profession-group. We shaded common KCs categories ({# times the illustrations are mentioned in a profession-group}; [# times the illustration is linked to a KC category within the profession-group]).

Table 7a KCs to which participants offered the *Double-slit experiment* as an illustration (n = 29; 9 KCs categories)

PR {4}	PER {9}	HT {4}	PER+PR {6}	HT+PERVPR {6}
Superposition	Superposition [3]	Superposition [2]	Superposition [3]	Superposition
Quantum measurement	Quantum measurement			Quantum measurement [2]
WP duality [2]	WP duality		WP duality	
	Heisenberg principle	Heisenberg principle	Heisenberg principle	
	Non-locality		Non-locality	Non-locality
	Statistical nature and probability			Statistical nature and probability
	Quantization	Decoherence		Entanglement

Table 7b KCs to which participants offered *Polarization* as an illustration (n = 23; 9 KCs categories)

PR {1}	PER {10}	HT {3}	PER+PR {5}	HT+PERVPR {4}
Quantum measurement	Quantum measurement	Quantum measurement	Quantum measurement [2]	Quantum measurement
	Superposition [3]	Superposition [2]	Superposition	Superposition
	Quantization [2]			Quantization
	Statistical nature and probability		Statistical nature and probability	
	Heisenberg principle		Mathematical foundations	Qubit
	Entanglement			
	Non-locality			

Table 7c KCs to which participants offered *Stern-Gerlach* as an illustration (n = 20; 8 KCs categories)

PR {3}	PER {7}	HT {3}	PER+PR {2}	HT+PERVPR {5}
Quantum measurement	Quantum measurement	Quantum measurement		Quantum measurement
	Superposition [2]	Superposition		Superposition
Quantization	Quantization			Quantization [2]
Qubit			Qubit	Qubit
	Heisenberg principle	Heisenberg principle		
	Statistical nature and probability		Mathematical foundations	
	Non-locality			

Table 7d KCs to which participants offered *Qubit* as an illustration (n = 14; 8 KCs categories)

PR {10}	PER {3}	HT {0}	PER+PR {0}	HT+PERVPR {1}
Superposition [2]	Superposition			Superposition
Quantum measurement [2]	Quantum measurement			
Quantization [2]	Two-level system			
Heisenberg principle				
Entanglement				
Mathematical foundations				
Statistical nature and probability				

Table 7e KCs to which participants offered *Mach-Zehnder* as an illustration (n = 13; 7 KCs categories)

PR {3}	PER {5}	HT {0}	PER+PR {0}	HT+PERVPR {5}
Superposition	Superposition			Superposition [2]
Quantum measurement	Quantum measurement			Quantum measurement
	Quantization			Quantization
Wave-Particle duality	Statistical nature and probability			Qubit
	Non-locality			

Table 7f KCs to which participants offered *Spin* as an illustration (n = 10; 4 KCs categories)

PR {1}	PER {5}	HT {0}	PER+PR {1}	HT+PERVPR {3}
Superposition	Superposition [2]		Superposition	Superposition
	Quantization [2]			Quantization
	Entanglement			Qubit

Table 7g KCs to which participants offered *Matter waves* as an illustration (n = 6; 4 KCs categories)

PR {1}	PER {0}	HT {1}	PER+PR {3}	HT+PERVPR {1}
Superposition		Superposition		Superposition
			Wave-Particle duality	
			Non-locality	
			Classic vs. Quantum models	

Table 7h KCs to which participants offered *Double-well* as an illustration (n = 6; 6 KCs categories)

PR {0}	PER {6}	HT {0}	PER+PR {0}	HT+PERVPR {0}
	Superposition			
	Quantum measurement			
	Quantization			
	Heisenberg principle			
	Statistical nature and probability			
	Non-locality			

Appendix B

Tables 8a-8i: The illustrations offered for the 9 most prominent KCs categories. {# KCs entries per profession-group}; [# repetition of illustration in a specific profession-group]; Illustrations offered by more than one profession-group are shaded.

Table 8a Offered illustrations for *Superposition*

PR{7}	PER {7}	HT {7}	PER+PR {5}	HT+PERVPR {6}
Double-slit exp.	Double-slit exp. [3]	Double-slit exp. [2]	Double-slit exp. [3]	Double-slit exp.
	Polarization [3]	Polarization [2]	Polarization	Polarization
Spin states	Spin states [2]		Spin states	Spin states
	Stern-Gerlach	Stern-Gerlach		Stern-Gerlach
Mach-Zehnder	Mach-Zehnder			Mach-Zehnder
Qubit [2]	Qubit			Qubit
Matter waves		Matter waves		Matter waves
		Light interference		Light interference [2]
		Wave interference	Wave interference	
	Classical vs. quantum		Classical vs. quantum	
Single photon interferometry				Single photon interferometry
Two photon interference	Birefringent crystals	Diffraction of light [2]	Quantum eraser	Not like statistical probability
Michelson interferometer	Double well		Delayed-choice exp.	Schrödinger's cat

Table 8b Offered illustrations for *Quantum measurement*

PR{6}	PER {4}	HT {6}	PER+PR {4}	HT+PERVPR {4}
Polarization	Polarization	Polarization	Polarization	Polarization
Double-slit exp.	Double-slit exp.			Double-slit exp.
Stern-Gerlach	Stern-Gerlach	Stern-Gerlach		Stern-Gerlach
Wave function collapse	Wave function collapse			Wave function collapse
Mach-Zehnder	Mach-Zehnder			Mach-Zehnder
Qubit [2]	Qubit			
Zeno effect	Space and velocity measurement	Statistical nature	Two level system	Zhou-Wang-Mandel experiment
	Double well	Schrödinger's cat	Malus' law with a single photon	

Table 8c Offered illustrations for *Quantization*

PR{3}	PER {5}	HT {3}	PER+PR {7}	HT+PERVPR {4}
Stern-Gerlach	Stern-Gerlach			Stern-Gerlach [2]
	Polarization [2]			Polarization
	Mach-Zehnder			Mach-Zehnder [2]
	Spin [2]			Spin
	Energy levels		Energy levels	
	Energy quantization			Energy quantization
	Analogy of standing waves and a particle in a box		Analogy of standing waves and a particle in a box	
			Spectra (atoms, stars) [2]	Spectra (atoms, stars)
			Atom model	Atom model
		Single photon states		Single photon states
Qubit [2]	Atomic orbitals	Energy and radiation freq.	Franck-Hertz exp.	

Table 8d Offered illustrations for *Heisenberg principle*

PR{2}	PER {3}	HT {6}	PER+PR {3}	HT+PERVPR {4}
	Double-slit exp.	Double-slit exp.	Double-slit exp.	
	Position & Momentum	Position & Momentum	Position & Momentum	
	Stern-Gerlach	Stern-Gerlach		
	Ontological vs. Epistemological			Ontological vs. Epistemological
		Single slit		Single slit
Operators and Commutators	Polarization	Energy & Time		Heisenberg's microscope
Qubit	Double well			Comparison to human behavior
	BB84			

Table 8e Offered illustrations for *Entanglement*

PR{5}	PER {3}	HT {3}	PER+PR {1}	HT+PERVPR {4}
EPR exp.	EPR exp.	EPR exp.		
Bell's inequality [2]				Bell's inequality
Teleportation	Teleportation			
Ekert 91	Entanglement of many particles	CHSH games		Double-slit exp.
Qubit	Spin			Interferometry of single object
	Polarization			

Table 8f Offered illustrations for *Mathematical foundations*

PR{4}	PER {4}	HT {4}	PER+PR {3}	HT+PER∨PR {0}
	Linear algebra [2]	Linear algebra		
	Two-level system		Two-level system	
Wave function		Wave function		
Bloch sphere			Bloch sphere	
Qubit	Space and velocity of electrons	The Schrödinger eq. As an operator eq.	Analogy to other fields of physics	
Quantum games	Dirac notation		Polarization	
	Matrices			

Table 8g Offered illustrations for *Qubit*

PR{8}	PER {0}	HT {2}	PER+PR {2}	HT+PER∨PR {1}
Stern-Gerlach			Stern-Gerlach	Stern-Gerlach
Coherent control			Two-level system	Spin state
NV-center			Bloch sphere	Polarization
Bernstein 1967				Single photon state
Two component vector (real and complex)				Mach-Zehnder
Dirac notation				
Quantum numbers				
Hadamard gate				
Quantum circuit				
Bernstein-Vazirani alg.				

Table 8h Offered illustrations for *Statistical nature*

PR{3}	PER {1}	HT {1}	PER+PR {2}	HT+PER∨PR {2}
	Double-slit exp.			Double-slit exp.
	Polarization		Polarization	
Classical vs. quantum				Classical vs. quantum
Qubit	Mach-Zehnder	Quantum dice	Electrons in an atom	Statistics
Single photon interferometry	Stern-Gerlach		Malus' law with a single photon	
Fluctuation phenomena	Double well			

Table 8i Offered illustrations for *Wave-Particle Duality*

PR{3}	PER {1}	HT {1}	PER+PR {4}	HT+PER∨PR {0}
Double-slit exp.	Double-slit exp.		Double-slit exp.	
Mach-Zehnder			Matter waves	
Tunneling				
Quantum interference experiments				

Abbreviations
CP, Classical physics; CSA, Coordination support action; HS, High school; KC, Key concept; PCK, Pedagogical content Knowledge; PER, Physics education researchers; PR, Physics researchers and educators at the university level; QCI, Quantum concept inventory; QP, Quantum physics; QT, Quantum technology.

Author contributions
A.M., H.P., P.B. and K.K-L. wrote the main manuscript text. A.M., H.P., P.B., K.K-L. and K.S., did analysis and validation. K.S. and F.G provided extensive review. F.G. prepared figure 1. M.B. enhanced figures 5a and 5b. All authors contributed to collecting the data: preparing the questionnaire and disseminating it. All authors reviewed the manuscript and provided feedback.

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Data availability
The supporting data for this study is not publicly available. However, upon reasonable request, the corresponding author can provide access to the supporting data to researchers for verification and replication purposes. Requests for access to the supporting data should be directed to Avraham Merzel at avraham.merzel@mail.huji.ac.il.

Declarations

Ethics approval and consent to participate
This study was conducted in accordance with the ethical principles outlined by the Ethic committee of the Hebrew University. The study involved the collection of data through an online questionnaire. Participants were informed about the nature of the study and provided their consent before participating. Participation in this study was voluntary and anonymous. Participants were informed that their responses would be kept confidential and used solely for research purposes. The data collected included participants' country of residence and profession, and no personally identifiable information was recorded in any way. By voluntarily participating in the online questionnaire, participants acknowledged their informed consent to take part in the study and agreed to the use of their anonymized data for research and publication purposes.
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Consent for publication
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Competing interests
The authors declare no competing interests.

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