FINNISH UNIVERSITY STUDENTS' SOCIOCULTURAL EXPERIENCES AND VIEWS OF QUANTUM PHYSICS

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Quantum physics is increasingly visible in the news, movies, and popular media. It will shape our future, but do university students notice or care about it? Here, we explore 270 Finnish university STEM and non-STEM students' everyday experiences (past), relevance perceptions (present), and study interests (future) of quantum physics via questionnaire-based research. We find that a student's field of study influences neither noticing the word "quantum" in their free time nor perceiving it as relevant to society and everyday life. Students express moderate interest in studying various quantum physics topics, although they commonly consider them important for others, not themselves. By revealing students' perceptions, preferences, and motivations, these results help customize quantum physics education and respond to diverse needs.

INTRODUCTION

The increasing visibility of quantum technologies in news and media creates a new sociocultural environment and increases people's awareness of quantum physics (QP). The beginning of this century has seen a new rise in the number of novel quantum technology research, as well as hardware, patents, and start-ups (this is called the *second* quantum revolution) (Seskir et al., 2022, 2023; Seskir & Willoughby, 2023). The estimated worldwide investment in related scientific research and technological innovations reaches 38 billion euros (QURECA, 2023). Many countries have developed educational initiatives to prepare "the quantum workforce" and raise general quantum awareness. Finland is no exception; quantum physics and technologies are visible in Finland in increasing news of quantum technologies and in political discussions and roadmaps (InstituteQ, 2023; BusinessQ, 2022).

The visibility of quantum technology is beneficial for society, but it may also conceal danger, such as building *quantum hype*, which may result if the media loses contact with reality (Ezratty, 2022). Hype can be identified by observing "quantum" this or that while watching a movie or buying supermarket products, such as quantum dishwashing tablets or made-in-Finland quantum magnesium supplements. Experts can quickly notice such applications and their quantum relevance; it is unclear if the same applies to non-experts. Of particular importance is to understand the perceptions of QP by the future quantum workforce, the students who recently started their university education. The way

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our quantum future shapes is based on the perceptions they have and the decisions they make today.

While the relationship between novel quantum technologies and society remains unexplored (Seskir et al., 2023; Wolbring, 2022), students' perceptions of QP tell us a lot about the impact of the visibility of quantum technologies on society. Moreover, current QP education literature has focused on the experts' points of view through developing teaching material for QP or empirical research on learning and teaching of QP (Bitzenbauer, 2021b; Michelini & Stefanel, 2023). Thus, shifting the research focus from content to students and their opinions will renew and benefit the QP education development.

THEORETICAL BACKGROUND: THE INFLUENCE OF THE SOCIOCULTURAL ENVIRONMENT

Students are exposed to quantum technologies and quantum hype through the sociocultural environment. The sociocultural environment has a pivotal effect on people's values and beliefs (Vygotsky, 1978). Values and beliefs, in turn, influence interests and attitudes toward different subjects, which in turn govern study decisions and career choices (Regan & DeWitt, 2015; Tytler & Osborne, 2012). The sociocultural environment also impacts identities, which develop as co-constructions between individuals and their surroundings and relationships (Carlone, 2022; Regan & DeWitt, 2015; Shanahan, 2009). Sociocultural environment can create views and "future imaginaries" about physics professions, which can be realistic and motivating or unrealistic and discouraging (Bennett et al., 2022; Johansson & Larsson, 2022). Sociocultural environment is an important source of knowledge. It can provide the first QP learning experiences (Bennett et al., 2022), even if the reliability of knowledge may be questionable.

We define attitudes as feelings or evaluative judgments toward a topic (Ajzen, 2001; Crano & Prislin, 2006; Kind et al., 2007). Attitudes toward science influence students' preferences and study choices (Regan & DeWitt, 2015). We use "view" as an umbrella term to describe students' attitudes, beliefs, and expectations and "perception" to describe students' thoughts on their knowledge and understanding.

Students' interests and identities change constantly (Renninger & Hidi, 2016). In this article, we look at interest through the interest development theory of Hidi and Renninger (Hidi & Renninger, 2006; Renninger & Hidi, 2016). The theory presents interest as a psychological state and cognitive and affective motivational predisposition to re-engage with the topic in question. It influences behavior (Regan & DeWitt, 2015; Renninger & Hidi, 2016) and aids learning (Renninger & Hidi 2016, 2020; Lee et al., 2014; Lent et al., 1994). According to the theory, interest develops in four phases: it starts with a triggered situational interest, continues to a maintained situational interest, evolves further to emerging individual interest, and possibly culminates in a well-developed individual interest (see Hidi & Renninger, 2006; Renninger & Hidi, 2016). External triggers and support are needed to generate interest and sustain its growth. To this end, sociocultural and educational environments play a central role, especially in the initial triggering and maintaining of situational interest; at later phases of interest development, individuals can act and maintain interest independently (Renninger & Hidi, 2016; Renninger et al., 2019). The visibility of QP in movies, news, and social media is a particularly powerful interest trigger, especially due to surprising and personally relevant information as well as visual and emotional content (Renninger et al., 2019). Particularly suitable triggers in educational environments are social interactions, role models, and meaningful engagement with QP.

Analogous to interest, we can define triggered identity work, a term introduced by Carlone that borrows the idea of triggered situational interest by Hidi and Renninger (Carlone, 2022). Triggered identity work is situational and short-term, usually triggered by external variables in sociocultural and educational environments. In QP context, triggered identity work can start, e.g., from reading QP news and hearing about quantum technology career opportunities. It can evolve into more enduring identity work, eventually leading to a quantum technology career choice. However, without proper maintenance, identity work can also vanish.

Finally, it is important to distinguish interest and curiosity. While both imply information seeking without extrinsic rewards, they are distinct regarding different triggers and duration (Renninger & Hidi, 2016). A knowledge gap triggers curiosity, and upon filling the gap, the curiosity is satisfied and can vanish or trigger interest (Renninger & Hidi, 2016; Peterson & Hidi, 2019).

QUANTUM PHYSICS AND RELATED TECHNOLOGIES IN FINLAND

According to the BCG Henderson Institute report, Finland has the potential to show leadership in private QP initiatives (Candelon et al., 2022). Moreover, better educational organization and national strategy and coordination can allow Finland to play a significant role in certain areas and applications of quantum technologies (Candelon et al., 2022; InstituteQ, 2023). Today, Finland is one of the few countries with its 5-qubit quantum computer (Business Finland, 2022; Candelon et al., 2022; The Finnish Academy for Science and Letters, 2023), 20- and 54-qubit computers being under construction (IQM, 2022). Research groups drive technological and theoretical development at seven national universities and several companies working on a large spectrum of new quantum technologies, from quantum sensors to quantum computers, from quantum computing software to quantum technology components (InstituteQ, 2023; The Finnish Academy for Science and Letters, 2023). The number of people employed by Finnish quantum companies is nearing 500 (InstituteQ, 2023). Finland also continues to work toward building quantum science and technology networks, ecosystems, and infrastructures.

The rise of quantum technologies in education is slower compared to business. The basics of quantum phenomena are excluded from the current curriculum of compulsory education (grades 1-9). Following, in upper secondary school, students choosing an extended physics curriculum will encounter a course in modern physics, which includes mentions of quantization, quantum technologies, and quantum structures (Finnish National Agency for Education, 2019). In addition to these, higher education institutes and quantum companies have outreach activities and courses on QP at different levels, *e.g.*, *Quantum Mechanics and Theory of Relativity to the Laypeople* — Massive Open Online Course (MOOC) by the University of Jyväskylä (https://www.jyu.fi/fi/avoin-yliopisto/opinnot/fysiikka-avoimessa-yliopistossa) and *IQM Academy* — free online quantum training course by IQM (https://www.iqmacademy.com/). Nevertheless, a proper education of QP is not possible until one is at the university level. Encounters with QP either remain accidental or depend on personal interest and curiosity.

Even without heavy mathematical formalism, learning QP requires a fundamental conceptual change that takes time and effort (Michelini & Stefanel, 2023; Sakurai, 1994). Consequently, quantum physics education research seeks to optimize the teaching and learning of abstract QP and to help students overcome difficulties (see, *e.g.*, Brundage et al., 2023; Emigh et al., 2020; Marshman & Singh, 2015, 2017; Modir et al., 2019; Tu et al., 2023; Winkler et al., 2021). QP education research also contributes to raising awareness and acceptance of quantum technologies in society (see, *e.g.*, Foti et al., 2021; Goorney et al., 2022; Meinsma et al., 2023; Satanassi et al., 2021). As the recently established Finnish Quantum Institute (https://instituteq.fi/) pointed out, we need to raise *"the readiness of Finnish society for the disruptive potential and implications that quantum technologies will have for society and the economy at large,"* for example, by developing targeted and well-structured outreach initiatives (InstituteQ, 2023). Such initiatives would also help mitigate quantum hype.

In addition to preparing a quantum-ready society, increasing the volume of quantum technology expertise and workforce can only be achieved by increasing the volume of quantum education (Candelon et al., 2022; The Finnish Academy for Science and Letters, 2023). Consequently, we need more opportunities and programs for higher education specializations as well as possibilities for retraining and upskilling through lifelong learning (InstituteQ, 2023; The Finnish Academy for Science and Letters, 2023; Greinert et al., 2023). Adopting quantum technologies requires interdisciplinary specialists and collaboration between experts from multiple disciplines (Hughes et al., 2022).

Earlier, Corsiglia et al. (2023) studied university students' perspectives and expectations on intuition in quantum mechanics, Palmgren et al. (2022) university students' self-efficacy beliefs in a quantum mechanics course during teaching reform, Testa et al. (2020) the effects of introductory quantum mechanics instruction on high school students' overconfidence bias, and Moraga-Calderon et al. (2020) the relevance of learning quantum physics from a high-school student's perspective. However, related research is still minimal, especially regarding the views of non-STEM students and the larger audience. By investigating students' QP views, perceptions, and past experiences, we could develop QP education that better suits their hopes and needs.

To attract university students with different majors to study QP and to work in the quantum technology sector in the future, we also need to understand their perceptions and views on QP and related technologies, which are constantly affected by the sociocultural environment. Our study aims to contribute to this understanding by addressing the following research questions (addressing students' different temporal perspectives):

1. Where do Finnish university students recognize QP in their lives? (past)
2. How do they perceive the relevance of QP? (present)
3. To what extent are they interested in studying QP topics? (future)

RESEARCH METHODS

Data collection

To address these questions, we designed a Finnish-language questionnaire for Finnish university students. The questionnaire addressed 1) their past experiences with QP, 2) their self-assessed knowledge of QP, 3) the media and contexts where they had come across QP, 4) their current views on the relevance of QP to them and their career, and 5) their preferences and interests to study QP. The questionnaire also collected background data about their major and studies before university.

The study and the questionnaire development were based on the work of Moraga-Calderon et al. (2020). They focused on students' topics of interest and perceptions of the relevance of QP on individual, societal and vocational dimensions; this focus relates well to our second and third research questions. For a wider perspective on the effect of the sociocultural and educational environment, we modified the questions and response items of Moraga-Calderon et al. (2020) and added new questions that took into account the visibility of "quantum" in Finland as well as its identity and interest triggers. We extensively discussed all questions and response items, and the questionnaire underwent multiple iterations.

In designing and formulating our questions, we followed the design principle by Moraga-Calderon et al. (2020): "to not underestimate students' judgment and capacity of reflection, and indeed listen to what they have to say." This principle suggested asking students about their own perceptions (not merely probing students' knowledge of QP) and preferred teaching formats and methods (not merely asking to choose from existing QP modules). The questionnaire was implemented using open, multiple-choice, and single-choice items (Appendix). The first question *In which contexts have you come across the word "quantum"?* was followed by a summary of the meaning of QP in the research. Then, students were asked about the frequency of QP encounters in different contexts, their self-assessed level of QP knowledge, the means of acquiring that knowledge, and one to five applications or technology items they know or suspect are related to QP. All these questions tested students' past experiences with QP and were related to the first research question. Following, the students were asked about the relevance of QP to suggested items and the influence of given items on their perceptions of QP relevance, which probed their current views related to the second research question. Finally, the students were asked about their interest in studying certain aspects of QP, their motivations to study QP in different contexts, and their preferred methods to carry out those studies; these questions were related to the third research question.

We distributed the questionnaire to Finnish university students using our networks and connections at the beginning of 2023. As a result, 270 students answered the questionnaire (122 men, 133 women, eight other genders, and seven declined to respond), 50% of which were studying STEM subjects (natural sciences and technical subjects) and 50% non-STEM fields (such as business, humanities, and social sciences). Most responses came from the University of Turku (201 students), others from the University of Helsinki, the University of Jyväskylä, and Aalto University.

Data analysis

The single-choice questions were analyzed separately for all students and STEM and non-STEM students to identify the influence of study major. Open-ended and multiple-choice questions were analyzed by inductive thematic coding (Braun & Clarke, 2006). The exception is the question that asks to list one to five applications or technology items students know or suspect are related to QP. For that question, we used pairwise comparisons to rank all 270 responses (181 unique) according to the quantum nature of the operational principle of applications or technologies listed in each response, with 7-8 comparisons per response (Kyne, 2023). Done by the first author, the pairwise comparisons resulted in a winning rate for each response, with a value between zero (classical-like application) and one (quantum-like application).

In addition, we analyzed the multiple-choice data with unsupervised machine-learning tools (Pedregosa et al., 2011). All answers were assigned numerical values on a linear scale, such as never/irrelevant/no effect/*etc.* equal to one, often/relevant/affects strongly/*etc.* equal to four, and similarly for other options. Moreover, gender assignments were female (1), other/not answering (2), and man (3); current study field assignments were non-STEM-related fields (1) and STEM-related fields (2); and study background was characterized by the absence (1) and presence (2) of advanced physics studies at the upper secondary level. This data was then analyzed using principal component analysis and K-means clustering (Lloyd, 1982).

RESULTS

Students' past experiences with quantum physics

Nearly all respondents (98%) had attended upper secondary school, half with advanced physics courses. Most students (84%) had encountered QP, but many did not know much about it (45%) or knew it a little (39%). Most non-STEM students (64%) responded that they didn't know much about QP, while most STEM students (70%) responded that they knew little about QP.

The students had gained their QP knowledge from news and articles (60%), upper secondary school advanced physics courses (35%), and nowhere (24%). Only 9% of students are studying QP courses at a university. Minor contributions to QP knowledge were reported from a school visit, exhibition, or similar event related to quantum physics, engaging with quantum physics as a hobby, and books, discussions, and various internet and social media resources.

With thematic coding, one to five QP applications from each student (some thousand applications in total) were divided into six categories:

1. Household appliances (e.g., cell phone, TV, computer, microwave, electronics in general, solar panels)
2. Nuclear (e.g., particle accelerator, hadron collider, CERN, nuclear power, nuclear technologies, fusion, fission)
3. Research instruments (e.g., microscope, laser, MRI, photonics, and quantum optics instruments)
4. Space and time (e.g., spaceship, space technology, satellites, space events, GPS, universal time, time machine)
5. Future technologies (e.g., quantum computer, qubits, cryptography, information processing, information security)
6. Misc (e.g., hairspray, light bulb, magnet, radio, bicycle, water boiler)

some of which are more and others less quantum-like categories. Often, a student's response included items from multiple categories.

The results of pairwise comparison of responses are shown in Fig. 1. STEM students provided more responses with values one (quantum-like applications), and non-STEM students with values zero (classical-like applications). Otherwise, there are no significant differences between students with different majors; all students list both quantum- and classical-like applications.

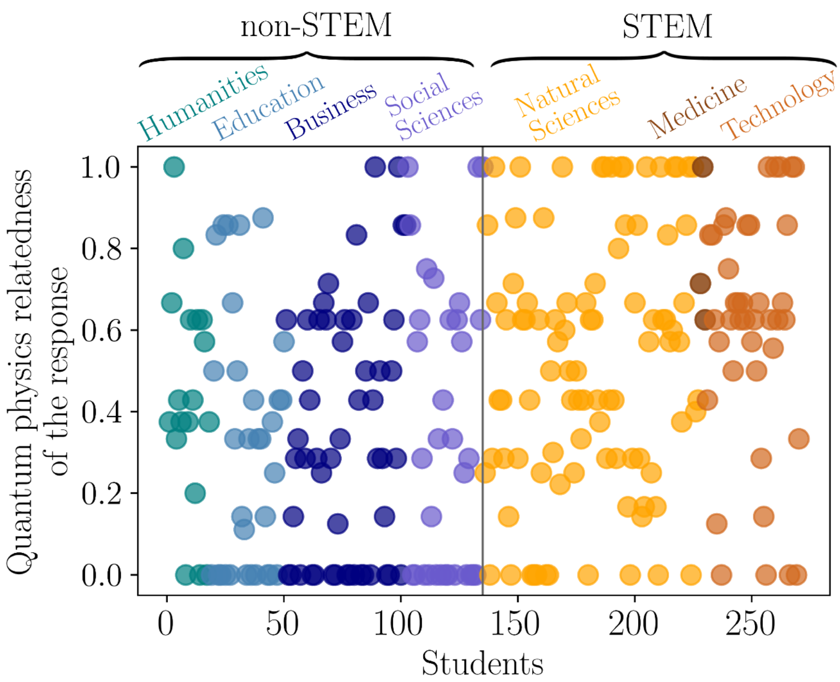

Figure 1. Familiarity with quantum applications. The plot shows each student's responses ranked according to the quantum nature of the operational principle of applications or technologies listed (zero being a classical-like application or technology, one being a quantum-like one). The vertical line divides non-STEM (on the left) and STEM students (on the right), and colors denote more detailed study fields.

Previous encounters with QP were diverse. According to students' open responses, they had encountered the word "quantum" in pop culture (43%), free time (39%), books or YouTube, and in their surroundings such as news and conversations (26%). These encounters were independent of the study major. "Quantum" had also been noticed in studies or work (46%), primarily by students in STEM fields (two-thirds). According to the multiple-choice question, the most important contexts for encountering QP were movies, TV, work, and studies (Fig. 2). Significant contexts are news and social media; the least relevant are radio and consumer products.

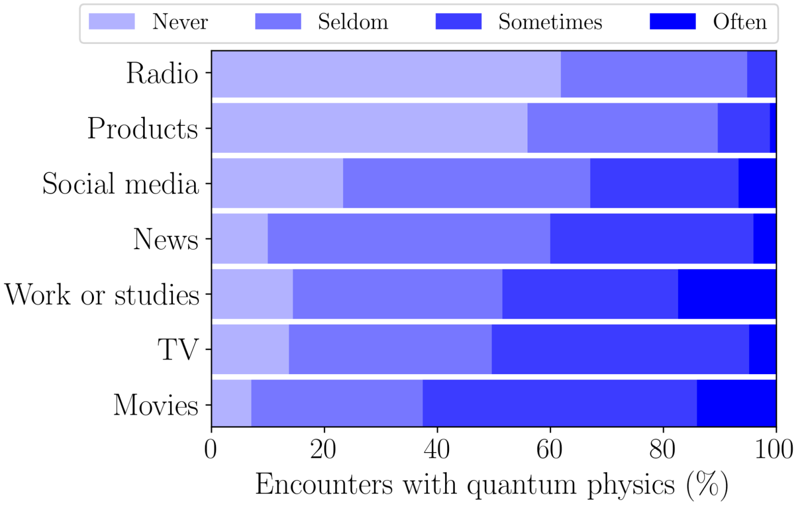

Figure 2. Encounters with quantum physics. The bars show how often students have encountered quantum physics in different suggested media.

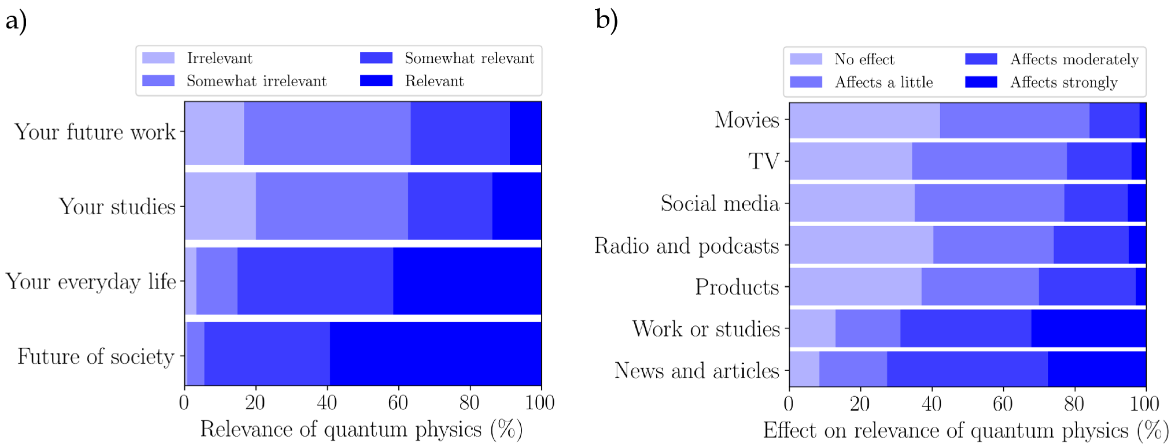

Figure 3. Relevance of quantum physics and how to influence it. a) Students' views on the relevance of QP to the different aspects of their lives. b) Students' views on how different influencers affect their opinion about the relevance of QP.

Present perceptions and future views of students on quantum physics

The majority of the students considered QP to be relevant or somewhat relevant for the future of society (94%) and their everyday lives (85%), but over 60% of them saw QP as mainly irrelevant to their studies and future work (Fig. 3a). Students reported that the relevance of QP is primarily influenced by news and articles (73%) and work or studies (69%) (Fig. 3b). Simplifying, students *consider QP relevant for society but not for themselves.*

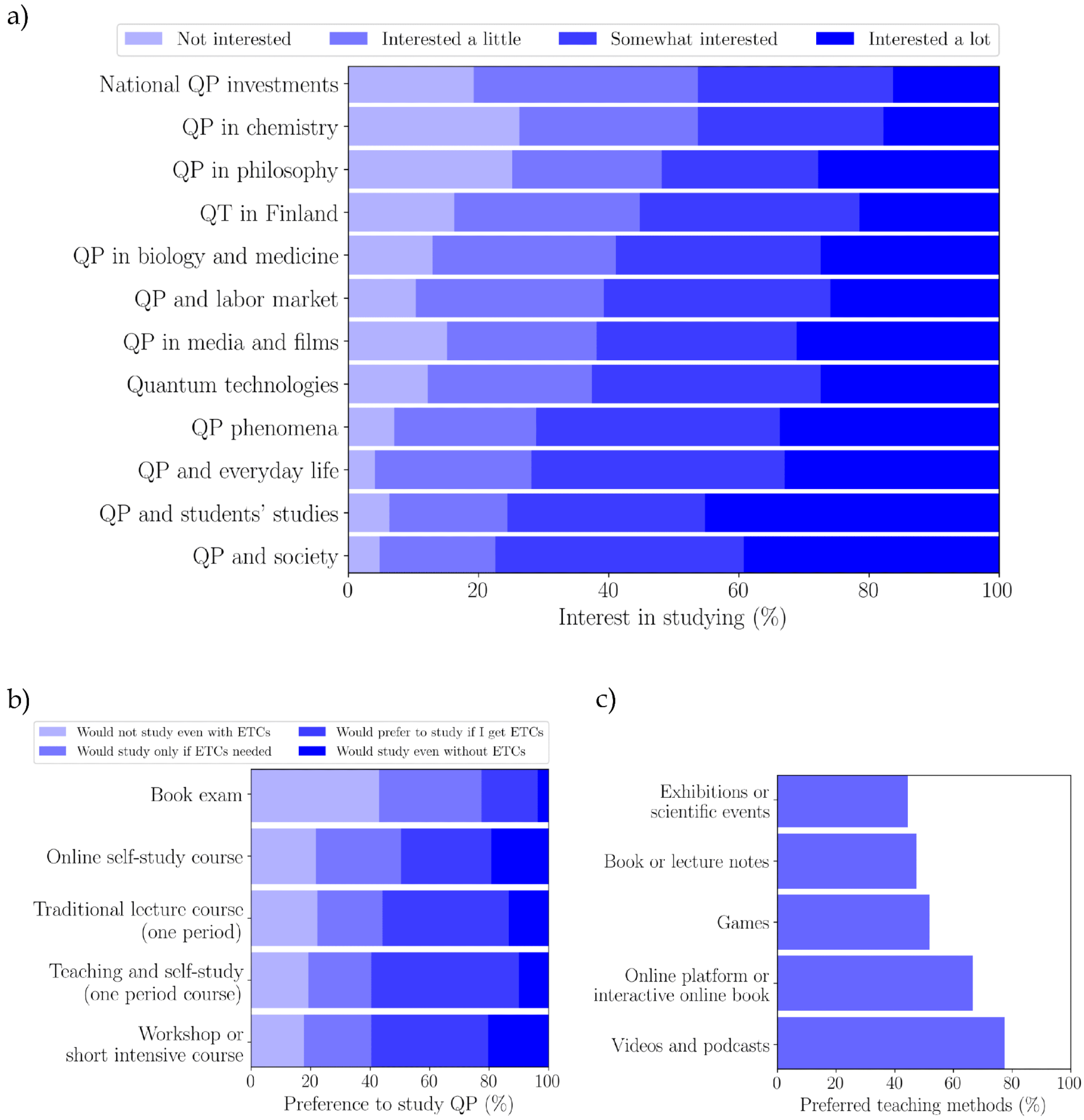

Figure 4. Why study QP and how? a) Students' interest in studying different topics or aspects of quantum physics. b) Students' motivations to study quantum physics in different contexts. c) Preferred study methods for the quantum physics topics in panel a.

Students expressed reasonable interest in studying several QP topics, especially regarding QP relevance to society and students' own studies (Fig. 4a). Should such studies fit into their curricula and study credits be given, they would prefer to study specific QP topics either in short intensive or full-length course (Fig. 4b). Regarding study methods, students prefer videos, podcasts, and online platforms (Fig. 4c). Half of the students would also prefer games. However, half the students still favor traditional textbooks and lecture notes.

Predicting interest in learning quantum physics

With most of the data discussed above, we carried out principal component analysis (PCA) and K-means clustering of students. As a result, the first PC characterizes the interest in QP, its importance for own studies, and related qualities; this component we term *Personal relevance* (Fig. 5). The first PC does not correlate with gender, current field of study, or the frequency of QP encounters. The second PC characterizes the study field, history with advanced physics studies at the upper secondary level, and the influence of movies, radio, TV, news, and social media; this component we term *Media influence.* Therefore, the perceived general importance of QP and interest in learning QP correlate little with the study field and the media influence; the cause-and-effect relation needs to be clarified.

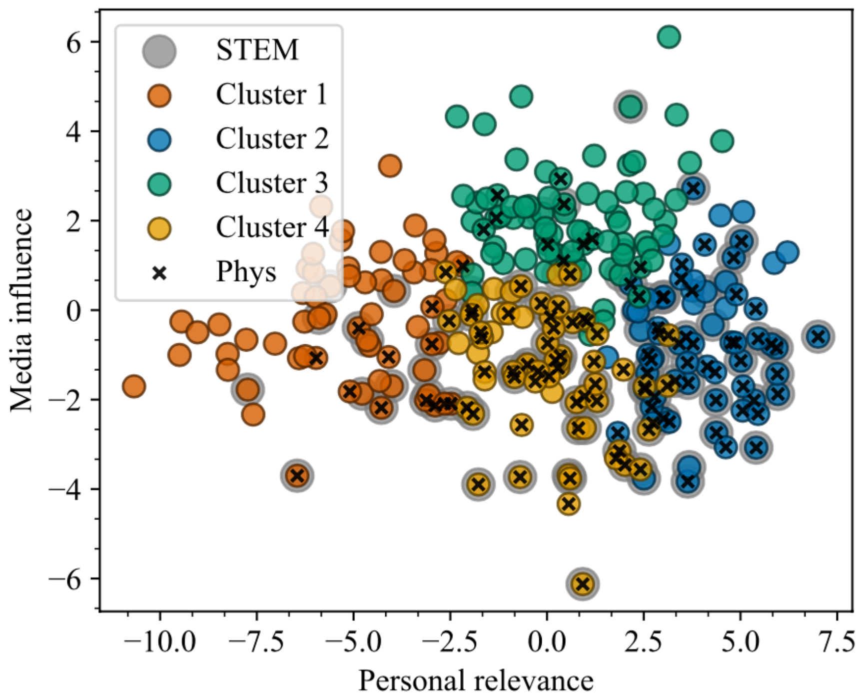

Figure 5. Analysis of multiple-choice questions by unsupervised machine learning tools. The students in the principal component plot are bundled by K-means clustering (colors). The plot identifies students with advanced physics studies at the upper secondary level (crosses) and students studying STEM fields at a university (grey shading).

The elbowing method, used to identify an appropriate number of clusters, revealed that it was challenging to cluster students (Rousseeuw, 1987). In other words, students' opinions are diverse in a continuous fashion, which implies that it is challenging to influence certain types of students by one-size-fits-all outreach. Therefore, we use here K-means with four clusters mainly for illustrative purposes (Fig. 5). The four clusters consist of non-STEM students not interested in learning QP (cluster 1), STEM students interested in learning QP (cluster 2), primarily non-STEM students with opinions of QP highly influenced by popular media (cluster 3), and STEM students with opinions uninfluenced by popular media (cluster 4). The tail of cluster 1 along the first PC is longer than that of cluster 2, implying that there is less range to be interested in QP and more range to be uninterested in QP.

Extremely favorable and unfavorable interests in QP happen when the influence of movies and popular media is neutral. Movies and popular media have the strongest influence on students with an impartial interest in QP; often, these are non-STEM students who lack a physics background at upper secondary school. A possible explanation for this is that students who know little about QP from other contexts are naturally more easily influenced by media. Moreover, as demonstrated by PCA, gender does not correlate with the QP interest and relevance. Background with advanced physics studies at upper secondary school often leads to studies in STEM fields, as expected (Fig. 5).

Finally, as QP educators, we are interested in understanding what leads to interest in learning QP. To this end, we performed multivariate linear regression to predict the interest in learning QP based on other background responses, obtaining a reasonable model ($R2=0.42$ and $F=32.7$ with $p<0.001$). The interest in learning QP is governed by perceived importance (coef *0.52*, $t=8.3$, $p<0.001$), level of knowing QP (coef *0.22*, $t=4.0$, $p<0.001$), and frequency of encountering QP (coef *0.17*, $t=2.1$, $p<0.05$). It is particularly reassuring to see that the interest is mostly influenced by perceived importance. QP *is* important, so this alignment forms a healthy foundation for developing QP interest further. One may summarize that an optimum way to nurture QP interest is to *frequently provide knowledge about QP, especially about its importance.*

LIMITATIONS

We could not obtain responses from all Finnish universities and all study fields uniformly, which resulted in an imbalance in the number of responses from different universities and fields. In addition, the number of responders could have been higher to more comprehensively present QP views and perceptions of Finnish university students.

The questionnaire was not validated, and response items in the questionnaire reflect to some extent authors' own expectations and experiences with QP in Finland. Also, we acknowledge the existence of possible uncertainties in the correct interpretation of responses, especially in open-ended questions, such as the one involving listing five quantum applications. Thus, in the future the questionnaire could include further clarification possibilities for open-ended questions.

Improving the method of collecting data about students' awareness of QP applications would be beneficial. The questionnaire did not request to specify the reasons why given applications were considered quantum-like. Thus, for most of the responses, we could not identify if students wrote applications based on knowledge or sheer guessing. This prospect for interpretation affected the pairwise comparison of items by creating a possibility of over- or underinterpreting some responses, especially the ones between the two extremes. One possible solution could be, after asking students to list five quantum applications, asking them to evaluate on Likert scale how sure they are about the relation of listed items to quantum physics.

DISCUSSION AND CONCLUSIONS

The second quantum revolution is indeed visible for Finnish university students, as almost all students have at least heard about QP independent of their chosen study field. Students learn QP from news and articles, not only high school courses or university studies. They also notice QP in popular culture, during their free time, and in their surroundings. Differences between STEM and non-STEM students' experiences due to the sociocultural environment are small, despite the plausible assumption that noticing QP in the first place would require some knowledge or interest—qualities that are more prevalent in STEM students. Consequently, as most students perceived their knowledge of QP to be limited, the situation leaves plenty of room for non-scientific "quantumness" and creates an imminent danger for quantum hype.

Nearly all students consider QP relevant to the future of society and their lives but less to their studies and future work. This attitude of QP being "*important, but not for me*" is known in the literature (Moraga-Calderon et al., 2020; Jenkins & Nelson, 2005; Osborne & Collins, 2001). As Moraga-Calderon et al. (2020) suggested, this attitude can arise "*from students not seeing the societal relevance of learning quantum physics.*" Because we found that students recognize their encounters with QP and are curious about them, we propose that this attitude may also derive from the absence of QP in the basic curricula of different study fields or from the sociocultural environment; this absence renders students unable to relate QP with their future studies and careers. Our proposal is aligned with the results of the ASPIRES project, which has shown that students with low Science Capital are likely to see science "not for me" (Archer et al., 2020).

STEM students notice QP in their studies and work, and they know more about QP applications and technologies, which indicates the influence of the present curriculum and educational environment on students. At the same time, while news, articles, studies, and work broadly influence students' views on QP relevance, social media and popular culture influence is particularly pronounced in non-STEM students. These observations demonstrate the influence of the sociocultural environment, especially with people ignorant of QP. Consequently, we argue that it is possible to control neither the reliability of knowledge nor the interest or identity triggering by the sociocultural environment. This lack of control leaves a good niche for educational and outreach efforts.

Fortunately, students' satisfactory interest and curiosity in different QP topics, regardless of gender and current field of study, is a significant motivational factor for learning and poses an excellent starting point for developing QP education (Renninger & Hidi, 2016; Peterson & Hidi, 2019). To avoid the harmful effects of quantum hype (Ezratty, 2022), to provide better educational solutions to raise the quantum workforce (World Economic Forum, 2022), and to enable students' shaping of educational paths and scientific identities (Holmegaard, 2015), we need to utilize students' existing motivation and find ways to provide all university students with the possibility to learn QP. Considering the poor clustering of students' responses in our study, basic QP education ought to be customized, taking into account the views, perceptions, and interests of each target group. Our findings further suggest teaching to be organized so that students would have the possibility to identify the relevance of QP at a personal level and relate QP to society, everyday life (*e.g.* technology), and personal studies (Fig. 4a). QP visibility in the sociocultural environment should be acknowledged in teaching, for example by correcting misconceptions from pop culture. Optimally, teaching would include videos, podcasts, games, and technology-enhanced learning environments (Fig. 4b&c), methods that are intensively studied in contemporary education research. Games and videos are helpful particularly for familiarizing non-intuitive quantum phenomena (Chiofalo et al., 2022; Foti et al., 2021).

Education in Finland faces many difficulties, as the students need to learn both the content and a spectrum of generic skills like problem-solving, critical thinking, and soft skills. The results of the PISA 2022 test show declining levels of mathematical skills among Finnish children, which challenges their further education. Consequently, we need to introduce quantum physics at universities more and more carefully, searching for ways to fit QP contents into students' overloaded schedules, avoiding pressure but enabling triggering and QP interest maintenance. However, learning QP can also be valuable without mathematical formalism, for QP can teach things about technology, the nature of science (Stadermann & Goedhart, 2021), and deterministic ways of thinking (Bitzenbauer, 2021a). One solution could be the gentle inclusion of QP knowledge in pertinent university curricula and the development of Finnish language MOOCs and other online learning resources, in addition to the existing *Quantum mechanics and theory of relativity to the laypeople* (https://www.jyu.fi/fi/avoin-yliopisto/opinnot/fysiikka-avoimessa-yliopistossa).

To summarize, our findings shed light on the influence of sociocultural environment on university students' QP views and perceptions and reveal students' unexpected extent of willingness and readiness to study QP. In contrast to reports echoing negative adolescence-time attitudes toward physics and science in general (Barmby et al., 2008; Schreiner, 2006; Steidtmann et al., 2022; Vedder-Weiss & Fortus, 2012), our findings indicate curiosity and interest in learning QP. We also find that gender plays no role in perceived relevance or interest in QP, even if it may influence physics specialization or study major in general (*e.g.* Barthelemy & Knaub, 2020; Stoet & Geary, 2018; Moshfeghyeganeh & Hazari, 2021). Aligned with the skills required in the quantum industry (Hughes et al., 2022; Aiello et al., 2021; Kaur & Venegas-Gomez, 2022), our findings also indicate an urgent need to educate all university students with basic knowledge of QP. Yet further research is required for more in-depth understanding of the factors underlying the observed students' views, attitudes, and perceptions.

APPENDIX

Tabular 1. The Questionnaire

Questionnaire items	Type of question
What subject do you study?	Open
In which university do you study?	Open
Tell about your upper secondary studies	Single-choice
Your gender	Single-choice
In which contexts have you come across the word “quantum"?	Open
How often have you encountered QP in the following contexts?	Single-choice
How familiar are you with QP?	Single-choice
How did you get to know QP?	Multiple-choice and open
Please list at most five applications or technology items you know or suspect being related to QP.	Open
To which of the following items do you think QP is relevant?	Single-choice
How much do the following items influence your perceptions on the relevance of QP?	Single-choice
How interested would you be in studying the following subjects?	Single-choice
Would you study the previous items and in which ways?	Single-choice
Which methods would you prefer for the earlier mentioned QP studies?	Multiple-choice and open
Free comment (non-obligatory)	Open

REFERENCES

Aiello, C. D., Awschalom, D. D., Bernien, H., Brower, T., Brown. K. R., Brun, T. A., Caram. J. R., Chitambar, E., Di Felice, R., Edmonds, K. M., Fox, M. F. J., Haas, S., Holleitner, A. W., Hudson, E. R., Hunt, J. H., Joynt, R., Koziol, S., Larsen, M., Lewandowski, H. J., … Zwickl, B. M. (2021). Achieving a quantum smart workforce. *Quantum Science and Technology*, *6*(3), 030501. https://doi.org/10.1088/2058-9565/abfa64

Ajzen, I. (2001). Nature and operation of attitudes. *Annual Review of Psychology*, *52*(1), 27–58. https://doi.org/10.1146/annurev.psych.52.1.27

Archer, L., Moote, J., MacLeod, E., Francis, B., & DeWitt, J. (2020). *ASPIRES 2: Young people's science and career aspirations, age 10-19*. UCL Institute of Education. https://www.sciencecentres.org.uk/documents/492/Aspires_2_full_report.pdf

Barmby, P., Kind, P. M., & Jones, K. (2008). Examining changing attitudes in secondary school science. *International Journal of Science Education*, *30*(8), 1075-1093. https://doi.org/10.1080/09500690701344966

Barthelemy, R. S., & Knaub, A. V. (2020). Gendered motivations and aspirations of university physics students in Finland. *Physical Review Physics Education Research*, *16*(1), 010133. https://doi.org/10.1103/PhysRevPhysEducRes.16.010133

Bennett, R., Zohrabi Alaee, D., & Zwickl, B. M. (2022). Analysis of Physics Students' Subfield Career Decision-Making Using Social Cognitive Career Theory. *Proceedings of the Physics Education Research Conference (PERC) 2022*, USA, 51-56. https://doi.org/10.1119/perc.2022.pr.Bennett

Bitzenbauer, P. (2021a). Effect of an introductory quantum physics course using experiments with heralded photons on preuniversity students' conceptions about quantum physics. *Physical Review Physics Education Research*, *17*(2), 020103. https://doi.org/10.1103/PhysRevPhysEducRes.17.020103

Bitzenbauer, P. (2021b). Quantum Physics Education Research over the Last Two Decades: A Bibliometric Analysis. *Education Sciences*, 11(11), Article 699. https://doi.org/10.3390/educsci11110699

Braun, V., & Clarke, V. (2006) Using thematic analysis in psychology, *Qualitative Research in Psychology*, *3*(2), 77-101. https://doi.org/10.1191/1478088706qp063oa

Brundage, M. J., Malespina, A., & Singh, C. (2023). Peer interaction facilitates co-construction of knowledge in quantum mechanics. *Physical Review Physics Education Research*, *19*(2), 020133. https://doi.org/10.1103/PhysRevPhysEducRes.19.020133

Business Finland. (2022, August 22). *Quantum technology company IQM Finland exports Finnish deep tech expertise with the help of Business Finland*. Retrieved April 9, 2024. https://www.businessfinland.fi/en/whatsnew/cases/2022/quantum-technology-company-iqm-finland-exports-finnish-deep-tech-expertise-with-the-help-of-business-finland

BusinessQ. (2022). *Business Roadmap for BusinessQ*. https://instituteq.fi/wp-content/uploads/2023/02/BusinessQ-roadmap-v1.0-2022.pdf

Candelon, F., Bobier, J.-F., Courtaux, M., & Nahas, G. (2022). *Can Europe Catch Up with the US (and China) in Quantum Computing?* BCG Henderson Institute report. https://web-assets.bcg.com/09/16/38b8f0114aada4ce45b6bca9f5c7/bcg-can-europe-catch-up-with-the-us-and-china-in-quantum-computing-sep-2022-r.pdf

Carlone, H. B. (2022). Understanding and Contextualizing the Field of Science Identity Research. In H. T. Holmegaard, & L. Archer (Eds.), *Science Identities*, (pp. 3-20). Springer. https://doi.org/10.1007/978-3-031-17642-5_1

Chiofalo, M. L., Foti, C., Michelini, M., Santi, L., & Stefanel, A. (2022). Games for Teaching/Learning Quantum Mechanics: A Pilot Study with High-School Students. *Education Sciences*, *12*(7), Article 446. https://doi.org/10.3390/educsci12070446

Corsiglia, G., Pollock, S., & Passante, G. (2023). Intuition in quantum mechanics: Student perspectives and expectations. *Physical Review Physics Education Research*, *19*(1), 10109. https://doi.org/10.1103/PhysRevPhysEducRes.19.010109

Crano, W. D., & Prislin, R. (2006). Attitudes and persuasion. *Annual Review of Psychology*, *57*(1), 345–374. https://doi.org/10.1146/annurev.psych.57.102904.190034

Emigh, P. J., Gire, E., Manogue, C. A., Passante, G., & Shaer, P. S. (2020). Research-based quantum instruction: Paradigms and Tutorials, *Physical Review Physics Education Research*, *16*(2), 020156. https://doi.org/10.1103/PhysRevPhysEducRes.16.020156

Ezratty, O. (2022). *Mitigating the quantum hype*. ArXiv. https://doi.org/10.48550/arXiv.2202.01925

Finnish National Agency for Education. (2019). *National Core Curriculum for General Upper Secondary Education 2019*.

Foti, C., Anttila, D., Maniscalco, S., & Chiofalo, M. L. (2021). Quantum Physics Literacy Aimed at K12 and the General Public *Universe*, *7*(4), Article 86. https://doi.org/10.3390/universe7040086

Goorney, S., Foti, C., Santi, L., Sherson, J., Yago Malo, J., & Chiofalo, M. L. (2022). Culturo-Scientific Storytelling. *Education Sciences*, *12*(7), Article 474. https://doi.org/10.3390/educsci12070474

Greinert, F., Müller, R., Bitzenbauer, P., Ubben, M. S., & Weber K.-A. (2023). Future quantum workforce: Competences, requirements, and forecasts. *Physical Review Physics Education Research*, *19*(1), 010137. https://doi.org/10.1103/PhysRevPhysEducRes.19.010137

Hidi, S., & Renninger, K. A. (2006). The four-phase model of interest development, *Educational Psychologist*, *41*(2), 111–127. https://doi.org/10.1207/s15326985ep4102_4

Holmegaard, H. (2015). Performing a Choice-Narrative: A qualitative study of the patterns in STEM students' higher education choices. *International Journal of Science Education*, *37*(9), 1454-1477. https://doi.org/10.1080/09500693.2015.1042940

Hughes, C., Finke, D., German, D.-A., Merzbacher, C., Vora P.M. & Lewandowski, H. J. (2022). Assessing the Needs of the Quantum Industry. *IEEE Transactions on Education*, *65*(4), 592-601. https://doi.org/10.1109/TE.2022.3153841

InstituteQ. (2023). *Finnish Quantum Agenda*. https://instituteq.fi/wp-content/uploads/2023/02/FQA-February-2023.pdf

IQM (2022, November 14). *Unimon: A new qubit to boost quantum computers for useful applications*. https://meetiqm.com/resources/press-releases/iqm-unimon-qubit (Accessed 9 April 2024).

Jenkins, E. W., & Nelson, N. W. (2005). Important but not for me: Students' attitudes towards secondary school science in England. *Research in Science & Technological Education*, *23*(1), 41-57. https://doi.org/10.1080/02635140500068435

Johansson, A., & Larsson, J. (2022). Identity Perspectives in Research on University Physics Education: What Is the Problem Represented to Be? In H. T. Holmegaard, & L. Archer (Eds.), *Science Identities*. (pp. 163-184). Springer. https://doi.org/10.1007/978-3-031-17642-5_8

Kaur, M., & Venegas-Gomez, A. (2022). Defining the quantum workforce landscape: a review of global quantum education initiatives. *Optical Engineering*, *61*(8), 081806. https://doi.org/10.1117/1.OE.61.8.081806

Kind, P. M., Jones, K., & Barmby, P. (2007). Developing attitudes towards science measures. *International Journal of Science Education*, *27*(7), 871–893. https://doi.org/10.1080/09500690600909091

Kyne, D. (2023, May 17). *Pairwise Comparison (Explanation, Methods, Examples, Tools)*. Retrieved April 9, 2024. https://www.opinionx.co/blog/pairwise-comparison

Lee, W., Lee, M. J. & Bong, M. (2014). Testing interest and self-efficacy as predictors of academic self-regulation and achievement. *Contemporary Educational Psychology*, *39*(2), 86-99. https://doi.org/10.1016/j.cedpsych.2014.02.002

Lent, R. W., Brown, S. D., & Hackett, G. (1994). Toward a Unifying Social Cognitive Theory of Career and Academic Interest, Choice, and Performance. *Journal of Vocational Behavior*, *45*(1), 79-122. https://doi.org/10.1006/jvbe.1994.1027

Lloyd, S. (1982). Least squares quantization in PCM. *IEEE Transactions on Information Theory*, *28*(2), 129–137. https://doi.org/10.1109/TIT.1982.1056489

Marshman, E., & Singh, C. (2017). Investigating and improving student understanding of quantum mechanics in the context of single photon interference. *Physical Review Physics Education Research*, *13*(1), 010117. https://doi.org/10.1103/PhysRevPhysEducRes.13.010117

Marshman, E., & Singh, C. (2015). Framework for understanding the patterns of student difficulties in quantum mechanics. *Physical Review Special Topics Physics Education Research*, *11*(2), 020119. https://doi.org/10.1103/PhysRevSTPER.11.020119

Meinsma, A. L., Kristensen, S. W., Reijnierse, W. G., Smeets, I., & Cramer, J. (2023). Is everything quantum 'spooky and weird'? An exploration of popular communication about quantum science and technology in TEDx talks. *Quantum Science and Technology*, *8*(3), 035004. https://doi.org/10.1088/2058-9565/acc968

Michelini, M., & Stefanel, A. (2023). Research studies on learning quantum physics. In M. F. Taşar, & P. R. L. Heron (Eds.), *The International Handbook of Physics Education Research: Learning Physics* (pp. 8-1–8-34). AIP Publishing. https://doi.org/10.1063/9780735425477

Modir, B., Thompson, J. D. & Sayre, E. C. (2019). Framing difficulties in quantum mechanics. *Physical Review Physics Education Research*, *15*(2), 020146. https://doi.org/10.1103/PhysRevPhysEducRes.15.020146

Moraga-Calderón, T., & Buisman, H., & Cramer, J. (2020). The relevance of learning quantum physics from the perspective of the secondary school student: A case study. *European Journal of Science and Mathematics Education*, *8*(1), 32-50. https://doi.org/10.30935/scimath/9545

Moshfeghyeganeh, S., & Hazari, Z. (2021). Effect of culture on women physicists' career choice: A comparison of Muslim majority countries and the West. *Physical Review Physics Education Research*, *17*(1), 010114. https://doi.org/10.1103/PhysRevPhysEducRes.17.010114

Osborne, J., & Collins, S. (2001). Pupils' views of the role and value of the science curriculum: a focus-group study. *International Journal of Science Education*, *23*(5), 441-467. https://doi.org/10.1080/09500690010006518

Palmgren, E., Tuominen, K., & Kontro, I. (2022). Self-efficacy and conceptual knowledge in quantum mechanics during teaching reforms and the COVID-19 pandemic. *Physical Review Physics Education Research*, *18*(2), 020122. https://doi.org/10.1103/PhysRevPhysEducRes.18.020122

Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., Blondel, M., Prettenhofer, P., Weiss, R., Dubourg, V., Vanderplas, J., Passos, A., Cournapeau, D., Brucher, M., Perrot, M., Duchesnay, É. (2011). Scikit-learn: Machine Learning in Python. *Journal of Machine Learning Research*, *12*(85), 2825-2830.

Peterson, E. G., & Hidi, S. (2019). Curiosity and interest: current perspectives. *Educational Psychology Review*, *31*(4), 781–788. https://doi.org/10.1007/s10648-019-09513-0

QURECA. (2023, July 19). *Overview on quantum initiatives worldwide 2023*. Retrieved April 9, 2024. https://qureca.com/overview-of-quantum-initiatives-worldwide-2023/

Regan, E., & DeWitt, J. (2015). Attitudes, Interest and Factors Influencing STEM Enrolment Behaviour: An Overview of Relevant Literature. In E. K. Henriksen, J. Dillon, & J. Ryder (Eds.), *Understanding Student Participation and Choice in Science and Technology Education* (pp. 63-88). Springer. https://doi.org/10.1007/978-94-007-7793-4_5

Renninger, K. A., Bachrach, J. E., & Hidi, S. E. (2019). Triggering and maintaining interest in early phases of interest development. *Learning, Culture and Social Interaction*, *23*, 100260. https://doi.org/10.1016/j.lcsi.2018.11.007

Renninger, K. A., & Hidi, S. E. (2016). *The power of interest for motivation and engagement*. Routledge/Taylor & Francis Group.

Renninger, K. A., & Hidi, and S. E. (2020). To Level the Playing Field, Develop Interest. *Policy Insights from the Behavioral and Brain Sciences*, *7*(1), 10-18. https://doi.org/10.1177/2372732219864705

Rousseeuw, P. J. (1987). Silhouettes: A graphical aid to the interpretation and validation of cluster analysis. *Computational and Applied Mathematics*, *20*, 53–65. https://doi.org/10.1016/0377-0427(87)90125-7

Sakurai, J. J. (1994). *Modern Quantum Mechanics* (S.F. Tuan, Ed.) (revised ed.). Addison-Wesley.

Satanassi, S., Fantini, P., Spada, R., & Levrini, O. (2021). Quantum computing for high school: an approach to interdisciplinary in STEM for teaching. *Journal of Physics: Conference Series*, 1929, 012053. https://doi.org/10.1088/1742-6596/1929/1/012053

Schreiner, C. (2006). Exploring a ROSE-garden: Norwegian youth’s orientations towards science - seen as signs of late modern identities. *Nordina: Nordic Studies in Science Education*, *2*(1). https://doi.org/10.5617/nordina.458

Seskir, Z. C., Korkmaz, R., & Aydinoglu, A. U. (2022). The landscape of the quantum start-up ecosystem. *EPJ Quantum Technology*, *9*(1), Article 27. https://doi.org/10.1140/epjqt/s40507-022-00146-x

Seskir, Z. C., & Willoughby, K. (2023). Global innovation and competition in quantum technology viewed through the lens of patents and artificial intelligence. *International Journal of Intellectual Property Management*, *13*(1), 40-61. https://doi.org/10.1504/IJIPM.2021.10044326

Seskir, Z. C., Umbrello, S., Coenen, C., & Vermaas, P. E. (2023). Democratization of quantum technologies. *Quantum Science and Technology*, *8*(2), 024005. https://doi.org/10.1088/2058-9565/acb6ae

Shanahan, M. C. (2009). Identity in science learning: Exploring the attention given to agency and structure in studies of identity. *Studies in Science Education*, *45*(1), 43-64. https://doi.org/10.1080/03057260802681847

Stadermann, H. K. E., & Goedhart, M. J. (2021). 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. *Physical Review Physics Education Research*, *17*(2), 020132. https://doi.org/10.1103/PhysRevPhysEducRes.17.020132

Steidtmann, L., Kleickmann, T. & Steffensky, M. (2022). Declining interest in science in lower secondary school classes: Quasi-experimental and longitudinal evidence on the role of teaching and teaching quality. *Journal of Research in Science Teaching*, *60*(1), 164-195. https://doi.org/10.1002/tea.21794

Stoet, G., & Geary, D. C. (2018). The gender-equality paradox in science, technology, engineering, and mathematics education. *Psychological Science*, *29*(4), 581-593. https://doi.org/10.1177/0956797617741719

Testa, I., Colantonio, A., Galano, S., Marzoli, I., Trani, F., & Scotti Di Uccio, U. (2020). Effects of instruction on students' overconfidence in introductory quantum mechanics. *Physical Review Physics Education Research*, *16*(1), 010143. https://doi.org/10.1103/PhysRevPhysEducRes.16.010143

The Finnish Academy for Science and Letters. (2023). *KVANTTITEKNOLOGIA Missä kehityksessä mennään? Mitkä ovat alan mahdollisuudet ja riskit Suomelle?* Suomalainen tiedeakatemia. https://acadsci.fi/wp-content/uploads/2023/02/tiedeisku_kvanttiteknologia.pdf

Tu, T., Li, C.-F., Xu, J.-S., & Guo, G.-C. (2023). Students' difficulties with the Dirac delta function in quantum mechanics. *Physical Review Physics Education Research*, *19*(1), 10104. https://doi.org/10.1103/PhysRevPhysEducRes.19.010104

Tytler, R., & Osborne, J. (2012). Student attitudes and aspirations towards science. In B. J. Fraser, K. G. Tobin, & C. J. McRobbie (Eds.), *Second international handbook of science education* (pp. 597–625). Springer. https://doi.org/10.1007/978-1-4020-9041-7_41

Vedder-Weiss, D., & Fortus, D. (2012). Adolescents' declining motivation to learn science: A follow-up study. *Journal of Research in Science Teaching*, *49*(9), 1057–1095. https://doi.org/10.1002/tea.21049

Vygotsky, L. S. (1978). *Mind in society: Development of higher psychological processes*. Harvard University Press. https://doi.org/10.2307/j.ctvjf9vz4

Wolbring, G. (2022). Auditing the 'social' of quantum technologies: a scoping review. *Societies*, *12*(2), Article 41. https://doi.org/10.3390/soc12020041

World Economic Forum. (2022). *State of Quantum Computing: Building a Quantum Economy*. (Insight Report, September 2022) https://www3.weforum.org/docs/WEF_State_of_Quantum_Computing_2022.pdf

Winkler, B., Bitzenbauer, P., & Meyn, J.-P. (2021). Quantum physics ≠ quantum physics. A survey of researchers' associations. *Physics Education*, *56*(6), 065031. https://doi.org/10.1088/1361-6552/ac28df