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Daria Anttila

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ABSTRACT

The second generation of quantum applications, like quantum computers and sensors, have emerged, and quantum physics has found its way to social media, films, news and TV. Educating the general public and the future quantum workforce with quantum mechanics basics is crucial. An excessive amount of literature has been produced in the field of quantum physics education exploring students' difficulties in learning quantum physics and presenting new teaching approaches, tools and materials. However, students' relation to quantum physics and experiences in studying it remained unexplored. To develop quantum physics education further we need to understand our students and hear their voices.

In this thesis, I focus on university students and investigate the five components of student affect in relation to studying quantum physics: interest, self-efficacy beliefs, motivation, emotions, and attitudes. Through questionnaires, I collected information about STEM (science, technology, engineering and mathematics) and non-STEM university students' encounters with quantum physics and interest to study it, investigated the potential of a one-day event to trigger interest in quantum physics among physics and mathematics university students, and followed affective experiences of physics students during an obligatory quantum mechanics course. The results showed that students have significant differences in their affective experiences. The common factor among both STEM and non-STEM students is an interest in quantum physics topics, which can be utilized as a good momentum for teaching and outreach. However, another common factor was found: the view that quantum physics is relevant for the future of society but irrelevant for students' own studies and future career.

With my research, I open a discussion on university students' affective experiences in interactions with quantum physics. My findings can be implemented in teaching design to maintain students' motivation and interest in quantum physics and enhance learning engagement. Future research could explore the underlying reasons behind students' emotions and attitudes toward quantum physics studying and give more insight into students' affective experiences.

KEYWORDS: Student affect, quantum physics education

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TIIVISTELMÄ

Toisen sukupolven kvanttisovellukset, kuten kvanttitietokoneet ja kvanttisensorit, ovat tulleet jäädäkseen, ja kvanttifysiikka on löytänyt tiensä sosiaaliseen mediaan, elokuviin, uutisiin ja TV-ohjelmiin. On tarpeellista opettaa kvanttimekaniikan perusteet laajalle yleisölle ja kouluttaa kvanttiteknologia-alan työntekijöitä. Opiskelijoiden hankaluuksia kvanttifysiikan opiskelussa on tutkittu ja uusia lähestymistapoja, työkaluja ja oppimateriaaleja kvanttifysiikan opettamiseen on kehitetty. Tutkimusta opiskelijoiden suhtautumisesta kvanttifysiikkaan ja heidän omista kokemuksista kvanttifysiikan oppimisesta on kuitenkin vähän. Jotta kvanttifysiikan opetusta pystyttäisiin kehittämään edelleen, on tärkeää ymmärtää opiskelijoitamme ja kuunnella heidän mielipiteitään.

Tässä väitöskirjassa keskityn yliopisto-opiskelijoihin ja tutkin opiskelija-affektin viittä komponenttia: kiinnostusta, itsepystyvyysuskomuksia, motivaatiota, tunteita ja asenteita. Kyselypohjaisissa osatutkimuksissa keräsin dataa eri alojen opiskelijoiden näkemyksistä kvanttifysiikkaan ja kiinnostuksesta opiskella kvanttifysiikkaa, tutkin lyhytaikaisen tapahtuman potentiaalia sytyttämään fysiikan ja matematiikan yliopisto-opiskelijoiden kiinnostusta kvanttifysiikkaan ja seurasin fysiikan opiskelijoiden affektiivisia kokemuksia pakollisella kvanttimekaniikan kurssilla. Tulokset paljastivat, että opiskelijoiden affektiivisissa kokemuksissa on huomattavia eroja yksilöiden välillä. Yhteiseksi tekijäksi nousi kiinnostus kvanttifysiikan aiheisiin teknis-tieteellisten ja humanististen alojen opiskelijoiden keskuudessa, jota voitaisiin käyttää vipuvoimana kvanttifysiikan opetuksessa ja kansantajuistamisessa nykyistä enemmän. Kuitenkin toiseksi yhteiseksi tekijäksi nousi opiskelijoiden asenne, jonka mukaan kvanttifysiikkaa pidetään tärkeänä yhteiskunnalle — mutta ei niinkään opiskelijoiden omille opinnoilleen ja tulevalle uralle.

Tutkimukseni avaa keskustelun opiskelijoiden affektiivisista kokemuksista kvanttifysiikan parissa. Tulokset soveltuvat kvanttifysiikan opetuksen suunnitteluun ja auttavat ylläpitämään opiskelijoiden motivaatiota ja kiinnostusta kvanttifysiikasta sekä parantamaan oppimista. Jatkotutkimuksena olisi tarpeen löytää selitys opiskelijoiden tunteille ja asenteille kvanttifysiikan oppimista kohden.

ASIASANAT: opiskelija-affekti, kvanttifysiikan opetus

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The process of becoming a scientist, or even a Doctor of Philosophy, is influenced by many variables in one's sociocultural and educational environments. In my journey, which has culminated in this doctoral thesis, *people* have played the greatest role.

When I was five years old, my mother used to take me to the most magical place in the world - a university - where she worked. I used to listen to her lectures on probability theory and dream that one day I would study at a university myself, probably something mathematical. My mother always supported this dream and never ceased to believe in me and my abilities. Then, around the seventh grade, because of the hard work of my second father, I fell in love with physics. He taught me physics beyond the compulsory curriculum and, with the support of my mom, had the greatest patience known to man. My first father brought balance to studying. He travelled with me and showed me the world. In high school it was clear: either mathematics or physics. I played smart and studied theoretical physics at the university.

The university is truly a magical place. It is the place where I was introduced to quantum mechanics and was in awe of my first theoretical physicist role models: Tom Kuusela, Iiro Vilja, Juha-Pekka Pellonpää, Teiko Heinosaari, Jyrki Piilo and Sabrina Maniscalco. I thank you from the bottom of my heart. You gave me the opportunity to learn and encouraged me to follow my passion for scientific outreach and teaching.

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Writing a PhD thesis involves reflection on both research and life. My reflection summarizes to *gratitude*. Gratitude to the extraordinary people in my life.

4.2.2025
Daria Anttila

DARIA ANTTILA

A passionate quantum physics education researcher, who wants to get everyone interested in quantum physics. Why? Because quantum physics is fun!

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List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

I D. Anttila, A. Lehtinen, & P. Koskinen. Finnish University Students' Sociocultural Experiences and Views of Quantum Physics. FMSERA Journal, 2024; 6(1): 25–46.

II D. Anttila, A. Lehtinen, & P. Koskinen. Can a one-day event trigger interest in quantum physics at the university level? European Journal of Physics; 2024; 45(4): 045708.

III D. Anttila, A. Lehtinen, & P. Koskinen. Academic emotions and learning engagement during an undergraduate quantum mechanics course. [Manuscript submitted for publication].

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Other Publications

This is a list of the publications produced which have not been chosen as a part of this doctoral thesis:

- C. Foti, D. Anttila, S. Maniscalco, & M. L. Chiofalo. Quantum Physics Literacy Aimed at K12 and the General Public. Universe, 2021; 7(4): 86.
- L. Piispanen, D. Anttila, & N. Skult. Online Quantum Game Jam. ICGJ '23: Proceedings of the 7th International Conference on Game Jams, Hackathons and Game Creation Events, 2023; 18-27.
- A. Merzel, P. Bitzenbauer, K. Krijtenburg-Lewerissa, K. Stadermann, E. Andreotti, D. Anttila, M. Bondani, M. L. Chiofalo, S. Faletic, R. Frans, S. Goorney, F. Greinert, L. Jurcic, Z. Koupilova, M. Malgieri, R. Mueller, P. Onorato, G. Pospiech, M. Ubben, A. Woitzik, & H. Pol. The core of secondary level quantum education: a multi-stakeholder perspective. EPJ Quantum Technology, 2024; 11(27).

1 Introduction

The United Nations has officially declared 2025 the International Year of Quantum Science and Technology. Quantum physics and technologies are important, and, to cite Thierry Breton, Commissioner for Internal Market of the European Union, "*this is now formally acknowledged beyond the scientific community*" [1]. Quantum physics not only explains and predicts natural phenomena on submicroscopic and microscopic scales around and inside us, but understanding it also affects our everyday life and the entire society. In the 20$^{\text{th}}$ century, the so-called *first quantum revolution*, starting with the development of quantum mechanics, brought us transistors, lasers, and magnetic resonance imaging. As a consequence, we now have computers, mobile phones, high-precision measurement devices, fast communication, and advanced medical practices and diagnostic methods just to name a few applications of this technology. Now we are living in the midst of the *second quantum revolution*, characterized by the ability to control individual quantum states and the development of quantum technologies in the fields of quantum computing, communicating, simulations, sensing and metrology [2; 3; 4; 5]. We can only speculate to which extent these new technologies will influence our everyday life, as they have the potential to affect, e.g., drug development, logistical optimizations, communication and data security, and GPS systems [2; 5]. It is clear that scientific effort in developing quantum physics and technologies is crucial.

Quantum technologies have also an impact on economics and politics, see [2; 6; 7]. To cite the Strategic Research Agenda by European Quantum Flagship, which aims to consolidate and expand European quantum technology excellence: "*It is now widely understood that the mastery of deep technologies will determine the future prosperity of countries and regions across the world. Sovereignty over these technologies will become the critical building block for the future economic development and digital self-determination of societies. Quantum technologies have a special role to play in this regard...*" [2]. There has been an increasing number of quantum technology patents, hardware, and start-ups [8; 9], and a lot of effort to build a global quantum ecosystem [5]. The worldwide investment in quantum research and innovation development is constantly growing and currently exceeds 40 billion euros [10]. The prediction for the global quantum technology market is 160 billion euros by the year 2040 [10]. Quantum industry also changes the job market, as the need for quantum workforce is increasing [11]. Working with quantum technologies requires a diverse workforce and specialists from different disciplines, and building the ecosystem requires collaboration between academic researchers, industry practitioners, educators, policymakers, and investors [5; 12]. Therefore, more opportunities for retraining and upskilling through lifelong learning and academic programs are necessary [7; 13].

Finally, quantum physics is becoming increasingly visible in social media, films, news and TV, creating a new sociocultural environment. ”Quantum” in the sociocultural environment can be related to quantum physics research and technological development, or it can be a product of quantum hype [14; 15]. One might notice the word ”quantum” while watching superhero movies or even when buying a new pack of dishwashing tablets. The sociocultural environment is entangled with learning; not only it can provide people with the first learning experience of quantum physics [16], but also it affects educational choices and professional identity building [17; 18; 19; 20; 21; 22]. The sociocultural environment also influences individuals’ attitudes and expectations toward quantum physics [16; 23]. The effect of quantum physics visibility in informal settings can be both good and harmful: sociocultural environment can trigger interest and motivate individuals to be in touch with quantum physics, but it can also disinform and discourage them from studying quantum physics [16; 23]. For example, the popularity of the TV series ”The Big Bang Theory” with the main character, Sheldon Cooper, being a theoretical physicist is good because viewers can grow curiosity and even an interest in quantum physics by watching series. However, Sheldon is represented in the series as a genius lacking social skills, which reinforces the already existing discouraging stigma around theoretical physicists [21]. Since it is practically impossible to control the reliability or quality of information provided by the sociocultural environment, a well-designed educational environment and outreach for everyone is highly important. Not only do we need to increase society’s understanding of quantum physics basics to avoid the harmful effect of quantum hype and keep on track with the changing world, but also we need to increase the acceptance of quantum technologies [2; 24; 25]. Eventually, the driving force behind all changes is people; they contribute to the development of science and technologies, make political decisions [25], and set the course of history through their attitudes, interests and understanding of the world.

Learning quantum physics, however, poses a challenge, as it requires a conceptual change toward the quantum-mechanical way of thinking (understanding and gaining intuition in quantum-mechanical processes) after years of practicing classical one [6; 26; 27; 28; 29]. Several studies have been conducted to explore students’ conceptual and mathematical quantum physics difficulties to develop teaching further, e.g., [30; 31; 32; 33; 34; 35; 36; 37; 38; 39; 40; 41]. In fact, understanding the cause of struggles in quantum physics studying has led to the development of numerous visualization tools [42; 43; 44], quantum games [43; 45; 46; 47; 48; 49; 50], videos [51] and online resources [24; 52; 53; 54; 55]. They, in turn, allowed further development of educational modules and interventions for high school students [56; 57; 58; 59; 60; 61; 62; 63] and general outreach [43; 64; 65]. To respond to the increasing need for a quantum workforce, also new formal and informal education programs have been developed [4; 66; 67; 68; 69; 70; 71]. Quantum physics education research has also tackled teaching approaches, assessment methods and teaching material development [72; 73; 74; 75; 76; 77; 78; 79; 80; 81]. However, students' own views on quantum physics and studying it are still underinvestigated. Successful learning includes more than just cognitive processes, usually measured through tests and evaluated by grades or passing a course. Testing an understanding of quantum physics concepts or abilities to perform calculations is important, but equally important is exploring the underlying *affective* processes in student learning, e.g., interest development, emotional trajectories, and forming of attitudes toward quantum physics. In this work we shed light on university students' relation to quantum physics and student affect in interacting with quantum physics in university settings, thus partially filling the research gap and giving a new perspective to quantum physics education development.

In Chapter 2 we discuss in more details challenges in quantum physics teaching and student difficulties with quantum mechanics basics. We wrap up the chapter with a short description of the current state of quantum physics education research. In Chapter 3 we describe five components of student affect we explored in our studies, interest, self-efficacy, motivation, emotions and attitudes. We consider them in the context of sociocultural and educational environment and the representation of quantum physics there. Chapter 4 presents three substudies, which form the basis for this work, and in Chapter 5 we summarize the results. We conclude with Chapter 6 and discuss the applications of our results for quantum physics education development and future research outlook.

2 Quantum Physics Education

Quantum physics education is valuable regardless of whether learners plan to pursue a quantum physics-related career or not. Learning about quantum physics can be compared to learning about Darwin's theory of evolution, as both theories are groundbreaking cultural achievements of science [82]. In addition, quantum physics teaching can provide students with an understanding of the generation, validation, and current status of scientific knowledge, and highlight the interplay between society, philosophy, and science development [59]. The teaching of quantum physics, even without going deep into mathematical formalism, also needs to address many challenges experienced by students, both conceptual and mathematical. Quantum physics education researchers have been exploring these challenges and looking for innovative ways to teach quantum physics.

2.1 Challenges

When students learn, they may come across difficulties. Partially, difficulties in mastering quantum physics are similar to the difficulties in developing expertise in classical mechanics: lack of global consistency in knowledge structure, lack of effective problem-solving skills, unproductive epistemology, cognitive overload, etc. [27]. However, phenomena of quantum physics have no analogies in classical mechanics nor can they be directly experienced in the surrounding world; quantum physics is unintuitive [83] and requires the adaptation of a new, non-classical way of thinking [6; 26; 27; 28; 29]. Inevitably, students experience difficulties reconciling quantum concepts with classical ones [28; 84]. Students also struggle to relate mathematical formalism to physical processes behind them, adapt to the probabilistic nature of quantum processes and understand the limitation of language to describe quantum physics phenomena, concepts and objects [30; 85; 86]. On top of that, in lower and secondary education, quantum physics teaching has only a small role and is usually non-obligatory [87], so deepening into the subject in university education can be extra challenging.

Students experience reasoning [84], conceptual [30], calculational and mathematical difficulties [33; 34; 35; 36; 37; 38], and struggle to visualize quantum phenomena [88; 89]. There is an excessive amount of literature exploring student difficulties, and almost any quantum physics topic is challenging in one way or another.

For example, a study by Krijtenburg-Lewerissa et al. on challenges in secondary and lower undergraduate quantum mechanics courses [28] and a review on student difficulties in upper-level quantum mechanics by Marshman and Singh [84] reveal conceptual and calculational difficulties with e.g., wave function, wave-particle duality, tunneling, angular momentum and uncertainty principle. Many studies demonstrate that quantum measurement is a difficult concept to understand which causes a lot of misconceptions even among advanced university students [38; 84; 90; 91; 92]. In addition to different concepts and topics, students experience difficulties with quantum-mechanical formalism, like problems distinguishing between vectors in physical space and Hilbert space [93]. A poor understanding of basic concepts of probability and its interpretations in physical systems amplifies difficulties further [86; 94].

In the following section, we deepen the abovementioned difficulties with examples. We describe difficulties students may encounter when studying the basics of quantum mechanics through the textbook ”Quantum Processes, Systems, and Information” by Schumacher and Westmoreland [95]. This book is used at the University of Turku in an obligatory for all physics students course ”Quantum Mechanics IA”. It plays a special role in our research because we tracked students’ academic emotions and learning engagement during this course (see Chapter 4.3 and 5.3).

The emphasis of the book is on information processes. The book relies on the ”*spin-first*” approach, where students get familiarized with the concept of spin-1/2 and qubits before being introduced to the Schrödinger equation (vs. ”position-first”, where students are introduced to quantum mechanics through Schrödinger equation and continuous basis of position probability amplitude wave function) [96]. Authors utilize the Copenhagen interpretation of quantum mechanics, where a measurement of an observable of a quantum system causes an immediate and irreversible collapse of the state of the system to an eigenstate of the operator corresponding to the measured observable, and the measured value is a corresponding eigenvalue.

2.1.1 Students’ difficulties with quantum mechanics basics

The book starts by introducing the concept of information and bits, followed by wave-particle duality. In the first chapter, only standard algebraic calculations of exponents (bits and probability calculations) and logarithms (Shannon’s entropy) are used. On the conceptual level, students may experience confusion, as wave-particle duality is challenging to rationalize even for advanced students [28; 84]. Also, wave function ϕ (probability amplitude of the state of a particle) can be misunderstood so that students overgeneralize the concept or struggle to distinguish between closely related ones [28]. For example, students may think of the wave function as the one describing a trajectory of a particle or can mix the amplitude of the wave ϕ with energy [28]. The misunderstandings can also arise from the familiarity with concepts like ”wave” and ”momentum” from classical mechanics because in quantum mechanical contexts they have other meaning [28; 84].

The second chapter describes a photon in the Mach-Zehnder interferometer and spin-½ particles in the Stern-Gerlach experiment, both with vector and matrix representation. Then, it proceeds with the introduction to states, time evolution, and operators, with bra-ket formalism. Here, students get the first outlook on fundamental concepts and equations needed throughout the whole course, e.g. phase shift, angular momentum (spin), ground state and excited states, stationary states, qubits, Hamiltonian, and the Schrödinger equation. Also, algebraic concepts, like basis, normalization, orthogonality, and orthonormality, are explained. With many new concepts, there is a risk of many new misunderstandings, like believing that quantum spin is related to a particle’s physical rotation [97; 98]. On top of the conceptual understanding difficulties, students may struggle mathematically, because of challenges in understanding the formalism and performing calculations [93]. For example, students may mix vectors and matrices, and interpret $\frac{1}{\sqrt{2}}(|z_+\rangle - |z_-\rangle)$ as $\frac{1}{\sqrt{2}}\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}$ instead of the correct representation $\frac{1}{\sqrt{2}}\begin{pmatrix}1\\ -1\end{pmatrix}$ [38]. Moreover, the research shows that it is common for students to struggle with basic matrix and vector calculations from linear algebra [38], leading to incorrect calculations like $\frac{1}{\sqrt{2}}(|z_+\rangle - |z_-\rangle) = \begin{pmatrix}\frac{1}{\sqrt{2}}\\ -1\end{pmatrix}$.

Chapter three is devoted to mathematical formalism and algebra, and maps Dirac notation to matrix representation. Here, students get familiarized with Hilbert space, orthonormal bases, operators (Hermitian, positive, unitary, normal), states, observables and their compatibility, expectation value calculations. Almost every topic here can cause difficulties [28; 84]. Students can have a hard time distinguishing between the Hilbert space and three-dimensional space [90]: for example distinguishing the orthogonal three-dimensional spin components of a spin-1/2 particle, S_x, S_y, S_z (chapter two), from the two-dimensional Hilbert space operators associated with these observables presented in this chapter. It can be challenging to understand what kind of vectors can form an orthonormal basis [84] or what change of basis represents, leading to misconceptions like believing that changing basis alters the physical system [33]. The lack of conceptual understanding of the physics meaning behind the calculations can lead to escalating struggles later on: e.g. calculation difficulties if students are using only the memorized mathematical patterns without understanding them (e.g. [32]), and difficulties in understanding how operators act on different states (e.g. [84]).

Chapter three also covers one of the hardest topics to understand — quantum measurement [38; 90], along with eigenvalues and eigenvectors. As pointed out by Singh, students have difficulties in relating quantum mechanical formalism to the measurement of a physical observable [90]. Students can respond to the question about the result of measuring S_x in state $-|x_-\rangle$ with $-\frac{\hbar}{2}|x_-\rangle$, instead of $-\frac{\hbar}{2}$ [38], signaling that they do not understand eigenstates and eigenvalues and the meaning behind them. They may be troubled to distinguish the eigenstates of operators corresponding to different observables, for example, energy eigenstates versus others [91]. Studies show that students may get the wrong idea about the form of a wave function after the energy measurement, confuse the measurement of energy with the measurement of position, and misunderstand how one affects the other [90; 91]. Also, it is challenging for students to understand and distinguish between the possible outcomes of an individual measurement of an observable and its expectation value, and more generally, between the measured value, the probability of measuring it, and the expectation value.

Chapter four introduces the basic distinguishability principle (the probability of correctly identifying the state of two distinct states in Hilbert space by a basic measurement), the general uncertainty relation quantum communication, quantum cryptography and quantum key distribution protocol BB84. In this chapter, understanding distinguishability and uncertainty poses an extra challenge. Students may think of the uncertainty as a measurement error, for example, caused by technical errors while measuring [28]. In addition, students may have problems understanding the difference between the physical ability to measure two different observables versus the certainty of the outcome of the measurement (uncertainty principle) [38]. Students also confuse the position-momentum uncertainty relation with an uncertainty relation of measurements related to two any other observables [38]. In the case of this book, such confusion may arise in distinguishing the general uncertainty relation and the time-energy uncertainty relation.

In chapter five students are familiarized with the highlights of the course: unitary evolution and the Schrödinger equation, both foreshadowed in chapter two. The understanding of this chapter requires knowledge from all of the previous chapters. For example, understanding a stationary state (a state of definite energy) from the second chapter creates a basis for understanding stationary states as presented here (eigenstates of energy operator). Combining these two definitions is crucial for understanding, distinguishing and correctly applying the properties of stationary and non-stationary states, which seems to be difficult for students [90]. Students are troubled to see why the Hamiltonian acting on an arbitrary state $|\psi\rangle$ does not give the same state back, $\hat{H}\psi = E\psi$, which would be true only for the stationary states, but in general it results in $\hat{H}\psi = \sum_{n=1}^{\infty} C_n E_n \phi_n \neq E\psi$, where $\psi = \sum_{n=1}^{\infty} C_n \phi_n$, with ϕ_n being stationary states and $C_n = \langle \phi_n | \psi \rangle$ [90]. Furthermore, in addition to conceptual and mathematical challenges with the time-independent Schrödinger equation, students also de-emphasize the time-dependent Schrödinger equation [90]. Another example is a challenge to explain the time-development of the wave function after a measurement of one observable has occurred [91]. This is a multilevel problem, and to grasp this subject, students need a proper understanding of the measurement of different observables (Chapter Three), wave function (Chapter One), and time-evolution (Chapter Five).

To summarize, the quantum mechanics course taught through the textbook ”Quantum Processes, Systems, and Information” by Schumacher and Westmoreland [95] presents new concepts gradually, repeating them with different contexts, before the more thorough definitions and mathematical descriptions. In this way, the information piles up with scientific links from one topic to another and forms a well-structured entity. This also means, that understanding new chapters requires a conceptual and mathematical understanding of previous chapters, which can create an extra challenge for students. If a student misunderstood a concept in Chapter One, they will not be able to relate physical process to mathematical formalism in Chapter Three. If a student is also unsure how to do matrix calculations, it would be impossible for them to calculate something related to the topic of Chapter Five.

2.2 Towards quantum physics education development

Research on difficulties in quantum physics studying has helped to develop quantum physics teaching approaches and tools, e.g. [32; 43; 44; 56; 61; 79; 99; 100; 101; 102; 103; 104; 105]. Quantum physics can be taught, for example, with the focus on the historical development of science, as it is usually done in secondary education [87], through spin-first or position-first approaches [96], by introducing topics conceptually or more mathematically, and utilizing different interpretations of quantum mechanics [28]. Different initiatives were commenced in Europe and worldwide to develop quantum teaching further [106], e.g. Quantum Technology Education pilots of European Quantum Flagship [107] and European Quantum Readiness Center [108]. New teaching methods and tools enabled the development of quantum physics education at secondary school [57; 58; 62; 101; 109; 110], for physics and non-physics university majors [66; 67; 68; 69; 70; 71; 111; 112; 113], and as retraining and upskilling [114] (for more excessive list see [107]). In addition, a number of opportunities were created for general public outreach and informal learning on the university level [24; 43; 65; 71; 115; 116]. Research has also focused on quantum physics topics selection for secondary [80; 117] and higher education [3].

Recently, more studies have been focusing on bringing the perspective of high school teachers on quantum physics teaching, e.g. a study exploring why and how high school teachers use nature of science in quantum physics teaching [59], a study investigating teachers’ and students’ views on challenges and opportunities in quantum physics teaching [118], and a study examining which key quantum concepts should be taught in high school based on the opinions of quantum scientists and physics teachers [80]. Also, the requirements for quantum workforce have been explored and considered in teaching design [4; 12; 13; 66; 106; 119; 120], leading, e.g., to quantum computing teaching modules [61; 121] (see also [107]).

It is also important to shift the focus from teaching substance to students themselves and explore students' own experiences and point of view on quantum physics teaching and learning. In 2020 Moraga-Calderon et al. studied the relevance of learning quantum physics from a high-school student's perspective [122]. They discovered that many students find quantum physics important, but not for them personally. Still, university students' opinions were unexplored. Then, in 2022 Palmgren et al. studied university students' self-efficacy beliefs in a quantum mechanics course during teaching reform [123]. One of the important findings demonstrated that students aiming at theoretical physics major reported higher self-efficacy beliefs than other physics students. In 2023 Corsiglia et al. clarified whether university students find quantum physics concepts intuitive, unintuitive or counterintuitive [83]. The results showed that most students consider quantum physics unintuitive instead of counterintuitive. However, students had diverse opinions on intuition and its role in studying quantum physics, which should be taken into account in designing quantum teaching [83]. Recently, Rosenberg et al. explored undergraduate STEM students' knowledge of quantum physics and related careers and interest in pursuing such a career [124]. They found that students were interested in quantum careers, even without much knowledge about quantum physics or related career opportunities.

Contemporary education emphasizes the role of students' affective experiences [125; 126; 127; 128; 129; 130; 131; 132; 133; 134; 135], yet only limited attention has been given to the related quantum physics education research. Even though the studies tackle affective variables, they do not provide a larger picture on university students' attitudes or interest processes in interacting with quantum physics. A noticeable research gap forms the absence of understanding of students' academic emotions and learning engagement while studying quantum physics. Also, students' backgrounds in encountering quantum physics in the sociocultural environment and quantum physics topics of interest remain unexplored.

3 Student affect through five viewpoints

The ultimate goal of teaching is learning, and learning includes also aspects and processes that cannot be measured by grades and academic success. In this section, we explore the role of student affect in studying and learning based on the existing literature. Following Hannula [136], blending different theories of affect, we use the definition of affect, which combines cognitive (e.g., beliefs, attitudes), motivational (e.g., values), and emotional (e.g., feelings) aspects of affect caused by individuals' initial physiological and psychological processes and the environment (sociocultural and educational).

In detail we describe the five components of student affect central in our research: interest, self-efficacy, motivation, emotions and attitude, and their connections to each other (Fig. 1). All five are influenced by the sociocultural and educational environment, and impact students' learning, retention, choice, and identity formation (Fig. 1). Students proceed with their studies, and later on careers, after they have made certain choices, in accordance to their perceived professional identities [21; 137]. The connections we explore in our research are marked by dotted arrows in Fig. 1.

3.1 Interest

Interest is one of the driving forces for all that we do as it influences our behavior and initiates reactions to and engagement with different contents, people, and tasks [19; 139]. We conceptualize interest following the definition and interest development theory of Hidi and Renninger: interest is a psychological state during engagement and a motivational predisposition to re-engage with the content [139]. Interest is developed from the interaction of individuals with the environment. It affects attention and effort, activates the brain's reward circuitry [139], and contributes to psychological well-being [140].

Interest develops in four phases: triggered situational, maintained situational, emerging individual, and well-developed individual interest [139]. The development and maintainment of interest requires triggering, an attention captivation in response to the environment, which usually leads to continued engagement [139]. Interest can evolve from situational to individual, following all four phases of interest development. Without triggering it can diminish or even disappear. Usually, during

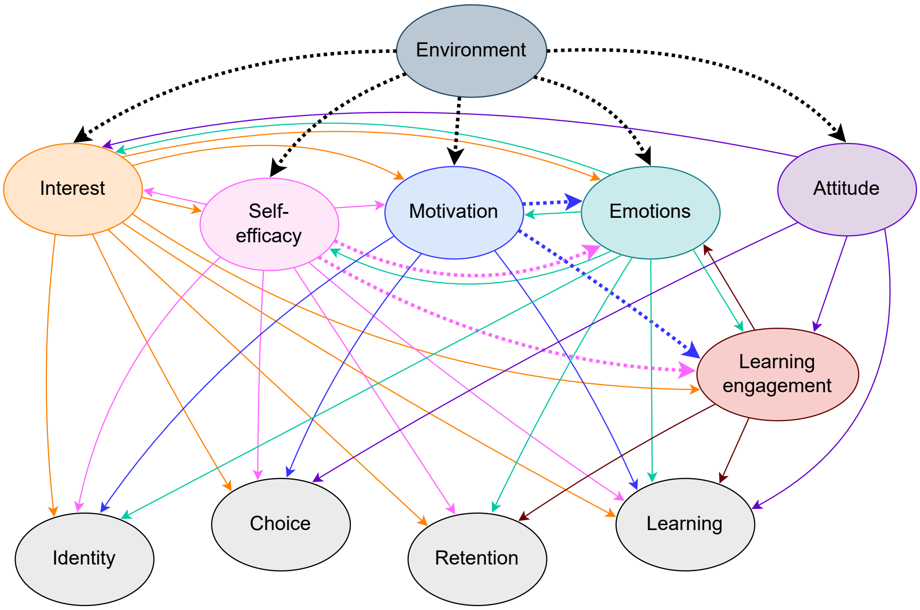

Figure 1. Mapping of interest, self-efficacy, motivation, emotions and attitude (five aspects of student affect) with environment, each other and their influence on learning, retention, choice and identity. Also learning engagement, an active involvement in learning activities [138], is situated on the map. The dotted arrows indicate the mappings explored in our research.

sitational interest development phases, external support is needed. The educational environment plays a great role; it can provide opportunities to be in touch with different subjects and interest triggers, like content personalization [141], social games [142; 143; 144], hands-on activities [144; 145], meaningfulness [139; 145; 146; 147] and surprise [145; 148; 149; 150], and teachers can become role models for their students [139]. During individual phases of interest development, a person posesses a vast knowledge of the content, values it, re-engages independently with it and can use self-sustained triggers.

Interest in the subject is a prerequisite for effective learning [139; 151; 152]. A student follows an interesting subject with increased attention [139; 153; 154] and sustained engagement [155]. Interest is one of the main factors in achieving an optimal learning state (see more in Chapter 3.4). Interest aids in understanding the subject [148], promotes conceptual change [139; 156; 157], influences the choice of learning strategies [139] and helps to overcome studying difficulties [139; 148]. A student is motivated to voluntarily re-engage with an interesting subject [139] and regulates their learning better [126]. They can have higher self-efficacy and value feedback [139]. In addition, interest positively influences academic achievement, performance, grades and test scores [139; 158; 159].

According to expectancy-value theory [160] and social cognitive career theory [161], interest is one of the key constructs for any choice (choice of study subject, educational choice or career choice) [19]. Research has shown that interest is one of the strongest predictors for choosing science courses or studies [162; 163; 164; 165; 166]. Interest helps to set and achieve goals, like completing a course or a degree [167; 168], and a lack of interest can lead to lower retention [169; 170; 171]. It is also important for identity development [137]. However, it is also well-known from the literature that interest in mathematics and science, especially in physics, decreases during adolescence [172]. Consequently, the lack of interest in science subjects leads to a decreasing number of students choosing them [173].

3.2 Self-efficacy

Following Bandura, we define self-efficacy as one's beliefs in their ability to complete a given task, and conceptualize it as a construct in social cognitive theory [174; 175]. Self-efficacy beliefs are formed from an individual's previous experiences of achievement or failure (mastery experiences), information learned from others' experiences (vicarious learning experiences), cultural norms and social stereotypes towards different disciplines (social persuasion experiences) and experienced emotions [174].

Self-efficacy is a motivational variable because it is one of the main conditions to launch actions possibly leading to success [176]. Self-efficacy expectations can be visualized on the basic motivational model by Urhahne and Wijnia as an impulse from "the self" into motivated actions that can possibly lead to success (Fig. 2) [176]. The model shows "the determinants and course of motivated action" [176], which arises from an interaction of an individual and the environment. It consists of six stages of operation: the situation, the self, the goal, the action, the outcome, and the consequences.

Self-efficacy predicts students' motivational outcomes, like effort and persistance, learning processes, like choosing learning orientation and strategy, and direct and indirect academic achievement [125; 126; 177; 178; 179; 180; 181; 182; 183; 184]. It also predicts conceptual understanding [185]. Students who believe in their abilities to accomplish and succeed in a given academic task, perform better and are motivated to choose more difficult tasks and more engaged in learning [181; 186]. They interpret difficulties as an opportunity to develop their skills, whereas students with low self-efficacy beliefs may be further convinced of their incompetence in the subject [178]. Academic self-efficacy is one of the strongest predictors of grade point average [187] and retention [180; 188].

Self-efficacy and emotions have a two-way connection. Self-efficacy beliefs influence students' academic emotions: if a student is facing a challenging academic task, but has high self-efficacy beliefs, they can feel enthusiasm instead of a frustra-

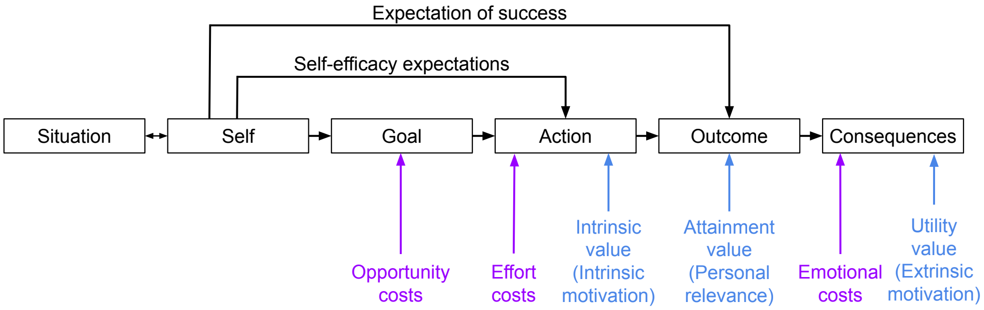

Figure 2. Situated expectancy-value theory and self-efficacy expectations combined with the basic motivational model. Value beliefs are in blue, and cost beliefs are in violet. Figure adapted from reference [176].

tion [189; 190; 191]. On the other hand, emotions like stress and fear can decrease students' competence beliefs [174]. Similarly, interest can have an influence on self-efficacy [139; 179], and also self-efficacy affects students' interest [125; 179; 192]. Students with low self-efficacy beliefs can become less interested in a subject when they are facing challenges [182].

According to the social cognitive theory [175] and social cognitive career theory [161; 167; 193], self-efficacy has an influence on choice [193]. Self-efficacy beliefs influence study choice, science major choice [127; 194], and academic career [178]. In addition, self-efficacy strongly relates to physics identity building [123; 195; 196; 197]. In theoretical physics, self-efficacy beliefs have a special role, as students aiming at theoretical physics major studies usually report higher self-efficacy beliefs than other physics students [123; 129]. We suggest as a partial explanation to this result a long ongoing stigma of theoretical physics being an extremely difficult subject to study, so only students truly believing that they can manage the studies consider choosing it. In addition, research has demonstrated that efficacy judgment can predict math anxiety [198]; and mathematical calculations are a prominent part of quantum mechanics studies.

3.3 Motivation

Motivation is closely related to interest [139], self-efficacy [179] and other variables, like self-determination, goals and expectancies, affecting engagement and learning [130]. Motivation changes in time, and is affected by sociocultural, educational and other environments, which are represented by ”situation” in the basic situational model in Fig. 2 [176]. For example, imaginaries about physics professions and future work learned from pop culture can be presented realistically or stigmaticly and can motivate or discourage [16]. Motivation can be then understood as the product of interaction between an individual, the ”self”, and their environment [176] (Fig. 2). The environment, or situation, sets a context for the sequence of motivated action.

In this thesis, we conceptualize motivation within the situated expectancy-value theory [199]. The theory describes how individuals base their achievement performance and choice on their expectation of success and task value beliefs [176; 199; 200]. The expectation of success is similar to the self-efficacy expectations, however, they are related to the perceived chance of success as an outcome of the action, and not the actual performance [176] (Fig. 2). Task value beliefs describe an individual’s reasons to perform the task, and consist of value and cost beliefs (Fig. 2) [199]. Value beliefs are then associated with different types of motivation. Attainment value, the importance of performing well in a task dictated by an individual’s own view of themself, is associated with personal relevance [176; 200]. Intrinsic value, or the enjoyment of performing a task, is related to the outcomes of the action and can be considered intrinsic motivation. Utility value, the importance of a task for the future from the perspective of the self, is related to the consequences of the action and is associated with the extrinsic motivation [176; 200]. Cost beliefs are represented by opportunity, effort and emotional costs, which are related to the goal, action, and consequences.

In educational settings, motivation explains student behavior and its influence on their learning. It leads to learning engagement [130; 201; 202] and active involvement in learning activities [138], which in turn influences student performance and retention [130; 201; 202; 203]. Motivation also affects academic performance and outcomes [187; 204], and can have a vast effect on identity [192; 205].

3.4 Emotions

Emotions and cognition are known to be coupled [135; 206; 207]. Emotions have a vast effect on studying and learning, from neurological processes to learning engagement [208; 209]. Positive emotions help to sharpen attention and transfer new information to short-term memory, but long-term stress prevents the formation of long-term memory [154]. Emotions originate from external and internal factors and are situational in nature [206]. In the university context, we speak about academic emotions, which can be classified to achievement (emotions related to success or failure of the exam), epistemic (emotions related to the formations of new understanding or questioning the existing one), topic (emotions triggered by learning content) and social (emotions in social learning contexts) [135; 208; 209; 210].

Emotions can strongly influence motivation to engage with academic tasks [208] and trigger interest in a subject [139; 145; 154]. They influence students’ learning strategies, approaches to learning and academic performance and achievement [130; 134; 135; 211]. They are related to study success and retention [203; 212; 213], can predict study grades [203; 212], and influence identity development and health

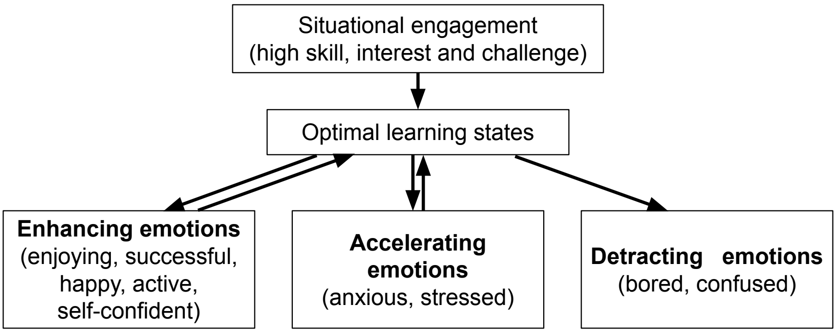

Figure 3. The relation between emotions, situational engagement, and optimal learning states. Optimal learning is caused by situational engagement containing high skill, interest, and challenge. Enhancing and accelerating emotions can positively influence or be consequential to optimal learning. Detracting emotions depletes the optimal learning state. Figure adapted from reference [203].

[208; 214].

Learning engagement combines emotional states with cognitive, motivational and behavioral factors [130; 201; 202]. It influences student performance, behavior outcomes, and retention [130; 201; 202; 203; 208]. When students are fully engaged in a learning process, they can experience flow — a learning state that provokes intense feelings of enjoyment and creativity [215; 216; 217]. Learning engagement can also lead to an optimal learning state characterized by high skill, interest and challenge experienced by a student (Fig. 3) [215]. The optimal learning framework is built upon the flow framework. Emotions have a two-way relation with optimal learning states: they can both influence and be influenced by optimal learning states [215]. When a student enjoys studying, feels successful, happy, active and self-confident, it enhances learning, and when a student is in an optimal learning state, they can feel enhancing emotions (two-way arrows in Fig. 3). Similarly with anxiousness and stress, which can accelerate learning (two-way arrows in Fig. 3), but too much of them can disadvantage learning [215; 218; 219; 220]. Finally, the most disadvantageous emotions a student can experience in educational settings are boredom and confusion, because they both detract from learning, In Fig. 3 there is a one-way arrow associated with them, pointing away from the optimal learning state.

3.5 Attitudes

We define attitudes as evaluative judgments towards a topic and separate them from feelings, which are usually defined as a part of attitude as well [221; 222; 223]. We do such separation because feelings and emotions are closely related [224]. Attitudes have the target object, direction and intensity, and consist of cognitive, behavioral and affective components [19]. For example, an individual can have a strong (the intensity) negative (the direction) attitude towards learning physics (the target object). Attitudes affecting science studying and learning are usually divided in two categories: attitudes towards science and scientific attitudes. Attitudes towards science are directed to scientific subjects and scientific attitudes are related to thinking like a scientist [19]. Students' attitudes play a role in study choice and students' preferences [19]. In addition, attitudes mediated through preconceptions, values, and beliefs, which are formed under the influence of the sociocultural environment [225], can affect interest [139; 226]. They also influence behavior and engagement in science [18; 197], and can have an impact on learning strategies, cognitive processes, educational achievement, and academic outcomes [197; 227].

3.6 Student affect and quantum physics studying

In Finland, studying quantum physics is voluntary at all educational levels; it is not a part of the obligatory education. For students to choose to study quantum physics and pursue a related profession or to participate in a quantum physics outreach program, students need to have motivation, an interest in the subject and a positive attitude towards learning quantum physics. They also need to have a realistic picture of quantum physics professions, studies and requirements. In addition, strong self-efficacy beliefs and learning-enhancing emotions can help students to stick with their choice. However, making a choice to study quantum physics can be difficult, because of the impact of negative stigmas from the sociocultural environment [16; 21; 23], and negative attitudes and declining motivation and interest towards physics and science during adolescence [172; 228; 229; 230].

Since the impact of the sociocultural environment (e.g., films and media) on students' interest, motivation, self-efficacy, emotions and attitudes towards quantum physics and its studying cannot be controlled through obligatory education, well-designed quantum physics outreach and educational initiatives are of the highest importance. It is necessary to develop quantum physics education to trigger and maintain students' interest and motivation, increase their self-efficacy and learning-enhancing emotions, and reinforce their positive attitudes towards quantum technological development and related professions. A better understanding of students' current relations with quantum physics and student affect with its causes and consequences is a necessary step towards quantum physics education development goals.

In Finland university education aims to sophisticate students scientifically and raise them to serve humanity [231]. It is also important for preparing quantum specialists and a new generation of quantum educators, who, in turn, will teach new experts and the general public about the basics of quantum physics. Ultimately, all students will influence the future of society with career and political choices based on their knowledge and attitudes towards quantum physics and technologies. Therefore, we set our focus on university students and pose the following research questions with the overall aim of developing quantum physics education:

1. What is university students' relation to quantum physics?
2. What is student affect in interacting with quantum physics in university settings?

4 Research materials and methods

To answer the research questions, we designed and implemented three questionnaire-based sub-studies. The first sub-study collected information about STEM and non-STEM university students' background knowledge, attitudes, contexts to encounter quantum physics and potential interest in studying it. The second sub-study investigated the ability of a one-day event to trigger interest and change attitudes towards quantum physics among physics and mathematics students. The third sub-study explored physics university students' academic emotions and learning engagement during an obligatory quantum mechanics course, as well as their self-efficacy beliefs and motivation at the beginning and at the end of the course.

4.1 University students' relation to quantum physics

4.1.1 Research design and data collection

As quantum physics is becoming increasingly visible in the sociocultural environment in Finland, we wanted to investigate if Finnish university students recognize it in their surroundings, how they perceive its relevance, and to what extent they are interested in studying topics related to quantum physics. The main purpose of the study was to get to know the students' own perceptions and preferences and to make what they have to say visible. At the beginning of 2023, we designed a Finnish-language questionnaire and collected responses from 270 university students. Half of them were STEM and half were non-STEM students. Students who had already chosen to specialize in theoretical physics or quantum technology were not included in the study.

The questionnaire covered students' educational background, self-assessed knowledge of quantum physics, previous encounters with it, perceived relevance of quantum physics, and preferences and interest in studying quantum physics. The questionnaire was designed to be short and quick to fill, and was inspired by the research of Moraga-Calderon et al., who explored secondary school students' topics of interest and perceptions of the relevance of quantum physics through three questions [122]. We modified the questions and response items presented in their study to meet our purposes and added new questions. Through these modifications we took into account our audience, so for example when monitoring university students' interest in studying quantum physics we removed too narrow topics and added more general ones instead.

The final questionnaire included open, multiple-choice and single-choice items. In the first questionnaire section, we collected students' background information (gender, university, study major, and previous education) and explored their past experiences with quantum physics. In this section, we asked students in what contexts they had come across the word "quantum". After this question, we explained what we mean by quantum physics. Then we provided students with a list of different contexts and asked about the frequency of encountering quantum physics in these contexts. Following, we asked students about their self-evaluated level of knowledge in quantum physics and the means of acquiring that knowledge. As the last part of the first sequence, we requested students to list one to five technological applications that they know or suspect are related to quantum physics.

The next questionnaire section was dedicated to the students' present views on quantum physics. The first question suggested a list of items and asked to rate the relevance of quantum physics in these items. Then, we asked how different aspects have influenced students' perceptions of the relevance of quantum physics.

The final section explored students' views on studying quantum physics and forecasted future possibilities for educational initiatives. Students were asked about their interest in studying the listed topics, their motivations for studying quantum physics in different settings, and their preferred methods for these studies.

4.1.2 Data analysis

We analyzed the responses to single-choice questions for all students and separately for STEM and non-STEM students to see the possible influence of study major. Open and multiple-choice questions were analyzed using inductive thematic coding [232], as multiple-choice questions also allowed for an open-ended response. As an exception, the open question asking students to list technological applications was analyzed by means of pairwise comparison [233] to create a ranking for all 270 responses (181 unique) according to their relatedness to quantum physics. As a result of the pairwise comparison, each unique response received a value between zero (classical-like application) and one (quantum-like application), depending on how many times it was chosen as more quantum-like than its random pair. The use of pairwise comparison allowed us to place responses on a continuous scale, which was more suitable because many technologies have both classical and quantum aspects. For example, a computer is a classical technology but relies on the functioning of transistors, which require an understanding of quantum mechanics. Since we didn't ask students about the underlying reasons for their answers, comparing the answers to each other gave us also an appropriate frame of reference.

Additionally, to gain more perspective on the multiple-choice data, we analyzed it with principal component analysis and K-mean clustering [234]. This method enabled us to see patterns in a simplified form of the data set. Finally, to predict the interest in learning quantum physics, we performed multivariate linear regression to all responses.

4.2 Physics and mathematics students' interest and relation to quantum physics before and after a one-day event

4.2.1 Event design

To trigger an interest in quantum physics, and theoretical physics more generally, we developed a one-day event in university education settings called Fun in Theory at the University of Turku in 2014. The event was offered annually to students until 2023. Initially, it aimed to motivate bachelor physics students to choose theoretical physics for their master's studies. Later, Fun in Theory was further developed to motivate students to be in touch with theoretical physics even without choosing it as a major. Eventually, the event was also aimed at mathematics students and had zero requirements for background knowledge in theoretical physics. During the event, students get an overview of theoretical physics research and its impact on society, learn about theoretical physics courses and specialization, are provided with motivational motifs, and participate in a unique gamified experience. In addition, the event aims to improve students' attitudes towards theoretical physics and its learning and to connect theoretical physics topics to other subjects and everyday life. The event is planned to implement many different interest triggers and to be relaxed, fun and mesmerizing. It consists of three parts: a lecture (information, 2 hours), a social game (application, 1,5 hours), and informal chatting with snacks (reflection, 1-2 hours).

Our research was based on the implementation of Fun in Theory in 2022, where the overall playful theme of the event was ”Relative Treasure Hunt”. A total of 60 students participated in the event, 15 of which participated in our study.

Lecture

The lecture mixed informative and motivational parts with activating questions. In the lecture we used pictures from popular films and games and samples of news, course materials, consumer products and technological applications to provide pedagogical links, address popular misconceptions and give students a realistic picture of theoretical physics research and studies. At the end of the lecture students were provided with low-barrier and easy-to-follow online resources for theoretical physics to sustain their interest. The first part of the event ended with a panel discussion, where teachers and under- and postgraduate theoretical physics students addressed questions and concerns anonymously written by the participants at the beginning of the lecture. Panelists also told students stories about their personal career growth and interest development and encouraged everyone to engage with theoretical physics. Since triggers work differently on different people, e.g. depending on their phase of interest towards theoretical physics and previous experiences and interests [139; 145; 235; 236], the lecture implemented as many triggers as possible:

- highly visual presentation [145]
- alternating structure of the lecture [145; 236]
- information, which might be personally relevant for students [141], like explaining how specifically they might benefit from theoretical physics courses in their future studies
- novel and surprising information [145; 148; 149; 150], like explaining to students how some popular films are actually based on legit quantum theories and demonstrating products of quantum hype like Quantum Stylist sewing machine by Singer
- humor and memes to achieve heightened emotions and capture attention [139; 145; 149]
- panelists as role models [139]

A social game: Relative Treasure Hunt

The second part of Fun in Theory included a social game, the Relative Treasure Hunt, played by the participants in teams. The game had a scenario and achievement goal — collecting the greatest number of playful ”diamonds” and ”prizes” from the nodes of an imaginary quantum network. The team collecting the greatest treasure won small prizes. The game took place in office rooms of the theoretical physics laboratory and included eight tasks. Each task lasted around 10 minutes and had a dedicated moderator. The moderator ensured that teams understood all related physics correctly and provided any help necessary. The game implemented the following triggers:

- gamification, to increase students’ involvement and satisfaction [142; 237; 238]
- social interaction among team members [143; 144]
- group work to complete tasks [144; 145]
- suitable challenge [215; 239; 240]

- meaningful engagement, as the game implemented information learned from the lecture and taught something new as well [139; 145; 146; 147]
- having fun [139; 145; 149]

The game also enabled feelings of success and achievement [145; 241]. Game tasks were various in nature, and included e.g. performative, physical and hands-on activity [144; 145] elements. For students feeling uncomfortable with social interactions, but still willing to participate to the game, moderators could suggest alternative ways for executing the task.

Informal chatting and snacks

The final part of the event included snacks offering and informal chatting with theoretical physics laboratory staff, teachers and theoretical physics students. It provided participants with the possibility to reflect on everything they had learned and experienced, repeat and emphasize interest triggering in theoretical physics topics and get more in touch with potential role models.

4.2.2 Data collection

This study aimed to investigate the potential of Fun in Theory to trigger interest in quantum physics and how the event changes students' attitudes towards quantum physics. To meet this aim, we developed three questionnaires and structured interviews. Because the validated tools to probe interest triggering were missing, we designed questionnaires and interviews on our own and based them on Hidi and Renninger's interest development theory [139]. We avoided asking students directly about interest triggering because it is unlikely that they can describe it reliably [139].

Students responded to the first questionnaire before the event, to the second questionnaire right after the game part of the event, and to the third questionnaire one week after the event. After that we conducted interviews. The first and the third questionnaires had the same set of nine questions phrased differently depending on when they were supposed to be completed. The second questionnaire used only a part of this question set (six questions), omitting the redundant ones. Once again, questionnaires were designed to be short and easy to fill, so that they would not negatively affect the overall impression of the event. 15-minute interviews were conducted after the third questionnaire. A total of 15 Finnish-speaking physics and mathematics students (nine men, five women, and one other) filled all three questionnaires necessary for this study, and five of them volunteered for interviews.

Questionnaires probed students' phase of interest [139] with three questions (before and one week after the event), and an interest-triggering potential of the event (in every questionnaire). To determine the interest-triggering potential of Fun in

Theory, we included questions about self-evaluated change in interest, change in attitude towards quantum physics, quantum physics topics of interest, and experiences about the event. To probe students' phase of interest, we included a question about quantum physics knowledge and self-evaluated gained knowledge due to the event, a question about students' free time engagement with quantum physics contents, and a question about their motivation to engage with quantum physics in their free time. A question about self-evaluated knowledge gain was also used for the analysis of interest triggering.

Interviews were designed to provide more information about students' experiences, and interest and attitude changes caused by the event. We started by asking students' expectations and reasons to participate to the event. Then, we asked students about attitude and interest change due to the lecture, the game and snacks & chat, and the influence of the environment, lecturers and task moderators on students' attitudes and interest triggering. We also asked what and when students learned during Fun in Theory and if they intended to study theoretical physics courses after the event. We finished the interviews by asking the students to mention some elements that made the event appealing to them and to tell if they would like to participate to Fun in Theory next year (with a different game and overall theme).

4.2.3 Data analysis

We analyzed the questionnaire data for 1) change in the phase of interest in quantum physics, 2) self-evaluated change of interest in quantum physics, 3) self-evaluated gained knowledge, 4) change of attitudes in quantum physics, 5) change in topics of interest within quantum physics, and 6) fulfillment of expectations. Interviews were recorded and transcribed.

For the phase of interest analysis, we adapted with alternations the behavior indicator table of Habig and Gupta [242]. The table of Habig and Gupta follows the work of Hidi and Renninger [139] and helps to determine the phase of interest development based on four behavioral indicators: frequency of re-engagement, capacity for independent re-engagement, depth of knowledge and voluntary re-engagement with the content of interest. There is a numerical value associated with each interest development phase, so a student's phase of interest is an average of numerical values for the phases of interest associated with all four behavioral criteria separately.

For the self-evaluated change in interest, we grouped students' responses into four categories. The first two questionnaires asked students about their current perceived interest in quantum physics, and the third questionnaire asked to evaluate their change of interest after the event.

To probe students' attitude change, we asked students to list three self-picked adjectives describing quantum physics. All adjectives were categorized into six bundles by emergent coding. In the results categorized adjectives are presented in a tabular format: 42 adjectives before the event (with a couple of technical rejections) and 45 adjectives right after the game and one week after the event.

Similarly, to probe quantum physics topics of interest, we asked students to list them in their own words. In summary, students listed 17 topics before the event and 19 topics right after the game and one week after the event. The topics were categorized into five motifs.

For the expectations and their fulfillment, we also categorized the free-form responses, and for the self-evaluated knowledge gain we just summed up the raw data.

4.3 Student affect during quantum mechanics course

4.3.1 Research context

For this study, in 2023 spring we followed emotions and learning engagement of 17 university students during their first obligatory quantum mechanics course, which was their first proper introduction to the basics of quantum mechanics in educational settings. The course was a part of the Bachelor of Science curriculum for physics students at the University of Turku, taught in the second study year. The course lasted seven weeks and contained two weekly lectures (14 lectures in sum) and weekly recitation classes starting from the second week (6 classes in sum). The course was taught in English by a postdoctoral researcher, and two visiting lecturers accompanied weeks 5 and 6.

Students received problem assignments, which were discussed in weekly 90-minute recitation classes. During the classes, students discussed their solutions in groups under the guidance of a teaching assistant (a theoretical physics doctoral student) before the correct solutions were revealed. Students also received points for solving the problems based on the correctness of their solutions and effort.

The course followed the textbook ”Quantum Processes, Systems, and Information” by Schumacher and Westmoreland [95], thus implementing the ”spin-first” teaching approach (see Chapter 2.1). In Chapter 2.1.1 we discussed difficulties students may encounter when studying quantum mechanics basics through this book. Weekly course contents, which can be linked to this discussion, and the questionnaire schedule are shown in Table 1.

Before lectures students were asked to read scheduled paragraphs of the book and respond to preliminary tasks in the Ville learning platform [243], from which students received points. The final assessment of the course was an exam, and the final grade was determined by points from the exam, preliminary tasks and solving the problems.

Table 1. Weekly course contents and questionnaire schedule. Questionnaire Q1 probed optimal learning, related emotions, self-efficacy, and motivation (plus student background on week 0). Questionnaire Q2 probed optimal learning and related emotions.

Week	Table of contents	Questionnaire
0	Pre-course questionnaire	Q1
1	Information and bits, Wave-particle duality, Photon in the interferometer	Q2
2	Photon in the interferometer, Spin ½, Two level atoms	Q2
3	Hilbert space and Operators	Q2
4	Observables, Adjoints, Eigenvalues and eigenvectors	Q2
5	Quantum cryptography, The uncertainty relation, Unitary evolution, The Schrödinger equation	Q2
6	Free particle in 1-D, Particle in a box	Q2
7	Recap of the course contents	Q1

4.3.2 Data collection

The purpose of this study was to investigate when university physics students experience optimal learning states, what kind of emotional trajectories they have and how self-efficacy beliefs and motivations are related to academic emotions and learning engagement during the quantum mechanics course. We used two different questionnaires, Q1 and Q2, to collect the data, scheduled weekly according to Table 1. Following this schedule, each student was supposed to fill in eight questionnaires. Part of the questionnaire Q1 was adapted from related parts of the validated questionnaire originally used to understand the motivations and retention considerations of university physics students in Finland [128]. It relies on the self-efficacy beliefs framework and three motivational aspects of task value beliefs (personal relevance, intrinsic motivation, and extrinsic motivation). To monitor students' optimal learning states and related academic emotions in both questionnaires, we adapted the questionnaire with validated measures by Schneider et al. [215], who adjusted the framework and questionnaire of Csikszentmihalyi and Schneider [244] for Finnish physics students. We collected data insitu, and not merely through pre- and post-course questionnaires, because the recalled experiences about the course, usually tested in the post-course questionnaire, can be unreliable [213; 245]. Both questionnaires used Likert questions on a 1-4 scale. In total, 17 Finnish-speaking students (6 women, 10 men and 1 other) filled all eight questionnaires. Of these students, 15 reported their age in the first Q1 questionnaire; the average was 22 years.

The first questionnaire, Q1, probed students' self-efficacy beliefs, motivation (intrinsic motivation, extrinsic motivation, and personal relevance), optimal learning state (skill, interest, challenge) and academic emotions related to optimal learning (enjoying, successful, happy, active, self-confident, anxious, stressed, bored and confused). It also collected background information, like age and gender. Students filled this questionnaire before the course and during the last week of the course (Table 1). The second questionnaire, Q2, contained only questions related to academic emotions and was filled by students weekly at the end of the recitation class (Table 1).

4.3.3 Data analysis

Optimal learning state was indicated by the simultaneous appearance of Likert scale grades 3 or 4 for interest, challenge and skill. We analyzed students' responses to the three questions related to optimal learning state probing for everyone individually and calculated an average value for the group to see average weekly changes in interest, skill, and challenge.

To determine students' emotional trajectories, we used principal component analysis for responses to questions related to interest, skill, challenge and emotions from all eight questionnaires. With principal component analysis, we were able to see variations across students and throughout the course.

Finally, we used multilinear regression analysis to predict students' optimal learning states and emotions based on their self-efficacy beliefs and different types of motivation (intrinsic motivation, extrinsic motivation, and personal relevance). The first set of response variables were the academic emotions combined into enhancers (happy, active, self-confident), accelerators (anxious, stressed), and detractors (bored, confused). The second set of response variables were interest, challenge, and skill. They were collected from Q2 questionnaires and the last questionnaire. Predictor variables were collected from the first questionnaire (before the course).

5 Results

5.1 University students' relation to quantum physics

The first sub-study sheds light on the impact of sociocultural and educational environment on students' relation to quantum physics. It also investigates quantum physics topics of interest and preferred study methods as seen by STEM and non-STEM university students. Luckily, students are moderately interested in quantum physics, but their attitude towards it has room for improvement.

5.1.1 The effect of environment on students' encounters with quantum physics

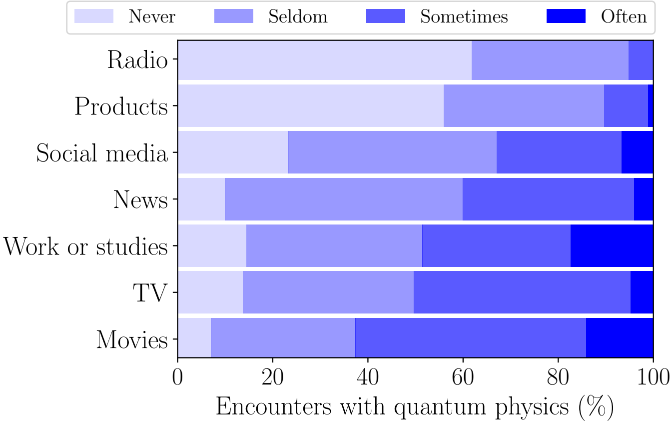

Figure 4. Encounters with quantum physics. The bars show how often students have encountered quantum physics in different suggested media.

Most students (84%) had encountered quantum physics, but many did not know much about it (45%) or knew it just a little (39%). Most non-STEM students (64%) responded that they didn't know much about quantum physics, while most STEM students (70%) responded that they knew little about QP. Nearly all students (98%) had attended upper secondary school, and half had taken advanced physics. However, 60% of students self-evaluated that they had gained quantum physics knowledge from news and articles, and only 35% from upper secondary school advanced physics courses. These results already demonstrate the effect of the sociocultural environment. Events related to quantum physics, books, hobbies, discussions and internet resources were only minor contributors.

Both STEM and non-STEM students listed a similar number of technologies relying on the mix of classical and quantum physics. Minor differences between students came from applications, which we evaluated clearly quantum- or classical-based: STEM students provided more responses with quantum-based applications and non-STEM students with classical-based ones.

According to the multiple-choice question, the most important contexts for encountering quantum physics were movies, TV, work, and studies (Fig. 4). Other significant contexts were news and social media. Similarly, students responded in the open-ended question that they had encountered ”quantum” (possibly including also quantum hype) in pop culture (43%), free time (39%), e.g. in books and 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).

5.1.2 Attitudes

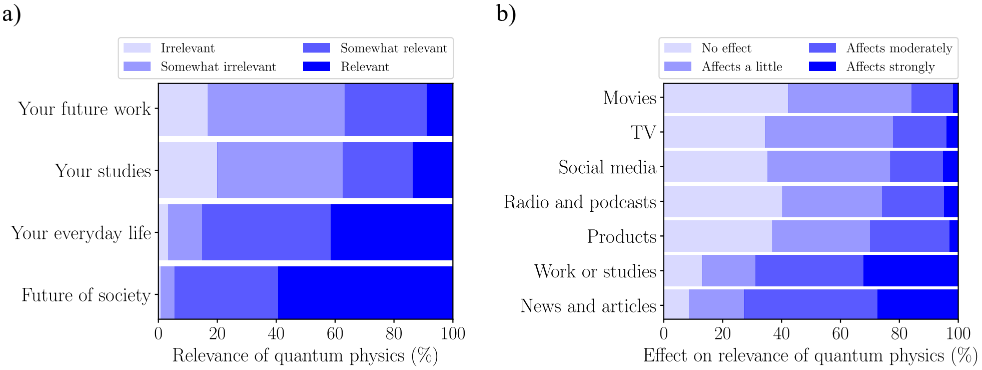

Figure 5. Relevance of quantum physics (QP) and how to influence it. a) Students’ views on the relevance of QP to the different aspects of their lives. b) Students’ views on how different influencers affect their opinion about the relevance of QP.

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. 5a). Students reported that the relevance of QP is primarily influenced by news and articles (73%) and work or studies (69%) (Fig 5b).

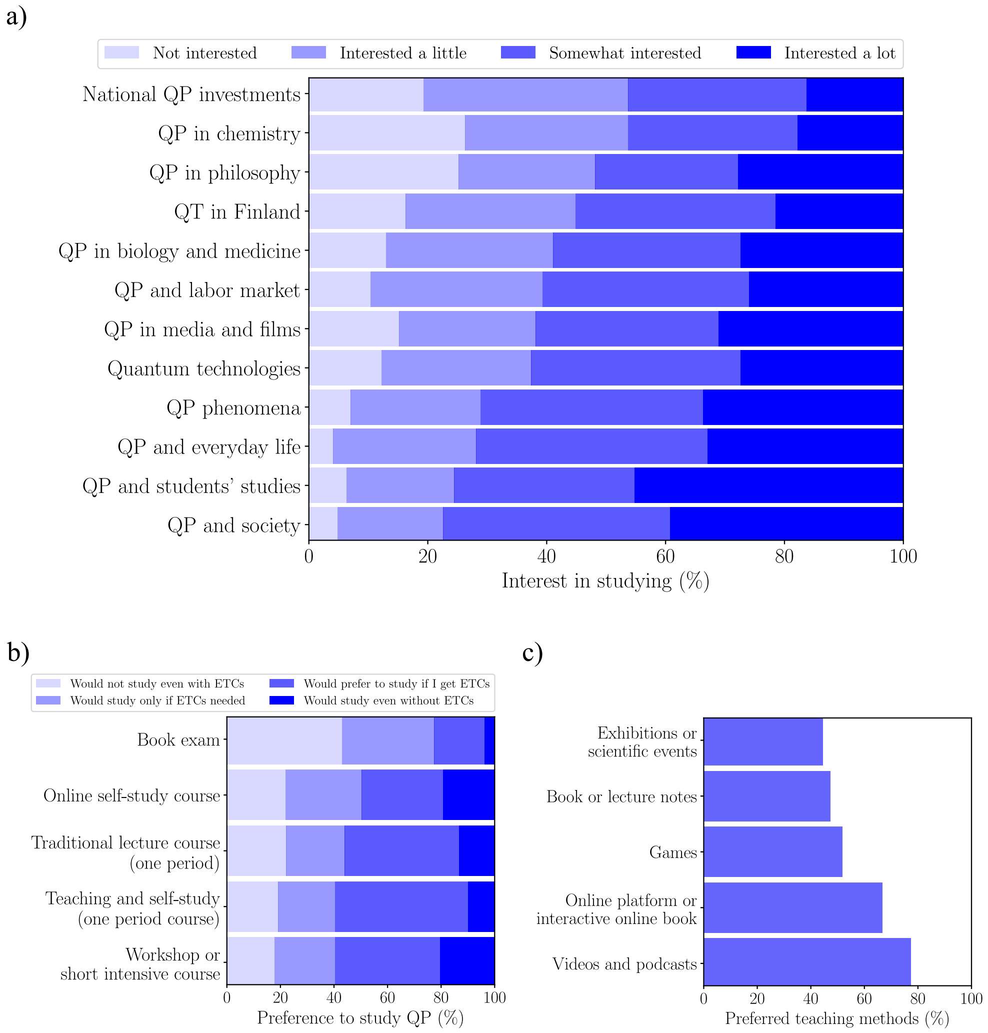

Figure 6. Why study QP and how? a) Students' interest in studying different topics or aspects of quantum physics. b) Students' motivations to study quantum physics in different contexts. c) Preferred study methods for the quantum physics topics in panel a.

5.1.3 Interest in learning quantum physics

Students' responses indicating their interest in studying the listed topics, their motivations for studying quantum physics in different settings, and their preferred methods for these studies are summarized in Fig. 6. Students expressed an interest in studying quantum physics topics, especially the relation of quantum physics with society, their studying field and everyday life (Fig. 6a). Also, an interest to learn quantum physics phenomena was in the top four. Should such studies fit into their curricula and study credits be given, students would prefer to study specific quantum physics topics either in a short intensive or full-length course (Fig. 6b). Regarding study methods, students prefer videos, podcasts, and online platforms (Fig. 6c). Half of the students would also prefer games. However, half the students still favor traditional textbooks and lecture notes.

To identify possible patterns, we did a principal component analysis and K-means clustering of all the data. We named the first principal component *Personal relevance*, which characterizes the interest in quantum physics, its importance for own studies, and related qualities. It does not correlate with gender, current field of study, or the frequency of QP encounters. The second principal component, named *Media influence*, 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.

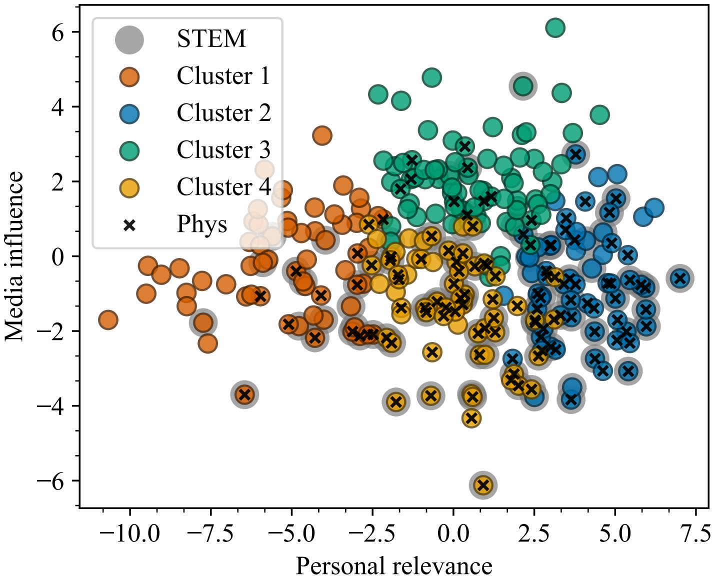

Figure 7. Analysis of multiple-choice questions by unsupervised machine learning tools. The students in the principal component plot are bundled by K-means clustering (colors). The plot identifies students with advanced physics studies at the upper secondary level (crosses) and students studying STEM fields at a university (grey shading).

It was challenging to cluster students, but we chose to use four clusters for the sake of discussion: students not interested in learning quantum physics (cluster 1), students interested in learning quantum physics (cluster 2), students with opinions of quantum physics highly influenced by popular media (cluster 3), and students with opinions uninfluenced by popular media (cluster 4). Primarily, STEM students were interested in studying quantum physics and had opinions uninfluenced by popular media (clusters 2 and 4). Usually, they had also studied advance physics courses in high school (Fig. 7). Consequently, the influence of media on non-STEM students' opinions of quantum physics can be explained by the accessibility of these resources and lack of educational experiences with quantum physics from other contexts.

The multivariate linear regression resulted in the model ($R2=0.42$ and $F=32.7$ with $p<0.001$), which shows that the main predictor of interest in learning quantum physics topics is perceived importance (coef 0.52, $t=8.3$, $p<0.001$), followed by quantum physics knowledge (coef 0.22, $t=4.0$, $p<0.001$) and frequency of encountering quantum physics (coef 0.17, $t=2.1$, $p<0.05$). This model can be easily understood from the perspective of interest development theory by Hidi and Renninger [139]: interest requires continuous triggering, mediated through encountering the subject of interest, and develops hand in hand with knowledge development. Here, perceived importance or personal relevance can work as a powerful interest trigger. In addition, perceived importance can be related to intrinsic motivation, and motivation eventually leads to choice, in this case to a possible choice to study quantum physics topics.

5.2 Physics and mathematics students' interest and relation to quantum physics before and after a one-day event

The effect of different interest triggers was explored in the second sub-study. Overall, Fun in Theory succeeded in changing students' attitudes towards quantum physics to more positive and realistic and managed to trigger students' interest in quantum physics, and theoretical physics more generally.

5.2.1 Interest

Students' phase of interest remained essentially unchanged after the event. Based on the phase of interest analysis, before and after the event 13 students remained in the situational interest development phase and two in the emerging individual interest development phase. However, one participant had the phase elevated from triggered to maintained situational, and two participants had it the other way around.

In the third questionnaire, the participants estimated the overall *change* in their interest due to the event. Eleven participants self-evaluated that their interest increased after the event, and four participants reported no change of interest. Interviews with five participants revealed in more detail how Fun in Theory affected different students. Three students evaluated that the event increased their interest in quantum physics, one student experienced interest elevation in cosmology, and for one student Fun in Theory didn't have any effect. Also, three out of five students reported an interest in taking theoretical physics courses as a minor. As expected, different students got their interest triggered by different means. For some students it was the social aspect that was especially appealing and for other students the main interest-increasing factor was new knowledge. For some students the lecture or the game worked best as an interest trigger, while others found that their interest increased constantly throughout the event.

5.2.2 Topics of interest

Topics that participants wanted to learn were divided into five categories (Fig. 8): *theoretical concepts* (e.g., quantum field theory, particle and nuclear physics topics, mathematical quantum physics, and tunneling), *applications of quantum physics* (quantum computing and med- ical physics topics), *everything* (responses like ”I want to start studying quantum physics one way or another” or ”Interested on a general level”), *nothing* (”I don’t know” or similar responses), and *non-quantum physics topics* (cosmology and theory of relativity).

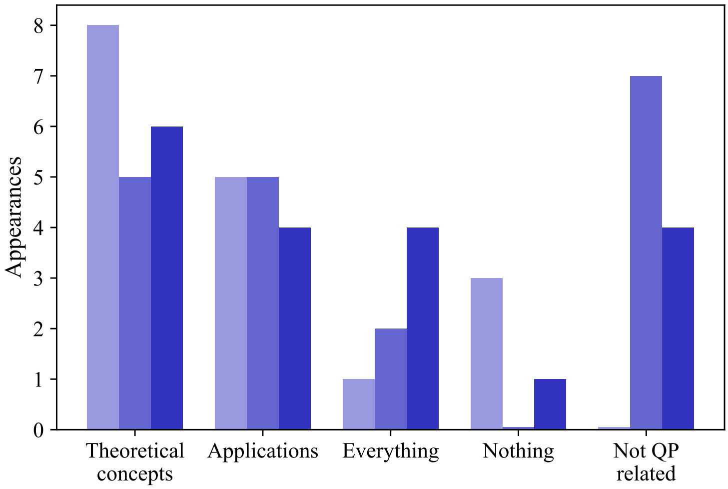

Figure 8. The topics participants wished to learn before (left bars), right after (middle bars), and one week after the event (right bars) in five categories.

Before the event students wished to learn mainly theoretical concepts and quantum physics applications, showing that students were already aware of them from their surroundings or earlier education. Right after the event the amount of such requests slightly decreased but remained somewhat stable also one week after Fun in Theory. After the event students also wished to learn non-quantum-physics-related topics. In addition, after the event students wished to learn more ”everything” and less ”nothing”.

5.2.3 Attitudes

The adjectives from student responses describing quantum physics were categorized in six groups: *appealing* (interesting, fun, great, beautiful, appealing, fascinating), *important* (fundamental, important, useful, visible, universal, current), *informative*

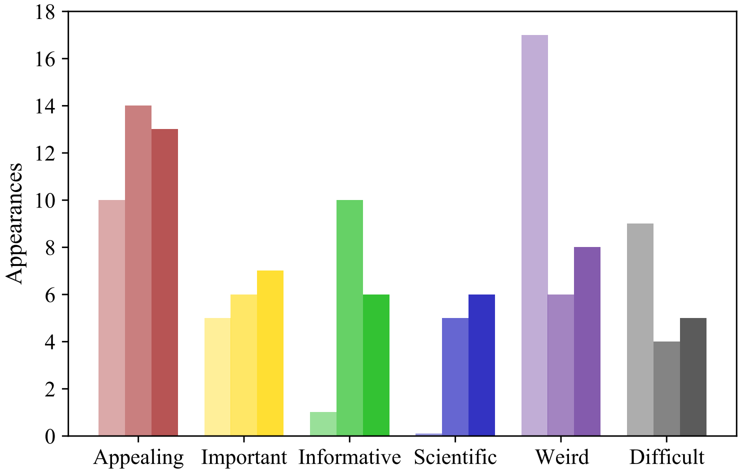

Figure 9. The cumulative appearances of different groups of adjectives before (left bars), right after (middle bars), and one week after the event (right bars).

(informative, large, deep, generally educating, general, versatile, every-day), *difficult* (difficult, challenging, hard), *weird* (unknown, scary, distant, weird, complex, hard to demonstrate, bizarre, non-logical, counterintuitive, unsure, mystical, special), and *scientific* (scientific, mathematical, random, nondeterministic, new, futuristic). Here, the adjectives in brackets represent English translations of all the adjectives students used in their responses. Collective results are presented in Fig. 9.

Before the event students perceived quantum physics as mainly *weird* and moderately *appealing* (Fig. 9), which reflects quantum physics representation from sociocultural and even educational environment [246]. Some students also described quantum physics with adjectives from categories *difficult* and *important*, and one student used an adjective from the category *informative*. No one perceived quantum physics as *scientific*. After the event students described quantum physics noticeably less as *weird* and *difficult*, but instead used more adjectives from categories *appealing*, *informative* and *scientific* (Fig. 9). From the individual-level analysis, we observed differences between students before and after the event. This demonstrates once again that initially students have different perceptions, and Fun in Theory influences them differently.

5.3 Student affect during quantum mechanics course

With the results of this study, we can understand students' emotional experiences in quantum mechanics learning. The findings identify similarities and differences between students.

5.3.1 Optimal learning states

The optimal learning state of a student was indicated by simultaneous appearance of Likert scale values 3 or 4 for interest, skill and challenge in their responses. On an individual level, six students never experienced optimal learning state during the course and ten students experienced optimal learning state at least once. Only one student (student 4 in Fig. 11) experienced optimal learning state on a weekly basis, except for week 7. On a group level, students' interest remained somewhat high throughout the course, even considering a slight decrease. Challenge and skill showed drastic changes around the middle of the course, when a deeper dive into quantum mechanics and its mathematical formalism started (Fig. 10). After week three students experienced a sudden increase in challenge and after week four a significant decrease in the perceived skills (Fig. 10). For a discussion of this finding, see Chapter 6.3. Overall, throughout the course, the average perceived skill was fairly low and the challenge rather high.

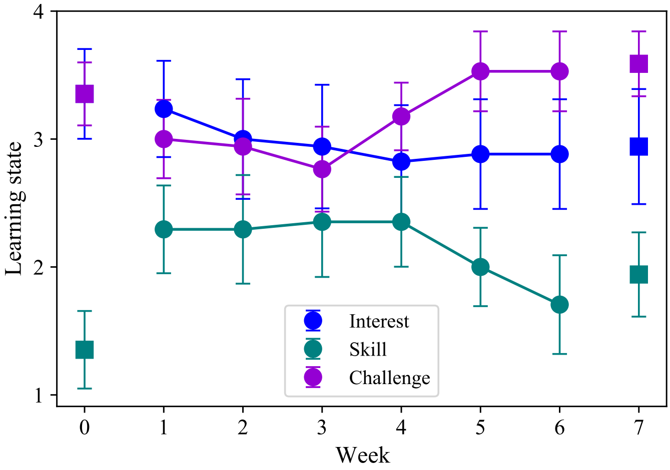

Figure 10. Learning states as described by weekly average values of interest, skill, and challenge. The optimal learning state would simultaneously include average interest, skill, and challenge values over 3.

At the end of the course, students reported higher skill, challenge and interest than on week six. In addition, before the course (on week 0) students considered themselves to lack skills for highly challenging, but still interesting, quantum mechanics (Fig. 10). On the first week of the course, students evaluated their skills higher and challenge lower. This is an expectation vs. reality situation, signaling the possible twisted attitudes and negative impressions towards quantum physics before the course learned from students' environment or earlier unfortunate quantum physics learning experiences.

5.3.2 Emotional trajectories

There was a large variation in emotional changes across students and throughout the course. The results of the principal component analysis are shown in Fig. 11. It was difficult to find descriptive names for the principal components because they combine all variables. We ended up naming the first principal component "*Overwhelm*", which is characterized by a lack of feelings of success, enjoyment, skill, interest, or self-confidence, and the second one "*Contentment*", which is characterized by happiness, stress, activity, challenge, enjoyment, confusion, and interest. The preferred emotional direction, representing states of optimal learning and enhanced feelings, resides in the upper left-hand corner of the diagram (high contentment and no feeling of overwhelm).

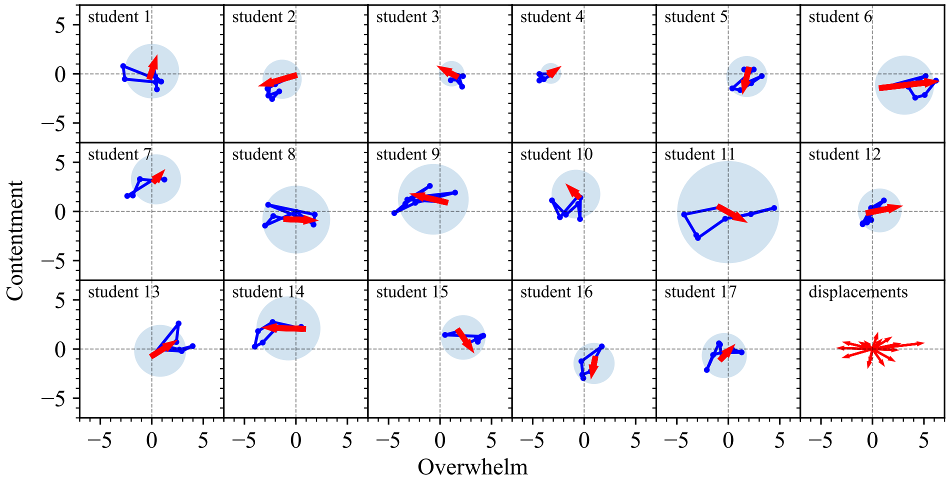

Figure 11. Emotional trajectories for all 17 students. Plots show how students' contentment and overwhelming feelings develop during the course. The blue-shaded sphere is a proportional root-mean-square variation of emotions, and the red arrows show the emotional displacement between the end and the beginning of the course. Students' emotional displacements are summarized in the bottom right panel.

Students experience different emotional trajectories (blue line in Fig. 11), also according to their size, and have different emotional displacements (red arrow in Fig. 11) of the principal component value at the end with respect to the beginning of the course. They also start the course at different emotional and learning states, which reflect the effect of the sociocultural and educational environment and earlier learning experiences with quantum physics.

The mutual trend, shown as an average over all 17 emotional trajectories in Fig. 12 goes through all quadrants: from the positive quadrant (high contentment and small overwhelm), to the decrease in contentment, followed by a steady increase in both contentment and overwhelm, to decreasing overwhelm, ending close to the emotional state at the start of the course. Because principal components are not fully complementary, a simultaneous increase in both can take place: on weeks 3-6 students feel more active, confused, stressed and challenged, and less skilled, self-confident and successful. However, this observation can be further explored, as well as a tendency of emotions and the learning state toward optimal at the end of the course (see also discussion in 6.3).

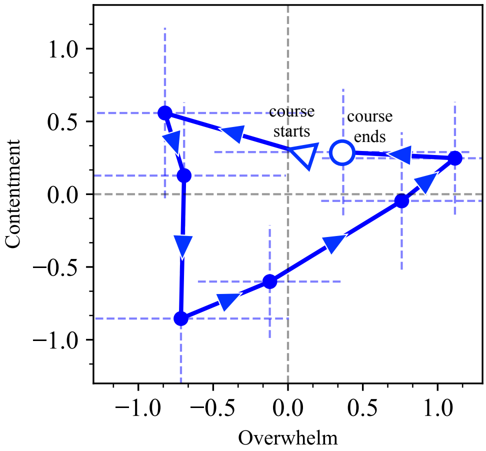

Figure 12. The emotional trajectory of the course averaged over 17 students. The dashed lines show the average standard deviations for the displacements between each step in the trajectory.

Overall, the results show how student affect, probed through learning engagement and academic emotions, is highly individual: students start at different points and have different experiences during the course (Fig. 11). Another central observation is the insufficiency of emotional displacement between the beginning and the end of the course to characterize the emotional trajectory during the course, especially visible in the mutual trend (Fig. 12).

5.3.3 Self-efficacy and motivation predicting academic emotions and learning engagement

The strongest predictor of emotions and learning engagement is intrinsic motivation (Table 2), which aligns with earlier results demonstrating a positive effect of intrinsic motivation on learning [247; 248; 249]. Self-efficacy contributes to the perception of skill and its lack promotes accelerating feelings and perceptions of challenge. The lack of extrinsic motivation and personal relevance also predict the perception of skill, and extrinsic motivation contributes to the feeling of challenge. These results demonstrate strong interrelations of different student affect factors.

Table 2. Multilinear regression coefficients (t- and p-values in brackets) for response variables (title row). Only statistically meaningful predictors ($p < 0.05$) are shown.

Response	**Self-efficacy**	**Intrinsic motivation**	**Extrinsic motivation**	**Personal relevance**
Enhancing		0.60 (4.2,< 0.001)		
Detracting		-0.49 (-2.7,< 0.05)		
Accelerating	-0.52 (-3.9,< 0.005)	-0.41 (-2.1,< 0.05)		
Interested		0.67 (3.6,< 0.005)		
Skilled	0.36 (4.7,< 0.001)	0.55 (4.9,< 0.001)	-0.22 (-2.2,< 0.05)	-0.19 (-2.1,< 0.05)
Challenged	-0.25 (-3.2,< 0.01)		0.27 (2.7,< 0.05)	

6 Discussion and Conclusions

All three sub-studies form a unified narrative with their results supporting each other. In the first sub-study, we explored the sociocultural experiences and views of STEM and non-STEM university students on quantum physics. In the second sub-study, we implemented the ”quantumness” of the sociocultural environment in educational approaches and games in a one-day event, Fun in Theory, to trigger physics and mathematics students’ interest in quantum physics. To understand physics students’ affective experience in interacting with quantum physics over a long period of time, in the third sub-study we explored student affect in studying an obligatory quantum mechanics course.

The first sub-study showed that students notice ”quantum” in the sociocultural environment, have a moderate interest in studying quantum physics topics, and almost unanimously think that quantum physics is important for society and their everyday life, but not for their studies or future work. For the second sub-study, during Fun in Theory, utilizing different interest triggers, we explained to the students how quantum physics can be a part of their studies and future careers. The results showed that Fun in Theory can indeed change students’ attitudes towards quantum physics to more positive and realistic, and trigger an interest in quantum physics. However, they also showed that such a short-lived event alone cannot elevate a phase of interest, which is consistent with the interest development theory [139]. Finally, the third sub-study showed that high interest in quantum physics topics can coexist with different emotions, ranging from contentment to overwhelm, and feelings of decreasing skill and increasing challenge. These results demonstrate that student affect should be considered when developing quantum physics teaching.

6.1 Student differences and similarities

Throughout all the sub-studies we found many factors that make each student unique: contexts to encounter quantum physics, phase of interest in quantum physics, attitudes towards quantum physics, and emotional experiences while studying quantum physics. Also, analysis of the first sub-study demonstrated that clustering students is challenging because their opinions are diverse in a continuous fashion. Therefore, quantum physics teaching and outreach should be designed to take into account students’ differences. It should be adapted to provide sufficient support to students, according to interest, motivation and self-efficacy beliefs they bring from sociocultural environment and previous educational experiences. Different knowledge background, misconceptions and impressions about quantum physics should also be understood and addressed in research and teaching.

The first step would include implementation of our results on student differences: different contexts to encounter quantum physics can be turned into scientific links to quantum physics topics, negative attitudes and emotions should be actively addressed in teaching and positive ones should be enhanced, e.g., by providing students with suitable challenge, necessary training for their skills, and constant triggering of interest (see also Section 6.4). Further measures may include collecting students' background information before and situational feedback during the teaching, implementing this information in teaching design and giving feedback to students during the teaching. Monitoring student affect and content understanding during the course creates an additional task for educators, but also enables the development of new methods and the use of already existing ones presented in the literature on quantum physics education research. For example, one can implement questionnaires, as in our second sub-study, to investigate learning engagement insitu, or interactive teaching tools, such as the use of clicker questions to check students' understanding of concepts and calculations for two-state quantum systems, as presented by Hu and Singh [38; 250].

All sub-studies also highlighted a common factor among students — a genuine interest in quantum physics topics. Maintaining students' interest and informing them about the relation of quantum physics to their field of study, society and everyday life could change students' perspective on the irrelevance of quantum physics to their studies and future career, a second common factor among STEM and non-STEM students. Also, university students' interest in quantum phenomena and theoretical concepts is important to acknowledge and utilize in teaching.

6.2 What is university students' relation to quantum physics?

Students have heard about quantum physics from their sociocultural or educational surroundings and have formed their relation to quantum physics based on these encounters. This attitude — ”important, but not for me”— was previously discovered among secondary school students towards quantum physics [122] and science [251; 252]. It has been well-preserved over decades, and we can assume that students take it from secondary school to university. Students don't see how quantum physics is relevant to them personally, because this information cannot be learned from the basic curricula of different study fields or from the sociocultural environment. This attitude is also related to the inability to see why quantum physics *learning* is important for each individual [122] and the lack of knowledge about possible quantum careers [124]. For example, for a student pursuing a career in business, learning the basics of quantum computing and being informed about the quantum ecosystem can be relevant, so later they could apply for a job in the quantum technology sector.

Furthermore, the results demonstrate a somewhat complicated relation to quantum physics even among physics and mathematics university students. On the one hand, both STEM and non-STEM students' perceived interest in learning quantum physics topics, seen in the first sub-study and in the responses to the questionnaire before Fun in Theory, indicates a positive relation to quantum physics. A similar result was observed by Rosenberg, with undergraduate STEM students being interested in learning more about quantum and quantum careers, even without prior familiarity with quantum concepts [124]. On the other hand, the results of the second sub-study also reveal stigmatized opinions on what quantum physics is like: physics and mathematics students describe it as mainly weird, moderately appealing, and difficult. The third sub-study reinforces this relation to quantum physics among physics students. Indeed, students see quantum physics as unintuitive [83], but the sociocultural and educational environment can also play a role in the formation of the ”weird and difficult” stigma. The way quantum physicists, lecturers and science communicators speak about quantum physics influences students' perceptions. Research on quantum physics education also emphasizes the role of educators in supporting students' understanding of quantum physics [118] and in career choice [124].

To summarize, university students find quantum physics relevant, but not that much for them personally, and its topics interesting, but also weird and difficult to study. Thus, we need to develop educational and outreach modules, that would change students' negative relations to quantum physics, or make already existing ones more visible and accessible for everyone. Students' already existing interest in quantum physics topics should be taken into account when designing teaching and outreach and used as a good momentum.

6.3 What is student affect in interacting with quantum physics in university settings?

Student affect in university education settings emphasizes differences between students. Although an average trend can be found for (un)optimal learning states and emotional trajectory of physics students in their first obligatory quantum mechanics course, students have very different emotional and learning engagement experiences. *How* students are different in their emotional trajectories is one of the most important findings of our research; they have both different spectrum and intensity of experienced emotions, and they start and finish the course with different academic emotions and learning perceptions. Accordingly, emotions and learning engagement measured only at the beginning and end of the course are insufficient to depict all the variations and individual differences during studying quantum mechanics. Now, our results provide further evidence for the importance of measuring academic emotions in situ, which was earlier highlighted by Lehtamo et al. when studying retention in the physics track [213].

Throughout the course, students' overall interest in quantum mechanics topics remains high, but perceived skill decreases and challenge increases towards the end of the course, remaining in an unoptimal learning state. Consequently, quantum physics teaching needs to be better optimized to help students achieve optimal learning state. A situational approach to measuring students' learning engagement should be adapted. In order to respond to the increase of challenge and decrease of skills students experience in quantum mechanics studying, the underlying reasons should be better understood. One possible reason may be an increasing challenge of mathematics presented in the course, building on top of conceptual understanding difficulties experienced by students. More research on the level of mathematical skills of university students should give new insights into the development of quantum physics education. Teaching should be adapted to the mathematical level of the students, which in turn should be constantly revisited.

From the averaged emotional trajectory, we observed that during the last week students tended more towards optimal learning state than in the previous weeks. This is an interesting observation that requires more exploration. It is unclear if this is a unique result for the course implementation with visiting lecturers, an undesirable effect of the distortion of the recalled experiences (vs. experiences in situ), or a desirable pattern identifying the improvement in learning towards the end of a course.

We found that intrinsic motivation was the main predictor of academic emotions and optimal learning states, followed by self-efficacy. These results are expected because motivation and self-efficacy are known to affect learning engagement [181; 201; 202]. Earlier, high motivation was also identified by university students in Scandinavia as one of the main driving forces for choosing STEM studies, which they perceived to require a high cost [253]. It seems only natural that intrinsic motivation helps students to persist in their chosen physics studies and achieve optimal learning states. In addition, research has demonstrated that students aiming at theoretical physics major in university studies report higher self-efficacy beliefs than other physics students [123; 129]. Consequently, we can expect self-efficacy to play an important role in the learning of quantum mechanics.

However, intrinsic motivation and self-efficacy change slowly, especially in university education settings, so they need to be constantly promoted. Again, our results on students' differences and similarities can form a ground for this task. Teaching should include explicit explanations of how students' previous encounters with quantum physics can influence their motivation and self-efficacy, stigmatic beliefs should be broken down and replaced by a realistic picture of quantum physicists and studying it. Intrinsic motivation can be stimulated by including students' quantum physics topics of interest in teaching, which could also add more value to studying. More generally, showing the value behind studying quantum physics is extremely important to balance the high cost [253], also visible in our results as a challenge in the quantum mechanics course. We need to demonstrate to students why knowing quantum physics is beneficial for them personally by showcasing links to other branches of science they are studying, and informing them about quantum careers and skill requirements. This, in turn, could also change students' attitude *"important, but not for me."* In addition, Fun in Theory, which managed to promote good and realistic attitudes towards quantum physics, provide students with motivational motifs, and enable students to experience achievement important for boosting self-efficacy, can be a first step to improve student affect variables. However, the positive effect of Fun in Theory needs to be maintained by a well-designed quantum physics teaching.

To summarize, in the context of studying quantum mechanics, students' academic emotions and learning engagement vary from individual to individual, with an average of moderately high interest, high challenge and low skill. Both emotions and learning engagement are mainly predicted by intrinsic motivation and self-efficacy beliefs. Our study on students' academic emotions and learning engagement during the quantum mechanics course gives novel results and highlights the corresponding research gap in quantum physics education research. We identify fresh perspectives for quantum education development, where new teaching methods [56; 61; 73; 74; 97; 101; 103], visualization tools [42; 43; 44; 104], quantum games [43; 46; 47; 48; 49; 50], and other novel developments can find their way to increase students' skills, minimize the perceived feeling of challenge, and eventually promote optimal learning. Because emotions are situational, discipline and course-specific [130; 254], we need to better understand students' emotions during quantum physics studying through different courses. Also, further correlating students' experiences with quantum mechanics topics and studying challenges known from literature, can give a new direction for the development of quantum physics education.

6.4 Developing quantum physics education

Combining the results presented here with previous studies on student difficulties [30; 31; 32; 33; 34; 35; 36; 37; 38; 39; 40; 41], teaching methods and materials [72; 73; 74; 75; 76; 77; 78; 79], concept inventory [3; 80; 81; 117], and quantum workforce requirements [4; 12; 13; 66; 106; 119; 120] can help to develop customized quantum physics and technology educational and outreach modules, beyond one-size-fits-all. Here we summarize recommendations for quantum physics education development:

1. Implementing the topics of students' interest (Fig. 8) can promote further interest development by capturing their attention, working as a trigger, and fostering knowledge.

2. In course design one may take students' preferred study methods and course length into account (Fig. 6).

3. Students' previous encounters with quantum physics from different contexts can be used to correct misconceptions, create links to new information, add

personal relevance for students and make teaching more fun and memorable.

4. Interventions, like Fun in Theory, can help to utilize a variety of interest triggers in quantum physics teaching and outreach nurturing interest development and the impact of different triggers on different individuals.

5. Active cultivation of students' motivation to be in touch with quantum physics is needed for efficient learning and choice making, including career choice. Students need to be motivated both beforehand and during the teaching. It can be done, e.g. by explaining students how quantum physics affects society and their study field (Fig. 8), and what kind of quantum studying and career perspectives exist.

6. Following students' learning engagement and academic emotions during quantum physics studying by the tools presented here, can help to react to students' struggles in situ by adapting teaching accordingly, and not merely for the next iteration of the teaching module. It can also bring a teacher new insights into students' experiences and help to relate to them.

6.5 Future research outlook

”Know your audience” is the first thing I was taught in university pedagogy courses focusing on teaching planning. The research presented here provides us with the current information on university students' affect and relation to quantum physics. However, in constantly changing sociocultural and educational environment it is crucial to explore these aspects more frequently, and build teaching modules and outreach based on the most current knowledge about our audience. To continue with this mission, a better understanding on reasons underlying students' emotions, attitudes and motivational variables, presented in the results of this research, must be understood. Also, more detailed research on what exactly students feel challenging or appealing in quantum physics according to their own perceptions and the development of validated tools to measure triggering of interest, the phase of interest development and students' relation to quantum physics are needed.

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