Title: Actual vs. implied physics students: How students from traditional physics classrooms related to an innovative approach to quantum physics

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Abstract

Calls for renewal of physics education include more varied learning activities and increased focus on qualitative understanding and history and philosophy of science (HPS) aspects. We have studied an innovative approach implementing such features in quantum physics in traditional upper secondary physics classrooms in Norway. Data consists of eleven focus groups with 58 participants from eleven physics classes, collected in 2013-2016 and analyzed thematically. Using the ‘the implied student’ (Ulriksen, 2009) as an analytical lens, we study the experiences of actual physics students against the student ‘implied’ by the innovative approach. The findings suggest that students struggled where the new approach holds implicit expectations that differ greatly from how students are expected to ‘do physics’ in traditional classrooms. For example, students found it difficult to monitor their performance in the absence of calculations and factual answers. However, students easily adopted visualizations as a new tool for reaching the familiar goal of content knowledge. HPS aspects motivated students, but were not necessarily seen as learning goals in their own right. There is a need for better alignment between learning activities, learning goals and assessment in innovations, and for making implicit expectations explicit so that students know what ‘doing physics’ successfully entails.

Introduction

During the last few decades, research on science teaching and learning, along with societal changes, has led to new visions for what constitutes quality physics education for a broad

range of students. Calls for improvement include emphasis on historical and philosophical perspectives related to science, incorporation of technology, and more varied, student-active and inclusive teaching and learning practices (see e.g. Bøe & Henriksen, 2013; Meltzer, Plisch, & Vokos, 2012; Meltzer & Thornton, 2012). However, tensions may arise when innovative approaches are introduced into a traditional physics teaching and learning culture (Carlone, 2003; Fraser et al., 2014). In this paper we study upper secondary physics students' experiences with an innovative approach to teaching and learning quantum physics, using learning resources that encourage discussion and collaborative learning and include history and philosophy of science (HPS). Applying Ulriksen's (2009) notion of an *implied student* as an analytical lens, the paper aims to understand how actual physics students navigate between the student role implied by their usual traditional physics classroom and the student role implied by ReleQuant's sociocultural and HPS approach to quantum physics.

The traditional physics classroom culture

We use the term “traditional physics classroom culture” to describe the strong disciplinary culture that exists within physics teaching, and which tends to emphasize physics content and basic laws rather than physics history, contexts and processes. Physics teachers' notions of “good physics teaching” tend to be topic-dominated and more transmissive than activity based, and teacher-centered instruction is dominating (Duit, Schecker, Höttecke, & Niedderer, 2014). Moreover, physics teachers are found to be more prone to content-driven, teacher-centered teaching than teachers in other subjects (Höttecke, Henke, & Riess, 2012). In their survey among Norwegian physics students and teachers, Angell, Guttersrud, Henriksen, and Isnes (2004) found that both students and teachers were happy with an instruction that was dominated by the teachers explaining from the blackboard followed by individual problem solving. These traditional physics classroom practices were found to dominate in Norwegian upper secondary physics also by the Trends in International Mathematics and Science Study

(TIMSS) Advanced (Lie, Angell, & Rohatgi, 2010), and similar patterns have been found in other countries (EVA, 2001; Häussler & Hoffmann, 2000; Mullis, Martin, Robitaille, & Foy, 2009; Osborne & Collins, 2001) and in university physics (Fraser et al., 2014).

Part of the traditional physics culture is that the subject is seen as particularly difficult and demanding (Dolin, 2002; Drury & Allen, 2002; Duit et al., 2014). This trait of physics is likely to reduce students' self-efficacy in the subject (Bøe, Henriksen, Lyons, & Schreiner, 2011). In Norway, Angell et al. (2004) found that physics students more than English or social studies students regarded their subject as difficult, while Bøe and Henriksen (2013) demonstrated that secondary students who had recently chosen post-compulsory physics, expected their subject to cost more time and effort than if they had chosen differently. Carlone (2003) found that traditional physics culture constructed physics as difficult, hierarchical, rigorous, and elitist, and argued that this impression undermined the goal of a physics that is more inclusive to a broad range of students. She also described the challenges involved in implementing a reformed physics course within a culture focused on achievement and with clear expectations for what counted as a "real physics" course. Archer, Moote, Francis, DeWitt, and Yeomans (2017) studied gendered patterns in post-16 physics participation in the UK, and argued that the traditional physics culture, which constructs the subject as hard and masculine, requires especially working class girls to undergo considerable identity work to make a physics identity possible. Johansson, Andersson, Salminen-Karlsson, and Elmgren (2016) studied available discursive positions in quantum physics in three introductory courses in Sweden, and concluded that the dominating focus was on a "shut up and calculate" culture emphasizing solving problems using the quantum mechanics formalism. The students had few opportunities to do quantum physics in an explorative or application oriented way, for example, by discussing interpretations of quantum physics or working with real-life applications of quantum physics, respectively.

The typical physics student is largely motivated by a strong interest in the subject in itself (Adams et al., 2006; Bøe & Henriksen, 2013; Lyons & Quinn, 2010; Maltese & Tai, 2010; Reid & Skryabina, 2002), though extrinsic motivational factors also contribute significantly to physics choices (Bøe & Henriksen, 2013; Mujtaba & Reiss, 2014). Although interest is a valuable driving force for motivation (Renninger & Hidi, 2015), the traditional physics culture has been criticized for not being more inclusive towards students with broader motivations (Hazari, Sonnert, Sadler, & Shanahan, 2010; Johansson et al., 2016; Krogh & Thomsen, 2005), for instance by including applications of physics in addition to pure science. A traditional physics student identity was characterized by Taconis and Kessels (2009) in their study of Dutch upper secondary students' impression of typical peers who chose different subjects. The typical physics student was described by peers as not very attractive, not particularly socially competent, not creative, but very intelligent and motivated. Hasse (2002) found that the discipline culture in a Danish undergraduate physics program included playful activities such as physics jokes, interest in science fiction literature, and playing with devising new experiments, and that males more often than females engaged in these activities and thus were included in the culture. Hazari et al. (2010) studied how physics identities were shaped by experiences in high school physics and career outcome expectations. They found that a physics identity correlated positively with wanting an intrinsically fulfilling career, but negatively with a desire for family time or for working with other people. A research report from 1990 (Lie & Angell, 1990) found similar choice motivations among Norwegian physics students, demonstrating that the interest-driven and ambitious physics student has dominated for quite some time.

Traditional physics teaching tends not to emphasize history, philosophy and the nature of science (NOS), even though such perspectives have long been advocated as important elements in science education in general (Abd-El-Khalick, 2013; Monk & Osborne, 1997) and

in physics education more specifically (Garritz, 2013; Henke & Höttecke, 2015; Johansson et al., 2016). This importance is reflected in curriculum documents such as the Next Generation Science Standards (NGSS, 2013) and in the Norwegian national curriculum for the post-compulsory physics subject for the final year of upper secondary school. For example, the Norwegian curriculum states that students should be able to “give an account of Heisenberg’s uncertainty relations, describe the phenomenon ‘entangled photons’ and give an account of their epistemological consequences”,¹ and that the physics subject should help students “create an awareness that physics is part of our cultural heritage and that the subject must be viewed in a historical perspective” and strengthen their “ability to differentiate between scientifically-based knowledge and knowledge not based on scientific methods” (NDET, 2006). Moreover, quantum physics has been shown to motivate Norwegian physics students due to its philosophical aspects (Angell et al., 2004), making the topic well suited as a starting point for implementing teaching and learning activities that foster understanding of NOS and of the historical and philosophical aspects of physics. Höttecke and Silva (2011) identified several obstacles to teaching history and philosophy of physics, namely the culture of teaching physics, teachers’ skills and attitudes, institutional framework, and textbooks. Many of these were seen in a study by Henke and Höttecke (2015) of a history and philosophy of physics project in German middle schools. This study also observed resistance to the approach and decreased motivation from many students. Yerdelen-Damar and Elby (2016) discussed how high-stakes testing, such as a final exam important to university admission, is an obstacle to implementing research-based, innovative teaching approaches as such testing tends to enhance teaching approaches associated with the traditional physics culture. They associated these traditional teaching approaches with surface learning, as opposed to deep learning, which they associated with linking physics concepts to each other and to real-life experiences.

The ReleQuant project

The ReleQuant project² develops web-based learning resources for general relativity and quantum physics in upper secondary school and studies the use of these in physics classrooms. ReleQuant employs a design-based research methodology (DBR), which entails that the research is situated in a real educational context (the physics classroom), focused on design and testing of an intervention (web-based learning resources) in several cycles (T. Anderson & Shattuck, 2012). In line with the iterative nature of DBR projects, the data used in this paper were in part collected to inform the next cycle of learning resource development. However, the aim of this paper is not to evaluate the learning resources but to study how actual physics students navigate between the student roles implied by the traditional classroom culture and the student role implied by the ReleQuant approach. Implications of the findings may of course overlap with resource development concerns. Also in line with DBR is the project's collaborative nature, where educators, physicists and teachers develop the learning resources together, to ensure material that is research based, theoretically sound and adjusted to students' and teachers' needs. The quantum physics material, which we focus on this paper, is designed to help students meet the competence aims described in the Norwegian upper secondary curriculum in quantum physics. These aims emphasize qualitative understanding rather than calculations and include philosophical and epistemological reflections on quantum physics and the nature of its break with classical physics. The ReleQuant material is based on a sociocultural view on learning, meaning that use of language is a crucial feature of emerging learning processes (Vygotsky, 1978) and that students make physics concepts their own through interaction with others (Mortimer & Scott, 2003). The learning resources, therefore, include a range of activities where students use oral and written language, often together with peers.

Central design principles for the learning resources are that they should (Bungum, Angell, Henriksen, Tellefsen, & Bøe, 2015; Henriksen et al., 2014):

- draw on sociocultural theories of learning;
- address documented conceptual challenges for students;
- facilitate students to use written and oral language in collaboration;
- allow students to explore digital animations and simulations of phenomena;
- illustrate how scientific knowledge is negotiated and developed as a human product;
- use examples from the history of physics in supporting conceptual development;
- inspire philosophical and epistemological reflections;
- show examples of how contemporary physicists may disagree on interpretations of quantum physics;
- clarify how quantum physics breaks with classical physics; the breaks should be formulated explicitly and may also make students more aware of the philosophical foundation on which classical physics is built;
- present examples and applications that are relevant to students' life-world; this should include technological applications as well as philosophical aspects of quantum physics
- support teachers' varied use of communicative approaches;
- support teachers to follow up and assess their students' learning.

An example from the current version of material is briefly presented as follows: The first teaching module in quantum physics is called *Need for a new physics*,³ and uses the nature of light as a starting point for working with the development of quantum physics and how it constitutes a break with classical physics. The students start with answering the question “What do you think light is?” in writing, based on their previous knowledge. After this, a short animated film follows that addresses the development of quantum physics, focusing especially on the nature of light, Einstein's work on the photoelectric effect and his quantum

hypothesis and Niels Bohr's opposition. The film ends up stating that we still have two models for light, the particle model and the wave model, and that physics in general is an ongoing human endeavor. Another film follows, where two physicists from the University of Oslo answer the question "What is light?" in quite different ways. The theoretical physicist explains it from a typical wave-particle duality perspective consistent with the so-called Copenhagen interpretation of quantum physics, primarily advocating the particle model. The other physicist favors the wave model, and explains how he is critical to the wave-particle duality in quantum physics. He points, for example, to the paradox that a point particle can have a wavelength. The students are then asked to discuss in pairs the question "Is it possible to imagine that light is both wave and particle?"⁴ When they are done, they see another short film where the same two physicists talk briefly about how their differences of opinion boil down to interpretations of quantum physics and philosophical points of view. The first module also includes sections on how quantum physics breaks with classical physics. Four other modules follow *Need for a new physics* in the learning resource; *Light as particles*, *X-rays*, *Particles as waves*, and *Quantum physics and philosophy*.

Theoretical perspectives

The implied student

Ulriksen (2009) presented *The implied student*, a concept he and his colleagues developed while studying the encounter between students and physics studies at two Danish universities. According to Ulriksen (2009), "The implied student could be understood as the study practice, the attitudes, interpretations and behavior of the student, that is presupposed by the way the study is organized, the mode of teaching and assessment, by the teachers and in the relations between the students, enabling the students to actualize the study in a meaningful way" (p. 522). The concept focuses on the meeting between structural and cultural characteristics and

the knowledge and experience of the students, and builds on previous work on identity and institutional culture by for instance Hasse (2002) and Becher (1989).

Fundamental to the concept of the implied student is the idea that studying is a process of socialization. Ulriksen draws on works describing enrolment into university as entering a specific disciplinary culture where students learn to ‘think, comprehend and engage with the discipline in a specific way’ (p. 518). Ulriksen describes how academic socialization also includes developing an identity as students within their disciplines, which means learning to be students in a way that others accept and recognize as belonging to that discipline. When students enter a study they meet a disciplinary culture with a set of structures and traditions such as curriculum and approaches to teaching and assessment. Teachers and older students are part of the culture and hold their own experiences and expectations. Ulriksen argues that each of these elements of a university study – content and structure, modes of teaching and assessment, teachers, and students – holds assumptions and expectations about what their students should be like. That is, each element contributes to one or more *implied students*.

The concept of the *implied student* has previously been used to analyze students’ meeting with higher science and technology education (Ulriksen, Holmegaard, & Madsen, 2017; Ulriksen, Madsen, & Holmegaard, 2017). In this paper we propose that the concept of the implied student can be useful also in upper secondary education. More specifically, we employ the concept to analyze the experiences of senior upper secondary students from traditional physics classrooms when they encountered quantum physics learning activities emphasizing collaborative learning and historical, philosophical and NOS contexts. As Ulriksen points out, students’ socialization to particular modes of teaching could be more difficult if they encounter alternative modes to those they are used to. Throughout the paper we employ the implied student as an analytical tool to interpret and understand our empirical data.

Development of physics interest and self-efficacy

Ulriksen (2009) describes how the concept of the implied student includes notions of how students act and express themselves in order to be recognized as good physics students by others. Since typical physics students are described in the literature as interest-driven, devoted and particularly clever (Bøe & Henriksen, 2013; Maltese & Tai, 2010; Taconis & Kessels, 2009), it is important to acknowledge that developing and expressing interest and self-efficacy is part of students' socialization into the physics classroom culture. For example, Mujtaba and Reiss (2014) found that enjoyment of physics lessons and students feeling that they do well in physics lessons were associated with intentions to continue with post-compulsory physics. Therefore, the ways in which the physics classroom culture and activities offer opportunities for interest and self-efficacy development can be viewed as part of the classroom's implied student. To better understand these aspects of our data, we include theoretical perspectives about interest and self-efficacy.

Students' experiences in classrooms influence their development of self-efficacy beliefs and interests (Bandura, 1997; Eccles & Wigfield, 2002; Renninger & Hidi, 2015). Self-efficacy beliefs and interest have both been found to predict achievement, engagement and educational choices (Bandura, 2012; Denissen, Zarrett, & Eccles, 2007). Self-efficacy beliefs, as conceptualized by Bandura (1997), are students' beliefs in their ability to succeed with tasks, courses or activities in a certain domain. Bandura outlined four primary sources of self-efficacy beliefs: mastery experiences (for example doing well on a physics test), vicarious experiences (for example watching a peer doing a physics problem), social persuasion (for example positive feedback from a physics teacher), and psychological states (for example anxiety in a test situation or enjoyment doing an experiment). It is important that the effect of these sources on self-efficacy beliefs depends on the students' interpretation of, for example, their mastery experiences. A student may get the wrong answer on a physics problem due to a

small mistake with a plus or minus sign while doing everything else correctly. If the student interprets the wrong answer as a total failure and does not recognize the mastery in conceptual understanding needed to solve other parts of the problem, her or his self-efficacy beliefs are unlikely to be affected positively. Mastery experiences have been found to strongly influence science self-efficacy (Britner & Pajares, 2006; Chen & Usher, 2013).

Interest represents a specific relationship between a person and an object, where an object can refer to a topic or subject matter as well as to concrete things (Krapp & Prenzel, 2011).

According to Hidi and Renninger (2006), interest develops in four phases: triggered situational interest, maintained situational interest, emerging (less-developed) individual interest, and well-developed individual interest. The more developed a person's interest in a subject matter is, the more the person will persevere in her or his efforts in the face of challenges and frustration (Hidi & Renninger, 2006). Opportunities for engagement and various degrees of support are needed to maintain and develop interest, especially in the early phases. Classroom environments and activities that engage students and enable them to connect to the content support development of interest (Renninger & Hidi, 2015). Activities that have been found to support interest development include collaborative work, contexts that relate new material to topics the students already have an interest in, and attractive computer environments (Hidi & Renninger, 2006). However, group work among peers may be less successful when the students are in different phases of interest (Renninger & Hidi, 2015).

The physics student implied by the traditional physics classroom

The literature review and theoretical perspectives presented above allow us to characterize the physics student implied by the traditional physics classroom, see Table 1. Although we believe it is helpful to describe the implied student as a person with certain preferences and characteristics, the descriptions do not refer to empirical entities but to analytical tools enabling us to interpret and understand our empirical data.

[Insert Table 1 here]

The dominance of transmissive, teacher-centered pedagogy in traditional physics classrooms (Duit et al., 2014) implies a student who is comfortable with this approach and learns well from it. These characteristics have previously been found to dominate among Norwegian physics students (Angell et al., 2004). Further, the traditional classroom implies a student who likes to solve physics problems, often by doing calculations, and a student who builds self-efficacy through solving such physics problems. The mastery experiences of getting correct answers and doing well on tests are likely to be important sources of self-efficacy (Britner & Pajares, 2006; Chen & Usher, 2013) and even interest (Renninger & Hidi, 2015) for the student implied by the traditional physics classroom. The implied student typically has a well-developed individual interest in physics already, especially in the subject in itself and in fascinating questions related to quantum physics, astrophysics and cosmology (Angell et al., 2004). She or he is largely motivated for learning as well as choosing physics by this interest (Bøe & Henriksen, 2013; Krogh & Thomsen, 2005; Lyons & Quinn, 2010), and this will help the student to keep going in the face of difficulty (Hidi & Renninger, 2006). Wanting to perform well on tests is likely to be another central motivational factor for such a student, since physics is regarded as particularly difficult (Dolin, 2002; Drury & Allen, 2002), and confirming a physics identity traditionally requires that students demonstrate they are brainy and dedicated enough to cope with it (Archer et al., 2017; Taconis & Kessels, 2009). The traditional physics classroom's emphasis on content knowledge (Duit et al., 2014) implies a student who likes to learn about physics content more than contexts and history, philosophy or NOS aspects and who sees learning physics content as the main goal of physics education.

The physics student implied by the ReleQuant approach to quantum physics

Our characterization of the physics student implied by the ReleQuant approach to quantum physics is based on the design principles for the ReleQuant material as outlined and

elaborated on in Henriksen et al. (2014) and Bungum et al. (2015) and on the actual web-based learning resources.

[Insert Table 2 here]

Because of their grounding in a sociocultural view on learning, the learning resources include a range of activities where students use oral and written language, often together with peers. Consequently, the physics student that is implied by the ReleQuant approach likes collaborative, student-centered pedagogy and learns well from it. She or he will also enjoy discussing physics with peers and will develop conceptual understanding by engaging in such discussions. The physics student implied by the ReleQuant approach welcomes visualization tools such as animations, films and simulations, and develops understanding of quantum phenomena through using them. Singh (2008) argued that visualization tools would help students make connections between the formal and conceptual aspects of quantum physics. The student implied by the ReleQuant approach enjoys learning about physics qualitatively, with very little mathematics, and regards such learning as worthwhile. Given that the final exams in physics in Norway place little emphasis on assessing the qualitative learning goals of the curriculum (Lange, 2016), the ReleQuant approach requires students to be willing to spend time and effort on learning topics that are likely to be less relevant for their written exam results. However, the qualitative focus of the ReleQuant material might be helpful in terms of an oral exam, for which a proportion of the physics students in Norway are randomly selected.

The physics student implied by the ReleQuant approach will like to learn about historical, philosophical and NOS aspects of physics and recognize them as learning goals in their own right. Parts of the NOS elements in the ReleQuant material demonstrate that physics is a constantly developing enterprise that includes unresolved questions, for example concerning

the nature of light. The approach, therefore, implies a student who is open to learning about and discussing unresolved questions where a factual answer is unavailable. Moreover, while working with the ReleQuant material, physics students have to develop self-efficacy through gaining qualitative conceptual understanding, both in peer and class discussions and with the help of visualization tools. She or he is motivated by a wish to understand physics qualitatively, is fascinated by quantum physics and motivated by historical and philosophical aspects of physics. She or he is likely to develop her or his physics interest through collaborative engagement with such topics and by understanding more of them qualitatively. This interest will help them endure when faced with difficulty (Hidi & Renninger, 2006), for example when trying to grasp counter-intuitive phenomena in quantum physics.

Aim and research questions

The main aim of this paper is to understand how actual physics students navigate between the student role implied by their usual traditional physics classroom and the student role implied by ReleQuant's sociocultural and HPS approach to quantum physics. Specifically, we ask the following research questions:

1. To what extent did the students express that they were used to traditional classroom practices?
2. How did the students respond to the inclusion of visualization tools such as films, animations and simulations?
3. How did the students respond to doing physics through written tasks and small group discussions?
4. How did the students respond to the inclusion of historical, philosophical and Nature of Science aspects?

Methods

Data collection

The current study uses data from four rounds of classroom trials of the ReleQuant resources in 2014-2016. A total of 58 students participated in eleven focus groups, one group from each of eleven senior upper secondary physics classes (students aged 18-19) in four medium to high-performing schools in suburban areas in Norway. The students were in their final year of upper secondary school and enrolled in the most advanced physics class available in Norwegian upper secondary school, namely Level 2 physics. 19 (33%) of student participants were girls, which is a slight overrepresentation compared to approximately 28% girls in Level 2 physics nationally in 2013-2016 (NDET, 2017). Participants were selected by their teachers, who were encouraged to include students of different genders and achievement levels. Nevertheless, as participation in the focus groups was voluntary, there might be a bias in the sense that the participating students were among the more motivated and self-efficacious students. The students worked with the ReleQuant quantum physics learning resources as part of their regular physics education. Their teachers were well familiarized with the ReleQuant material prior to using it, having attended project seminars, taken part in workshops and given feedback to earlier versions of the material. In each of the four rounds of classroom trials, the focus groups were conducted after the students had completed their work with the learning resources, typically a week or two after they worked with the first module (Need for a new physics). This means that the students had worked with all or most of the in total five modules from the ReleQuant material when the focus groups took place. Each focus group lasted approximately 30–45 minutes.

The focus groups were moderated by a researcher in the project, primarily the authors of this paper, but two focus groups were moderated by another researcher in the project group and

two others by two master students. All focus groups used an interview guide informed by classroom observations, teacher interviews, and previous research. Major discussion topics concerned how working with the ReleQuant resources had influenced students' learning, motivation and epistemological reflections.

Analyses

Audio recordings of the interviews were transcribed by the authors and several research assistants, and coded, primarily by the first author, using the HyperRESEARCH software. The coding was done in several rounds and followed the procedure of thematic analysis (Braun & Clarke, 2006). The analysis was mainly inductive, but with a view to our research questions which directed attention to motivation, NOS, HPS, and differences between students' regular physics learning activities and those provided through ReleQuant material. Themes usually consisted of several codes or sub-themes that tended to be described in similar ways. For example, the "history, philosophy and NOS" theme consisted of the three separate codes "historical perspectives", "philosophical perspectives" and "NOS". Since the ReleQuant material often presents philosophical perspectives and NOS aspects in a historical context (for example using Schrödinger's cat and the development of quantum physics), it is not surprising that those three codes tended to group together. Resulting themes and sub-themes are shown in Figure 1. Lines between themes indicate that the themes tended to co-occur in statements and that focus groups talked about them in a certain way. For example, the line between the themes "use of language" and "traditional classroom practices" represents the fact that the students often talked about talking and writing physics as different from their usual classroom practices, and specifically that they missed the list of correct answers that they usually checked their answers against. The most interesting of the relationships between themes are discussed in the results section. An additional layer of codes was added to indicate how statements made by students adhered to the characterizations of the

students implied by traditional physics classroom and/or the ReleQuant approach (see Table 1 and Table 2).

[Insert Figure 1 here]

To give a little insight into the coding, we include a few examples of excerpts and their codes from the thematic analysis as well as from the additional layer with implied student codes. An excerpt coded as “implied traditional” as well as “use of language” is:

Yes, I think it was a bit difficult to adjust to not using formulas. [...] I’ve had [this teacher] for two years now and have become very used to doing physics through mathematics and formulas and that, so it has become very natural. And like now when we only start with sort of a language [...], it was quite troublesome to adjust to it.

The following excerpt was coded as “implied ReleQuant” and “visualization”:

And it was nice with the animation that popped up on the side when [the physicists in the films] were talking. You kind of were given a picture of what they talked about so you understood a lot better.

There were also statements coded with both “implied traditional” and “implied ReleQuant”. This occurred mainly when students expressed interest in quantum physics or HPS aspects (as presented in the material), an interest which is characteristic of both the student implied by the traditional physics classroom and by the ReleQuant approach. Two examples of quotes coded with “implied traditional”, “implied ReleQuant”, and “motivation” are:

It’s a bit more unknown, which is what, I think, appeals to most that take physics, like finding out stuff that is unknown and explore it a bit, and like relativity and so on it is very special stuff.

You included the Schrödinger's cat experiment, I thought that was very interesting to think about. So, it is motivating to get, or at least I think it is motivating when you include stuff like that. A somewhat different way of thinking.

The second and third authors did not code the material directly, but were involved in validating the interpretation of the codes and discussing the development of themes and interpretations during the analysis. Only robust patterns in themes are reported as findings. This means that although there were differences in the extent and depth to which the eleven focus groups discussed the themes, and although there were differences of opinion and experiences among students within a focus group, the reported findings represent consistent patterns that were found repeatedly across the material.

Results and discussion

This section answers the research questions by presenting the main results from the thematic analysis and discussing them in light of Ulriksen's (2009) *implied student* and the body of research literature presented in the introduction. In particular, we discuss the results against the characterizations of the physics students implied by the traditional classroom and the ReleQuant approach using illustrative quotes from the focus groups. The main themes in the analyses draw on data comprising a range of quotes from many students in different focus groups. Therefore, we do not use pseudonyms or any other means of indicating which of the 58 participants gave the quotes used as illustrations here.

The ReleQuant students appeared to be socialized into traditional physics classrooms

All eleven focus groups included several statements within the "traditional classroom practices" theme, confirming that the participants came from classrooms largely characterized

by traditional modes of teaching, motivation and assessment, as found in previous studies among Norwegian physics students (Angell et al., 2004). The respondents in our study talked about the ReleQuant approach as very different from their usual teaching, which is described as dominated by the teacher lecturing from the blackboard followed by individual problem solving. This excerpt from one of the focus groups illustrates this:

I mean physics has often been very like you read and then you do problems. [Murmurs of agreement from others.] And you pay attention to the teacher as he writes stuff on the blackboard.

A student in a different focus group said:

It's very different, [...] that you're supposed to formulate and explain things instead of doing calculations, we're not used to that. It's a totally different way of learning, really.

They also express a strong focus on assessment, tests and exams in line with the implied student of the traditional physics classroom (Carlone, 2003; Yerdelen-Damar & Elby, 2016). A quote from one student illustrates how the cleverness and importance of achievement is part of what identifies them as physics students (Francis et al., 2017; Taconis & Kessels, 2009).

But we, who take physics, we want to get good grades.

They appear to be socialized into a culture oriented towards test outcomes and final qualifications. The participants came from generally medium to high-performing upper secondary schools in the Oslo area which can be expected to have competitive school cultures. Secondary physics students in Norway are generally high performing in their other subjects as well as in physics and have been found to be ambitious in the sense that their physics qualifications are important because they provide access to university studies (Bøe &

Henriksen, 2013). Although it may seem contradictory, such extrinsic, utility based motivation tends to live side by side with strong interest for physics among traditional physics students (Bøe & Henriksen, 2013; Mujtaba & Reiss, 2014) and the ReleQuant students were no exception. Interest in and fascination by quantum physics was apparent in their discussions, as illustrated with this quote:

I looked more forward to the physics the lessons now, also because of the topic, it is very cool.

In this respect, the students implied by the traditional classroom and the ReleQuant approach are largely aligned, and it is not surprising that the actual physics students were able to satisfy and develop their interests while working with the ReleQuant material. Quantum physics may be a particularly good topic for innovative physics teaching this way, because of Norwegian students' general fascination with and interest in quantum phenomena (Angell et al., 2004; Rødseth & Bungum, 2010). In this way our experiences differ from those of Henke and Höttecke (2015), who studied the implementation of an HPS approach to physics in Germany and described students' lack of motivation as an obstacle to successful implementation of the approach.

Students welcomed innovative approaches to traditional outcomes

The ReleQuant approach emphasizes digital visualizations of abstract phenomena and social learning activities such as 'talking physics'. The focus group participants expressed great appreciation of the animations and films, all eleven focus groups talked about them as helpful for learning. This finding is illustrated by the relationship between the "visualization" and "learning" themes in Figure 1. Although these students were socialized into classrooms where the implied student is expected to like and learn well from the teacher explaining on the blackboard, they seemed to embrace the opportunity to learn from digital visualization tools.

I think it's been easier to do it this way. There were a lot of animations and films and that. And that makes it easier to learn when it's that ... like ..., a lot of it is not logical.

A student from another focus group expressed how the visualization tools prepared him for future tests:

Great to have those explanatory videos, at least I think so, because it is like very close to, especially the oral (exam), for the oral exam it is great to be able to in a way open a video, and you see it and polish up [your knowledge] a bit.

One way of understanding this finding is recognizing that the students welcomed a new tool for reaching a traditional outcome, namely increased content knowledge (Höttecke et al., 2012). Generally, visualizations have been found to promote learning in physics (Lee, Linn, Varma, & Liu, 2010; Müller & Wiesner, 2002). Although working differently than they were used to, the students' focus was still on understanding physics content, content that is generally considered to be particularly difficult to grasp because of its abstract and counter-intuitive nature (Henriksen et al., 2014; Krijtenburg-Lewrissa, Pol, Brinkman, & Joolingen, 2017). Here too, therefore, the student implied by the ReleQuant approach does not differ much from the student implied by the traditional classroom, and the actual students have little problem “doing physics” in this way:

In this topic I felt it worked better, actually, to be able to visualize it. For example, the stuff with interference and that. I wouldn't have understood it if you were to try and explain it on the blackboard, with electrons and interference and stuff. Then it was a lot easier to just “Oh, yeah, that's how it is” when you see it on the video. So I felt it worked very well to have videos.

Students struggled to monitor their performance in small-group discussions

The students expressed a more ambiguous response to the emphasis on written tasks and ‘talking physics’ in small-group discussions. The students tended to like these activities when they experienced them as helpful for conceptual development, primarily by letting them draw on other people’s insights or by making clear to them what they had not yet completely understood. Angell et al. (2004) also reported that their respondents wanted more qualitative teaching even if they appreciated the general dominance of problem solving. One of our focus group participants gave this comment to the use of small-group discussions:

You do learn from each other, though. When it is in this type of topic, where [scientists] are not entirely sure, then you might come up with new ideas [...] and new ways of explaining things. And that’s good.

However, ten of the eleven focus groups expressed uncertainty and frustration with these tasks in terms of achievement and self-efficacy. Students struggled to determine how well they had performed. In particular, they wanted the opportunity to check whether or not the answers or arguments they had given were correct, as is usually possible with quantitative problem solving. The following quote illustrates the struggle to monitor their performance:

[Quantum physics] is proper physics, but it doesn’t have that much calculations and stuff. So it’s hard to demonstrate knowledge.

A few students found working without being able to check their answers right away to be practically worthless:

It gives us nothing to do tasks without a list of correct answers [to check our answers against].

Others expressed a less categorical wish for immediate feedback:

What I might like was a bit more [...], maybe not a list of correct answers, but maybe which formulas and concepts [...], because that is important for the oral exam and even if you cannot have a list [to check your answers against], just knowing which concepts are smart to use, because that's what you're graded on anyway.

Table 1 describes the student implied by the traditional classroom as one who develops self-efficacy through solving mainly quantitative problems correctly and doing well on tests. The student implied by the ReleQuant approach cannot rely on mastery experiences with such problem solving, but rather develops and maintains self-efficacy through being able to use physics arguments or expressing their conceptual knowledge well in words. Our actual physics students seemed to struggle to adopt the new strategies for building self-efficacy that are implied by the ReleQuant approach. This was not unexpected. These students were socialized into a traditional classroom culture and thus used to developing self-efficacy and confirming their identity as good physics students in certain ways. The ReleQuant approach removed some of the structures that supported those processes, such as access to undisputable and correct answers to quantitative problems. This underscores the need for supporting students to develop new strategies for building self-efficacy when introducing ways of teaching and learning that change their usual mastery experiences. In the ReleQuant approach, for example, students may require help to recognize successful argumentation in physics as an achievement.

Moreover, the students' wish to perform in a traditional manner can limit the gains from small-group discussions. For example, if students feel that talking about physics in class is a performance where they have to demonstrate their cleverness and verify their physics identity, it may be intimidating to discuss a topic they have not yet fully understood. One student said:

It's a bit like the teacher pointing to a student who didn't raise their hand. Not everyone is as comfortable expressing those thoughts, especially since it's a topic we haven't learnt much about beforehand.

It may be that to students socialized into traditional physics classrooms, saying something out loud in class is a way of demonstrating what you know rather than a way to learn more. This is also a main point for Hattie (2009) who emphasizes the need for creating classroom environments where error is welcomed as a learning opportunity and students can feel safe to learn and explore knowledge and understanding.

A related aspect of the small-group discussions is that many of the tasks ask questions to which there are no clear, unambiguous answers in physics. For example, students are asked to discuss whether or not light can be both waves and particles and if Schrödinger's cat can be both dead and alive at the same time. The wave-particle duality of light and quantum superposition (problematized in the thought experiment 'Schrödinger's cat') are both conceptually challenging topics where philosophy and interpretations of quantum physics come into play (Cheong & Song, 2014; Henriksen, Angell, Vistnes, & Bungum, 2018; Myhrehaugen & Bungum, 2016). This seemed to fascinate but also frustrate students, as illustrated by the connection between the "motivation" and "history, philosophy and NOS" themes in Figure 1 and shown in these two quotes from different focus groups:

It is confusing because it goes against so much else that we have learnt, but it is very exciting because it is quite new and it is quite temporary, things you cannot quite explain so it becomes very exciting and you kind of, you want to try to find these things out for yourself.

If people who research this all the time don't know what's going on, then I don't think I will be able to deduce it.

The last quote may be a reference to a discussion a couple of minutes earlier in the same focus group, concerning a task where students were asked to discuss the wave particle duality of light after watching a film where two physicists expressed conflicting views on what light is.

The students' frustration can be understood in light of the student implied by the ReleQuant approach. She or he views working with unresolved questions and the history and philosophy of physics as important parts of physics education (Table 2), whereas our participants were socialized into a traditional physics classroom which tends to focus on established content knowledge more than unresolved questions and philosophical aspects (Table 1). Not being able to gain full conceptual insight, for example concerning the nature of light, was therefore unsatisfactory for many students.

HPS aspects stimulate interest, but are they “real physics”?

As described above, visualization tools tended to be described as helpful for learning. In contrast, historical and philosophical aspects were usually described as interesting or motivating rather than as having an effect on learning. Two students in different focus groups commented on the use of HPS aspects like this:

I liked that you included some history too, like Einstein and Bohr and the great physicists. A bit of where it comes from. It's interesting to [...] hear a bit about that too.

I also think it is important, or not very important, but that it can be ok – although it may not, we may not learn more physics – that we know a bit more about where it comes from.

The last quote sheds light on the perceived lack of connection between historical and philosophical aspects and physics learning, and on how such perspectives are considered to be

“not very important, but ok” to include. The nine focus groups that discussed HPS aspects (two of the focus groups failed to discuss this theme), talked about them in terms of motivation more than learning. This finding is illustrated in Figure 1 by there being a line between the themes “History, philosophy and NOS” and “Motivation”, but no line between “History, philosophy and NOS” and “Learning”. Six of the focus groups included explicit statements suggesting that HPS aspects were not seen as proper parts of physics, that is, as learning goals in their own right. When they studied quantum physics practices in three university quantum physics courses in Sweden, Johansson et al. (2016) found that historical aspects, although mentioned in the course plans, were mainly treated as outside of what was expected from the students in terms of doing physics well. Rather, the students were expected to focus their efforts on solving problems with calculations in a traditional physics culture way. Most of the historical aspects used in the ReleQuant material are primarily there to help the students achieve learning goals related to the nature of science rather than content knowledge. For example, one of the learning goals is that students should be able to “give examples of the fact that knowledge in physics is created by humans, through disagreement and over time”. The implied student of the ReleQuant approach, therefore, recognizes historical, philosophical and NOS aspects as learning goals in their own right. Our participants, however, expressed views more in line with the implied student of the traditional physics classroom, who views content knowledge to be the primary aim of physics education. We could say that the implied students of the ReleQuant approach and the traditional classroom align in the sense that HPS and NOS aspects motivate, but they disagree on whether there is something important to learn from them. One of the actual students expressed:

I don't think [HPS aspects] should be important on tests. That in a way it is more background information.

The students' understanding of what is important to learn is connected to the broader structure and context of the classroom culture they are socialized into (Johansson et al., 2016; Ulriksen, 2009). Our participants were in their last year of upper secondary school in a study program aimed at preparing them for university studies. Their choices to take physics indicate interest in physics as well as plans to use their physics qualifications to gain entrance to prestigious university studies (Bøe & Henriksen, 2013; Mujtaba & Reiss, 2014). It is, therefore, not surprising that many of the focus group participants talked about upcoming tests and exams. However, quantum physics topics tend to be less emphasized in national physics exams in Norway than in the curriculum (Lange, 2016). Therefore, students with a strong focus on exams may prefer to spend their time and effort on mechanics and electromagnetism instead of quantum physics, to maximize their achievement outcome.

Conclusions

In this paper we have studied the implementation of a sociocultural and HPS approach to quantum physics in traditional upper secondary physics classrooms. The results add to the existing literature describing how various types of teaching and learning innovations play out in different educational settings – in this case Scandinavian upper secondary physics classrooms – and which tensions may arise in the meeting between a traditional physics classroom culture and innovative approaches. We have looked at the data through the lens of *the implied student* (Ulriksen, 2009), which enabled us to view the actual physics students' experiences against descriptions of the physics students implied by a traditional physics classroom culture and by the ReleQuant approach. Thereby we have demonstrated how this analytical concept, originally developed in a higher education context, can be fruitful also in a secondary school setting.

The findings suggest that the students were socialized into a traditional physics classroom culture and that this framed their experiences of working with the ReleQuant learning resources. The sociocultural and HPS oriented learning approach to quantum physics present in the ReleQuant material has an implied student who in some respects differs significantly from the student implied by the traditional physics classroom culture while there was better alignment in other aspects of the two implied students. The students in our study easily adopted features of the ReleQuant approach that allowed them to ‘do physics’ in ways that were close to what they were used to in their traditional classrooms. For example, digital visualizations of quantum phenomena were embraced as helpful tools for learning content knowledge, i.e. for achieving a traditional goal. However, students struggled with aspects of the ReleQuant material that required them to change their strategies for learning as well as developing self-efficacy and maintaining their good physics student identities. In particular, many students were frustrated that they could not immediately check whether the written and oral tasks were done correctly, and they expressed uncertainty about how much they had learnt and how well they had done. Moreover, students found historical, philosophical and NOS aspects to be motivating. A similar finding was reported by Levrini et al. (2014) for Italian upper secondary students after a teaching intervention on optics and the nature of light where HPS aspects had a central role. Despite this interest and motivation, however, students in our investigation did not necessarily see HPS aspects as learning goals in their own right. This strengthens the impression that the actual physics students in our study had more in common with the student implied by the traditional physics classroom than by the student implied by the ReleQuant approach.

Implications

The study demonstrates how attempts to reform physics education must take into account the classroom culture the students are socialized into. However, rather than creating material that is well familiar to students and thus will reinforce traditional practices, we argue that learning resources should provide targeted support allowing actual physics students to develop strategies for ‘doing physics’ like the students implied by novel approaches. This will be important in the context of developing a modern and inclusive physics education with varied teaching and learning activities that spark the interest of diverse groups of learners and that include HPS aspects and qualitative understanding as well as traditional content knowledge and calculation exercises.

Yerdelen-Damar and Elby (2016) explored how Turkish upper secondary physics students who were engaged in a curriculum focusing on developing sophisticated personal epistemologies, displayed “epistemic compartmentalization” when faced with a high-stakes testing regime: Although the students could express quite sophisticated views on knowing and learning physics in an ideal situation, they resorted to memorization and rote learning in view of the upcoming test. The students took “different epistemic stances toward what counts as knowing and learning physics in different contexts” (p. 14), such as the context of the high-stakes test versus a context where a student was free to learn physics solely with the aim of understanding it more deeply. The authors suggested that to resolve this situation, high-stakes tests should incorporate elements that encourage deep approaches to learning in order to avoid that students resort to memorization and repetitive rote problem solving.

This raises the broader issue of how assessment practices to a large degree determine classroom practice in science education (K. J. B. Anderson, 2011). As Biggs and Tang (2011) pointed out, “quality learning” results when there is *constructive alignment* between intended learning outcomes, teaching/learning activities, and assessment practices. In the case of the ReleQuant approach, the teaching/learning activities were designed to align with curricular

learning aims; however, there are indications that the national exam, which the students would take only a few weeks after working with the ReleQuant material, often downplays qualitative learning goals such as those addressed in ReleQuant (Lange, 2016). Thus, one component of the constructive alignment chain is missing from the classroom context we have addressed through the present study. An important issue in future projects promoting innovative teaching and learning in physics is to include assessment practices as an integrated part of the research and development process. For quantum physics in particular, Krijtenburg-Lewrissa et al. (2017) underscored “the need for more empirical research into student difficulties, teaching strategies, activities, and research tools intended for a conceptual approach for quantum mechanics” (p. 010109-1). Wang and Buck (2016), discussing obstacles to the successful implementation of argumentation in high school physics, pointed out the lack of widely accepted criteria for assessment of student performance in discussions.

This study shows how secondary physics students sometimes struggle to navigate among implicit expectations in their physics classroom practices and culture, for example in terms of monitoring their performance in written tasks or discussions as opposed to mathematical problem solving. Our findings point to a need for making implicit expectations explicit to students and letting them know what ‘doing physics successfully’ entails. This corroborates Hasse (2002), who described how some of the expectations for a “promising physics student” at a Danish physics institution were only implied in the institutional culture and were not made explicitly clear to the students. This resulted in feelings of frustration and alienation among the students (particularly young women) who had not internalized these cultural codes. In general, the students in our study liked the ReleQuant approach to quantum physics and greatly appreciated, for example, the visualizations. However, they also resisted aspects of the innovation that challenged their traditional physics classroom notions of what success in

secondary physics looks like and what proper physics is, reinforcing Carlone's (2003) findings.

Our results demonstrate that students as well as teachers require support in order to successfully adopt new learning resources, and that this support should take into account the implicit expectations within the material. As a specific example, the latest and officially released version of the ReleQuant quantum physics learning resource includes an introductory section called "Learning with the *Quantum physics* program". This section presents the type of learning activities they will encounter, such as discussion tasks and HPS perspectives, and it explicitly points out that the students will practice thinking and making arguments like physicists, sometimes concerning questions to which there are no unambiguous factual, answers. Also included in the latest version are explicit learning goals in the beginning of each section of the *Quantum physics* program, including goals such as "use physics arguments in a discussion about whether light can be both waves and particles" and "write short, argumentative texts about the wave nature of particles". In accordance with the design-based research approach, these changes were made as a result of early phases of the research reported here and implemented prior to the last round of classroom trials and data collection.

We do not argue that actual physics students should be transformed to be like any of the implied students we have described. Rather we assert that we should strive to develop physics classroom cultures that allow students to 'do physics' in successful ways within a range of activities and approaches that foster learning and motivation.

One limitation of this study is that it includes students from only five upper secondary schools, all from the Oslo area. Further, Norway is a small country with a physics curriculum that stands out internationally with its inclusion of HPS and NOS aspects in quantum physics, such as epistemological consequences of entangled photons. However, the findings

corroborate and expand on previous research (e.g. Carlone, 2003; Hasse, 2002; Krijtenburg-Lewrissa et al., 2017) and we believe it is relevant beyond the Norwegian context.

In this paper, we have seen that recent calls for renewal of physics education include more varied and inclusive teaching and learning approaches and increased focus on qualitative understanding and HPS aspects. We have described how the ReleQuant project responds to these challenges in the case of quantum physics and have discussed what happens when a reform effort like this meets the traditional physics classroom culture. Furthermore, we have demonstrated that the concept of an *implied student* is a useful analytical lens for describing the tension between traditional expectations to a physics student and the expectations inherent in reformed approaches. Finally, we have pointed out the need to be aware of this tension and to make expectations explicit to students and teachers when introducing reforms. Examples include making HPS perspectives explicit as learning goals in their own right (also by including such perspectives in assessment) and helping students to recognize quality argumentation in physics as an achievement.

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Tables

Table 1: Characterization of the implied student of the traditional physics classroom

The implied student of the traditional physics classroom

- likes transmissive, teacher-centered pedagogy
 - learns well from transmissive, teacher-centered pedagogy
 - likes to solve physics problems, especially using calculations
 - likes to learn physics content more than contexts, history, philosophy or NOS aspects
 - sees learning physics content as the main goal of physics education
 - develops self-efficacy through mastery experiences in problem solving and on tests
 - is motivated by interest in the subject in itself
 - is fascinated by quantum physics, astrophysics and cosmology etc.
 - has a well-developed individual interest in physics
 - develops this interest by listening to the teacher and solving problems
 - prefers physics problems to have right-or-wrong answers
 - is motivated by a wish to perform well on tests
 - maintains drive and motivation when faced with challenging subject matter
 - is recognized by peers as having a physics identity
-

Table 2: Characterization of the implied student of the ReleQuant approach

The implied student of the ReleQuant approach

- likes collaborative, student-centered pedagogy
 - learns well from collaborative, student-centered pedagogy
 - likes to discuss physics with peers and the teacher
 - develops conceptual understanding by discussing physics and doing written tasks
 - develops conceptual understanding by seeing phenomena visualized in animations, films or simulations
 - likes to learn about the history, philosophy or NOS aspects of physics as well as content knowledge
 - sees history, philosophy or NOS aspects of physics as learning goals in their own right
 - views unresolved questions in physics as relevant to physics education
 - develops self-efficacy through arguing well in physics discussions
 - develops self-efficacy through being able to articulate a qualitative understanding of challenging physics concepts
 - is motivated by historical and philosophical aspects
 - is fascinated by quantum physics, astrophysics and cosmology etc.
 - develops interest through qualitative understanding of physics
 - develops interest through working collaboratively
 - is motivated by a wish to understand physics concepts qualitatively
 - maintains drive and motivation when faced with difficulty
 - is willing to spend time on topics and tasks that might be less relevant in exams
-

Figure caption

Figure 1: Themes and sub-themes resulting from thematic analysis of focus groups with students who had worked with the ReleQuant learning material. The lines between themes indicate that themes tended to co-occur in focus group statements.

Footnotes

¹ The official translation says «cognitive consequences», but the original Norwegian text is better translated as «epistemological consequences».

² <http://www.mn.uio.no/fysikk/english/research/projects/relequant/>

³ <http://filarkiv.viten.no/quantum-physics/> (English version). (Previous versions used when data for this paper were collected, differed in some aspects, but not in ways important to this paper.)

⁴ In trial classrooms, students recorded these discussions on their mobile phones and sent the recording to their teachers. The recordings were also shared with the research team.

Figure 1