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How student-centred teaching in quantum chemistry affects students' experiences of learning and motivation—a self-determination theory perspective

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This paper represents the second contribution from an action research study on a bachelor-level quantum chemistry and spectroscopy course. In the proposed instructional model, active learning principles are extended outside lectures to form a student-centred course structure. The new model resulted in superior learning outcomes compared to a class where active learning elements were limited to course lectures, as demonstrated by previous research. In this article, I try to understand this improvement through an analysis of student motivation and experiences in the framework of self-determination theory. Based on my analysis of student feedback data and interviews, tasks that facilitated direct interaction with peers or course staff were seen as key factors in enhancing learning and motivation. In addition, the presence of various interconnected course components that supported students at different stages of the learning process was experienced as central to learning. Together, these two publications demonstrate that the incorporation of active learning principles outside lectures can substantially improve both learning and motivation.

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1 Introduction

In recent decades, active learning approaches have begun replacing traditional instructional methods as the literature attesting to their effectiveness has expanded (Prince, 2004; Ruiz-Primo *et al.*, 2011; Freeman *et al.*, 2014). Prince (2004) defined active learning to include any approach that requires students to reflect and participate in meaningful activities that engage them in the learning process. He delineated four subcategories of active learning: activating practices adopted inside the classroom, collaborative learning, cooperative learning, and problem-based learning. All of four of these categories have found support within the pedagogical literature. For example, a recent meta-analysis by Freeman *et al.* (2014) found an average improvement of 0.47 standard deviations on examinations and concept inventories when comparing traditional instruction to courses where the lectures incorporated active learning, such as group problem-solving. Similarly, several meta-analyses (Johnson *et al.*, 1998; Springer *et al.*, 1999; Lou *et al.*, 2001) have demonstrated the positive impact of collaborative learning on retention, academic achievement, and motivation. Here, collaborative learning refers to instructional methods where students work together in small groups towards some common goal, and thus, for example, includes the more structured cooperative learning framework (Prince, 2004).

Related to active learning, student-centred teaching revolves around moving the spotlight away from the teacher and onto the learner and his actions (Slunt and Giancarlo, 2004; Wright, 2011). According to Weimer (2002), teacher-centredness manifests itself in the balance of power, the role of the teacher, the function of course content, the purpose and processes of evaluation, and the responsibility of learning within the classroom. For example, teacher-centred courses often focus on covering the allotted course material with little regard to how the students learn. This results in an overabundance of content that guides students towards surface-level learning. In contrast, student-centred learning is characterised by flexibility in content delivery where individual students' learning needs are accommodated (Cornelius and Gordon, 2008). By taking a new perspective on the student–teacher interaction, student-centred approaches can promote a deep approach to learning (Baeten *et al.*, 2010).

Student-centred teaching and active learning principles are particularly important in the instruction of topics such as quantum mechanics where the need for a paradigm shift, together with large variations in student motivation, preparedness, and goals make learning challenging (Marshman and Singh, 2015). Furthermore, even if the students possess the prerequisite

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mathematics skills, their transference into applied contexts is often difficult (Sadaghianin, 2005; Thompson *et al.*, 2006; Hadfield and Wieman, 2010; Becker and Towns, 2012) but essential because many quantum mechanical concepts can only be accurately grasped through the application of mathematics (Tsaparlis, 2001). As a result, undergraduate students display a myriad of alternative conceptions (Tsaparlis, 2007; Tsaparlis and Papaphotis, 2009) which originate, for example, from the overgeneralisation of concepts from appropriate contexts to inappropriate ones (Singh, 2008).

To overcome challenges in learning and motivation, I have studied the impact of incorporating active learning and student-centred instructional strategies in a two-year action research (Eilks and Ralle, 2002; Tripp, 2005; Gibbs *et al.*, 2017) initiative utilising a mixed method approach (Johnson *et al.*, 2007). In the first study from this initiative, substantial learning gains were observed following the extension of active learning principles from the lectures to the remaining course tasks (Partanen, 2018). In this second study, the goal is to understand these findings by delving into students' experiences of motivation and learning—particularly in relation to the different course components adopted in the final course structure. These include the pre-lecture exercises, lectures, extempore exercises, problems, and self- and peer-assessment. Self-determination theory (SDT) is used to provide a framework for the motivational part of the current analysis.

The rest of the article is organised as follows: In the following two subsections, SDT and the research questions are outlined. Section 2 details the study samples, course background, and research methods. A summary of the employed teaching strategies is provided in Section 3 while Section 4 includes a discussion of the results. Finally, conclusions and implications for future teaching are considered in Section 5.

1.1 Self-determination theory

Motivation provides one of the cornerstones of high-quality learning. In self-determination theory motivation is divided into two fundamentally different types: intrinsic and extrinsic motivation (Ryan and Deci, 2000, 2002). Extrinsic motivation is oriented towards and dependent on the outcomes of our action, which are separate from the action itself. In contrast, intrinsic motivation is based on the satisfaction derived directly from acting and not on any contingent rewards or punishments. Within these two types, the amount of motivation is determined by how well our basic psychological needs of relatedness, competence and autonomy are fulfilled. These psychological needs are further seen as quite distinct from personal motives, desires or strivings. For example, the pursuit of some motives can become detrimental to one's well-being if it undermines basic need fulfilment.

A number of sub-theories within SDT help to explain variations within intrinsic and extrinsic motivation. Cognitive evaluation theory (CET) describes how the needs for competence and autonomy play central roles in intrinsic motivation. In CET, changes in the perceived locus of causality are connected to changes in feelings of autonomy. For example, when tangible rewards are provided, feelings of intrinsic motivation often decline due to a shift towards a more externally perceived locus of causality (Deci *et al.*, 1999; Ryan and Deci, 2002). On the other hand, events like receiving positive feedback can result in an increase in perceived competence, which tends to positively impact intrinsic motivation (Deci *et al.*, 1999; Ryan and Deci, 2002). To complicate things, according to CET the interpretation of different events is heavily influenced by the interpersonal climate in which they occur.

For extrinsic motivation, the organismic integration theory (OIT) outlines how to prompt behaviours and promote self-regulation and task-persistency when intrinsic motivation is lacking. It subdivides extrinsic motivation into five categories based on the degree to which one has internalised regulation or the values underneath it (Ryan and Deci, 2000). In amotivation, no intention to act is present and people either do not act at all or simply go through the motions without intending to accomplish their goal. In external regulation, the task is performed solely to satisfy an external demand or a socially constructed contingency. Introjected regulation involves a superficial internalisation of external regulation, but the behaviour is still quite controlling and is based on a contingent sense of self-esteem (Deci and Ryan, 1995). A more internal perceived of locus of causality is present in identified regulation, where the value of the task is personally endorsed. However, it may still not reflect the person's overarching values. In contrast, while behaviour continues to be motivated by its outcomes, in integrated regulation these outcomes are fully congruent with one's values and the rest of the self. In contrast to intrinsic motivation, all three of the basic psychological needs are integral for achieving integrated regulation: People need to feel competent enough to perform the required action, which must also be valued by significant others. Whether the internalisation promoted by relatedness and competence results in identified or integrated regulation is determined then by the amount of autonomy support (Ryan and Deci, 2002).

1.2 Research questions

This study aims to understand why student learning improved under the course structure described in Section 3, based on an analysis of student motivation and experiences. Students' views on the impact of different course components to their learning is investigated to provide suggestions on how to further improve the proposed course structure and to identify factors that might have contributed to its success. This led to the formulation of the following research questions:

1. Did student motivation change during the course? If so, what were the reasons behind this change and how did different course components impact motivation?

2. How did students experience the impact of different course components on learning?

2 Methods

2.1 Course background

At the University of Helsinki, the Structure of Molecules and Spectroscopy (SMS) is an obligatory study unit for second- or third-year chemistry majors in the Chemistry Eurobachelor-program. It is a 5 ECTS credit unit, where one credit corresponds to 27 hours of work. While most of the course material is novel, the students should possess a rudimentary understanding of some quantum mechanical concepts, like the wave function, from previous courses. The required mathematical tools are introduced in a first-year Mathematics for Chemists course. During the two-year study period, SMS was staffed by the author as the principal teacher and two or three teacher's assistants (TAs), who were graduate students at the Department of Chemistry.

2.2 Qualitative instruments

Both interviews and questionnaires were utilised in the data collection. The interviews were conducted on a self-selected sample of student volunteers at the end of the course. The interview questions were modified from an earlier study (Partanen, 2016), with further questions added in 2017 regarding the new exercise structure. The original questions were developed as follows: the initial interview form was reviewed by two experts in university pedagogy, revised, tested on four students from a previous years' courses, revised again and reviewed by the same experts before being employed in the interviews. The added questions were reviewed by two experts in university pedagogy. To complement the interview data with more representative sampling of student experiences and attitudes, an extensive feedback questionnaire was administered for the whole class at the end of the course. The questionnaire was modified from an earlier one on thermodynamics (Partanen, 2016). It included both open questions and Likert-like multiple choice questions, and was reviewed by an expert in university pedagogy.

2.3 Study sample and analysis

Most of the enrolled students were either chemistry or chemistry education majors. The number of students was 77 in 2016 and 71 in 2017. Of these, 56 and 60 were included in the qualitative analysis, respectively. To be included, students had to have accumulated exercise points throughout the course. Alternatively, they had to both possess some exercise points and have either participated in the end-of-course exam or taken a conceptual test at the beginning and the end of the course. For further details about the test and the inclusion criteria, see Partanen (2018). The online questionnaire received 53 responses in 2016, and 59 in 2017, corresponding to a 95% response rate in 2016, and a 98% one in 2017 with respect to the number of students who qualified for the analysis. For the interviews, six volunteers participated in 2016 and nine in 2017. The interviews were first recorded and then transcribed. Student responses were categorised into different themes through a process of inductive content analysis (Elo and Kyngäs, 2008).

2.4 Ethical perspectives

This study is an example of action research (Eilks and Ralle, 2002; Tripp, 2005; Gibbs *et al.*, 2017) where pedagogical research is conducted by the course staff. While this type of research is common in chemistry education, the dual role of the course staff poses an inherent threat to the validity of the results. To allay this problem, I provided mostly grading guidelines for the various course task with minimal personal involvement in the grading process. In general, this study followed the methodology of my previous research (Partanen, 2016), where the ethical aspects were reviewed by two experts in university pedagogy. Furthermore, the whole action research initiative was conducted in close collaboration with the university pedagogical assistance staff at the University of Helsinki, which provided institutional oversight.

During the first lecture, students were told that results such as grade averages and student feedback would be used in pedagogical research. The feedback form also stated that its results would be employed in pedagogical research. Responding to the feedback form was optional, but a small amount of course credit was offered for those who did. Students volunteered for the interviews through the feedback form, where they were given the following information translated here from Finnish into English:

One of our goals is to do pedagogical research based on the developmental work in this course. For this research, we need student volunteers who are ready to share their opinions about the course in an interview lasting about one hour. This interview will be organised a few weeks after the end of the course, so the discussions will have no effect on course grading. The interviews will be conducted by people not associated with the course. The volunteers will be contacted via email. Your responses are vital for the continued development of the course!

Great care was taken to preserve anonymity in the feedback forms. While the form contained the student ID, this was only used for marking the exercise points that the students received for completing it. Students could also give feedback completely anonymously through a standard online form available in all of the university's courses or through the discussion forums described in Section 3.

3 Overview of course practices

The cyclical course structure and the adopted assessment practices are summarised in Fig. 1. For a more thorough discussion of the different course tasks and the underlying pedagogical reasoning see (Partanen, 2018). The course consisted of weekly problem bundles and 35 hours of lectures with each lecture lasting either 90 or 135 minutes. In 2016, a total of six such weekly bundles were included, whereas in 2017 this was dropped to five. Course information and lecture materials were dispensed through a Moodle-based online learning environment† with forums available for students to ask questions or discuss weekly exercises. The platform was used to manage the logistics of the different course tasks. It also contained a course diary detailing what topics would be covered in the upcoming lectures and the corresponding pages in the course-book (Atkins and de Paula, 2014). Full lecture recordings were uploaded to the platform approximately one day after the

† Moodle, https://moodle.helsinki.fi/, accessed 7.2.2018.

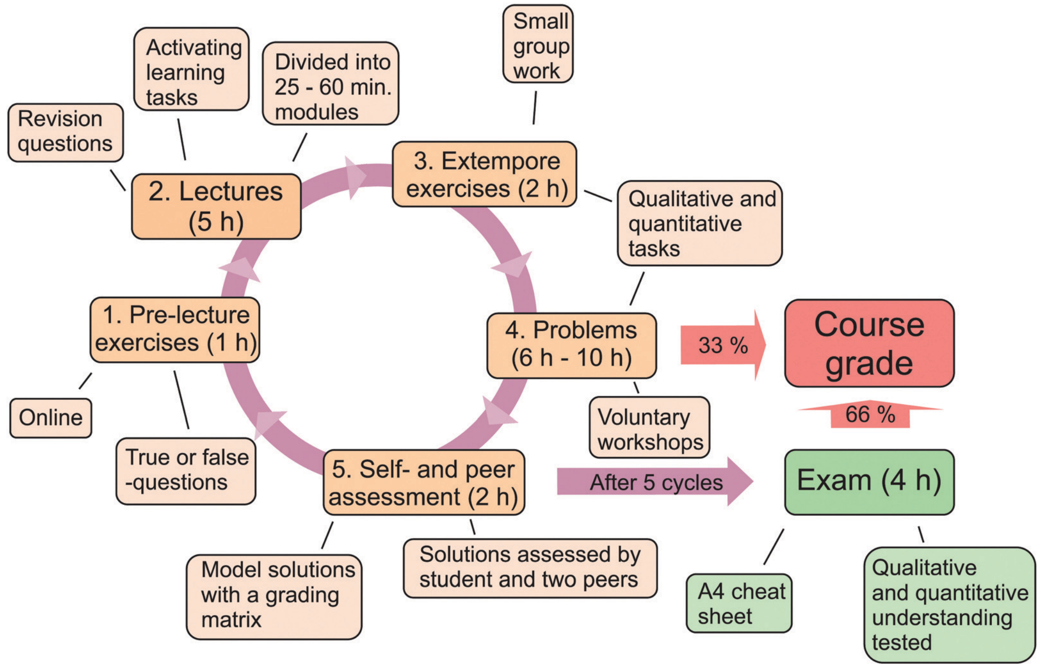

Fig. 1 A summary of the cyclical course structure and assessment practices. Both at the beginning and end of the course, there was one week when only lectures were organised. The intended number of hours per week that students spend in each activity is given in parenthesis.

relevant lecture. The University of Helsinki's Presemo-system‡ was used for anonymous communication between student and teacher, and during voting activities in the lectures.

A third of the grade was determined by the percentage of points obtained from course activities, including the pre-lecture exercises, extempore exercises, problems, and participation in self- and peer-assessment. The remaining 2/3 was determined by the exam. The full set of 1/3 of course points from the exercises was awarded for obtaining 90% of the maximum, but students could get extra credit for exceeding this amount. Because the style of exam questions influences and directs student learning (Carson and Watson, 2002), approximately half of the exam questions probed students' conceptual understanding. To undermine rote-learning, the students were allowed to bring an A4-size self-written cheat sheet to the exam.

Pre-lecture exercises

The first element of the cyclical course structure was the pre-lecture exercises. These consisted of four true or false-questions that were published biweekly. The questions were intentionally simple and focused on the core concepts of the upcoming material. They were made available a few days before the relevant lecture on the Moodle platform, which provided immediate feedback on students' responses.

Lectures

The lecture material was divided into a series of 25 to 60 minute modules with about 10 minute break between each two. Every module delved into one central course theme and contained a number of activating learning tasks such as quantitative exercises, discussion questions, multiple choice voting, and drawing assignments. The two principal goals in introducing the module structure were to break up the lecturing into manageable pieces and to engage the students in collaborative learning (Prince, 2004). The tasks were often drawn from studies on undergraduate alternative conceptions but were annually adjusted based on previous lectures.

At the beginning of each lecture, the students discussed answers to a set of three to five review questions from each of the previous lecture's modules. These questions were carefully aligned with the module's learning goals and, in addition to the activating tasks, constituted another channel of direct feedback on student learning. They were given out at the start of a new module and stayed visible throughout the module.

Extempore exercises

The third part of the cyclical structure was a two-hour extempore session where groups of 2–4 students were given a set of exercises to work on with aid from a TA. About fifteen students were present in each session. The solutions were discussed at the end of the class based on answers offered by the groups. The exercises contained both qualitative and quantitative elements. For example, the pictorial presentations of wave functions and the information that could be gleaned from such images were recurring topics. Sample exercises are provided in the Appendix of the companion article (Partanen, 2018).

Weekly problems

The first three parts of the weekly cycle, *i.e.*, the pre-lecture exercises, the course lectures, and the extempore exercises

‡ Presemo, http://presemo.helsinki.fi/, accessed 7.1.2018.

prepared the students for the weekly problems. Three problems and one bonus task were given out every week. The problems were mathematically and conceptually more demanding than the extempore and the pre-lecture exercises. Some had the students write small essays while others had them interact with simulations, sketch various functions, derive equations, and look for information online. While the focus was on the quantitative side of quantum mechanics, most problems included qualitative parts that required students to comment on their results in some meaningful way. In an attempt to make the problem-solving process more tangible, complicated calculations were broken down into sub-tasks which the students performed in different parts of the problem. Sample problems are provided in the Appendix of the companion article (Partanen, 2018). Three two-hour drop-in problem-solving workshops were organised every week. Each workshop had either the principal instructor or a TA present to provide in-task guidance and to facilitate positive interdependence through group work.

Self- and peer-assessment

The final part of the course consisted of self- and peer-assessment of problem solutions. The gradings were based on an instructional matrix and model solutions. In addition, the students were obligated to give written feedback on the other students' solutions, for example, by justifying why they had subtracted points in a given exercise. Clear instructions on how to perform the self- and peer-assessment were available on the course platform. Each student was tasked with assessing their own paper and those of two randomly assigned peers. To enhance the validity of the assessment, the final grade was calculated as an average of the three numbers. In cases where the minimum and maximum grades differed substantially, the course instructor provided a definitive verdict. Following the recommendations by Ballantyne *et al.* (2002), the students remained anonymous to each other throughout the assessment process and received credit based on both the number and the quality of their assessments.

The course arrangement in 2016

While the lectures were similar between 2016 and 2017, in 2016, the course exercises included only pre-lecture assignments and a set of harder problems. There were no extempore exercises or self- and peer-assessment of problem solutions in 2016. Instead, students' solutions were marked by a TA who provided more extensive feedback on one pre-agreed exercise per week. As in 2017, an open workshop was organised at least six hours per week to facilitate student solution of the problems.

4 Results and discussion

All the interview excerpts given in this section have been translated from spoken Finnish into English. In labelling the quotes, the letter A indicates that the quote is from a 2016 interview, whereas the letter B is reserved for 2017. To protect the anonymity of the respondents, all interviewees will be referred to as female. In a few quotes, clarifying words have been added in parentheses when the reference is not obvious from the quotation itself.

4.1 Changes in student motivation

The majority of interviewed students entered the course with a low sense of competence. This was reflected in their motivation, with many displaying externally regulated extrinsic motivation as exemplified in this quote from student B5:

So my motivation started from thinking I will go to this course, I will not understand anything, but I will try to do some things to get a passing grade.

These issues with motivation are not confined to SMS, as studies have found that a substantial minority of students typically enter physical chemistry courses with negative preconceptions and low expectations of success (Nicoll and Francisco, 2001; Partanen, 2016). The experienced lack of competence also made many students set their initial goals low. However, as the course progressed most interviewed students, including B5, either changed their goal from a passing grade to a better one or reoriented their goals towards understanding. Indeed, at the end of the course the majority of interviewed students reported a desire to understand at least the fundamental topics, indicating a shift towards more internalised forms of regulation. For example, one interviewee whose goals became more aligned with understanding also described how the personal significance of course topics had become apparent when she could see the connections to spectroscopy or chemical bonding.

In contrast to the group of students whose motivation and goals soared during the course, for others, no substantial changes were observed. Many of these students focused on understanding and demonstrated typical features of intrinsic motivation in the interviews. For example, student A6, an aspiring math teacher who chose the course to supplement her secondary studies in chemistry, described her goals in the following manner:

I entered this course because it seemed interesting... I had read physics in the secondary primary school and this course included physics, mathematics and chemistry... so my goal was to learn something new. And because the Schrödinger equation had only been mentioned in the secondary primary school, I got to learn more about it and that was my goal.

This quote also illustrates the central role of autonomy in facilitating intrinsic motivation (Ryan and Deci, 2002) and, conversely, the potentially detrimental effects that the obligatoriness of a course can have on motivation, as hinted on in the previous quote from student B5. By shifting the perceived locus of causality away from the student, the act of imposing external goals can decrease intrinsic motivation (Mossholder, 1980). Perhaps due to sampling bias, no interviewed students seemed to possess extrinsic motivation with external regulation throughout course.

What explains the increase in motivation and more internalised forms of regulation? According to the interviews, the role of other students was central to motivation and the creation of a positive course atmosphere in both years. On the affective side, peers provided social support and helped with emotional regulation, particularly through a shared acknowledgement of the challenging nature of quantum mechanics. Several interviewees described how this resulted in a collectivistic commitment to understanding the material and a sense of community where learning quantum mechanics was a valued activity. The other students thus helped in satisfying the basic psychological need of relatedness, which is crucial for promoting internalisation of regulation and especially extrinsic motivation (Ryan and Deci, 2000).

Peers also impacted internalisation and motivation by promoting feelings of competence: experiences of group learning, feedback from peers during assessment and discussions, and the recognition that everyone was struggling with the course topics, all contributed to the feelings of learning and understanding that enhanced competence. Thus, tasks that promoted peer interaction such as the extempore exercises and workshops were seen as crucial components in elevating motivation. These findings align with the ones from Liu *et al.* on the positive effect of flipped classroom and peer-led team learning on motivation in organic chemistry courses (Liu *et al.*, 2018).

As expected based on the link between relatedness and extrinsic motivation, peer interaction was experienced as particularly important by students with friends who were highly engaged with the course material. Not only did they have a group to work with during course activities, but this group also provided scaffolding through the coordination of study activities such as problem-solving sessions. In contrast, interviewees who did not possess such friends at the beginning of the course reported an improvement in course atmosphere as they got to know their fellow students. For intrinsically motivated students like A2, relatedness seemingly played a lesser role, in line with predictions from the CET (Ryan and Deci, 2002). For example, when asked to assess factors impacting attainment of her learning goals she said

...then as a negative factor maybe that many of my friends viewed this course as useless. Not that I let that bother me. Still, maybe if I had had a very motivated circle of friends, I mean they did want to get the exercises done, but it could have added something more to it.

For some, peer interactions had a negative effect on motivation. As indicated by previous studies (Partanen, 2016), fear-mongering by senior students was the most typical reason why so many students entered the course with low feelings of competence and expectations of success. Some students were frustrated by the heterogeneity of the student population as other students wanted to go through mathematical manipulations that had been covered in previous courses. This forced them to engage in tasks that were not perceived as beneficial for their learning, potentially undermining their sense of autonomy.

Beside fellow students, the approachable and helpful course staff was reported as one of the main factors facilitating a positive learning environment, helping students to achieve their learning goals, and improving motivation in both years. This is unsurprising in light of the extensive meta-analysis by Lei *et al.* linking teacher support with positive academic emotions (Lei *et al.*, 2017). Two students in 2017 highlighted the enthusiastic attitude of the course staff and genuine concern for learning as crucial components in promoting motivation and a good learning environment and in promoting motivation. Indeed, according to Baeten *et al.* (2010), teacher's involvement and dedication towards changing student conceptions facilitates the adoption of deep learning strategies within student-centred learning environments. Of the teacher's actions, student A6 felt that particularly the devotion to reviewing material helped improve the learning environment:

...because the lecturer was so, like, helpful, and still he always, for example, reviewed the previous topics and to me that also means or if some lecturer doesn't review but just moves on then he just assumes that people know everything even though they have fallen off the track. So this lecturer didn't assume that we knew this thing already but rather repeated the stuff, even really old things which supported my motivation, because I could actually follow and trust the lecturer.

From the SDT point of view, there is thus a lot that the course staff can do to support the fulfillment of student's psychological needs to improve motivation. By fostering competence, positive feedback has been shown to enhance intrinsic motivation, and lead to a greater internalisation of extrinsically motivated activities (Deci *et al.*, 1999; Ryan and Deci, 2002). The same is true for more concrete supports of competence like the assistance provided by course staff. Furthermore, maintaining an atmosphere of trust, genuine caring, and acceptance can enhance feelings of relatedness while autonomy can be supported, for instance, by gently guiding the student with pointers and challenging her with questions instead of giving out ready answers.

Many interviewed students reported that the different course tasks had also affected motivation. The effects of individual course components to motivation are considered in detail in Section 4.2. On one hand, boosts to perceived competence like experiences of understanding and completing challenging course tasks were reported by many as very motivating. On the other hand, tasks that were too challenging tended to undermine competence and motivation: For example, during the mathematics-heavy first weeks of the course, the difficulty of the first two problem sets together with the novelty of the quantum mechanical concepts caused motivation to wane for a number of students. However, as the concepts became more familiar and the students felt more secure in their understanding, their feelings of competence started to increase, resulting in increased motivation.

Related to the challenging nature of the course tasks, lack of time was perhaps the most prominent factor negatively impacting motivation. Some students admitted to having enrolled to too many other courses, which made it hard for them to keep up with the various course tasks and forced them to choose which ones to prioritize. For others, their motivation to participate in either the pre-lecture exercises, extempore exercises or course problems suffered because they repeatedly failed to complete the tasks in time.

4.2 Perceived impact of individual course components on learning and motivation

4.2.1 Pre-lecture exercises (2016–2017). As is evident from question 2.1 in Fig. 2, most students in both 2016 and 2017 felt that the prelecture-exercises supported learning. This positive disposition also manifested in active participation, as the response rate was greater than 80% for all prelecture exercises in both years. This is unsurprising, as previous studies (Johnson *et al.*, 2007; Seery and Donnelly, 2012) have shown a high level of student engagement with pre-lecture activities even when they had minimal impact on course grade.

When asked what made the prelecture exercises useful to learning, students said that they highlighted the most important topics of the coming lectures and encouraged studying the course material beforehand. Indeed, by reducing intrinsic cognitive load, pre-lecture exercises are known to especially improve learning and engagement for students with no previous subject knowledge (Moravec *et al.*, 2010; Stull *et al.*, 2011; Seery and Donnelly, 2012; Kinsella *et al.*, 2017). According to one interviewee, the exercises also helped to reduce stress because after responding one could still ask questions and obtain insight into the material from the lectures. This relates to Dobson's finding that increased familiarity with course material can improve students' readiness to discuss it during lectures (Dobson, 2008).

One of the most frequent objections to the prelecture exercises was that insufficient time was provided for reading the material carefully enough to answer the questions. This is connected to another common objection that the true or false questions were sometimes perceived as being intentionally misleading. By negatively impacting competence, *i.e.*, the perceived ability to achieve a valued outcome like exercise points, this resulted in frustration and a decrease in motivation. However, as shown by questions 2.2 and 2.3 in Fig. 2, these experiences were not shared by most students in either year. Instead, according to SDT, the increased sense of competence and understanding during lectures should increase both extrinsic and intrinsic motivation and could help explain the findings in Section 4.1.

The usefulness of the prelecture exercises was also influenced by the question format: one interviewee felt that true or false questions were too simple, and provided little benefit to learning. Yet others described how they had neglected them due to their small impact on the total grade. Even against the backdrop of the high response rates, this underscores the importance of making course tasks relevant to both learning and grading to facilitate participation for the more extrinsically motivated students. In this light, slightly more challenging and rewarding pre-lecture exercises might improve the exercise system by guiding more students to read through the relevant pages before the lectures and reflect more on the course content.

4.2.2 Course lectures (2016–2017). As shown by the self-report data in Fig. 3, lecture attendance remained relatively high in both years, although a small diminishing effect of an overlapping laboratory course can be seen in the 2016 results. This high participation went hand-in-hand with high perceived value for learning during the interviews. For example, when four of the interviewed students in 2017 were asked to rank the significance of the different course components, the course lectures were always in the top two. Similarly, when students were asked in an open field of the feedback–questionnaire what was the best part of the course, lectures were one of the most common answers in both years.

The reasons students felt that the lectures facilitated learning were manifold, but could be divided into three general categories: course material, lecturer's behaviour, and student activation. First, a number of students in the interviews described how the materials promoted learning. Two students reported that the visuality and the focus on schematics, figures, and charts facilitated the creation of multiple types of mental representations, and made the lectures easier to follow. This is unsurprising, given the limited capacity of the working memory and the reduction in cognitive load resulting from presenting the material in pictorial form (Clark *et al.*, 2006). Furthermore, as shown by questions 4.1 and 4.2 in Fig. 4, students in both years felt that the material supported studying with the coursebook while opening new perspectives to it. Indeed, one interviewee described how the lectures not being just a summary of the coursebook especially supported understanding of those concepts that were hard to understand based on the book.

Second, as in the case for motivation, the lecturer's behaviours were perceived as significant contributors to student learning. Some highlighted the importance of the teacher's enthusiasm towards the taught topic and active interest in student learning. Others felt that constantly tying the new material to the concepts of previous lectures facilitated learning and helped students see the bigger picture. Still others commented that it was the

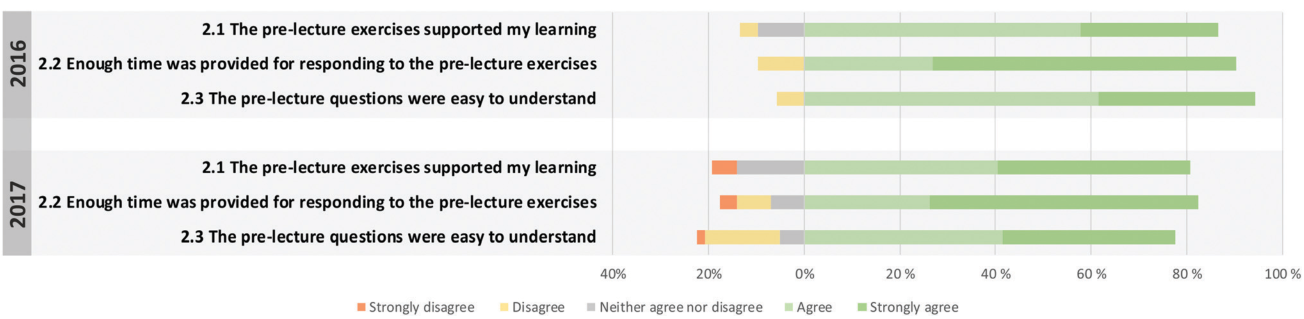

Fig. 2 Student responses to Likert questions regarding the pre-lecture exercises in 2016 and 2017.

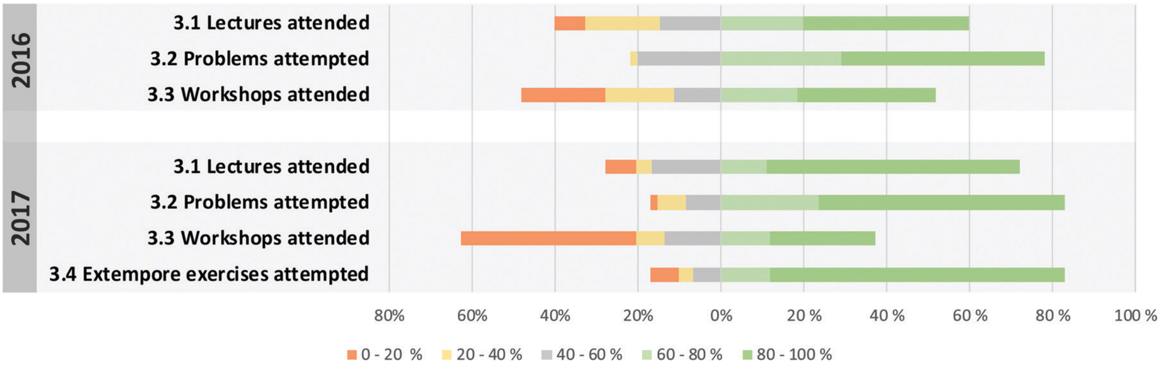

Fig. 3 Self-reported student attendance percentages for some course components.

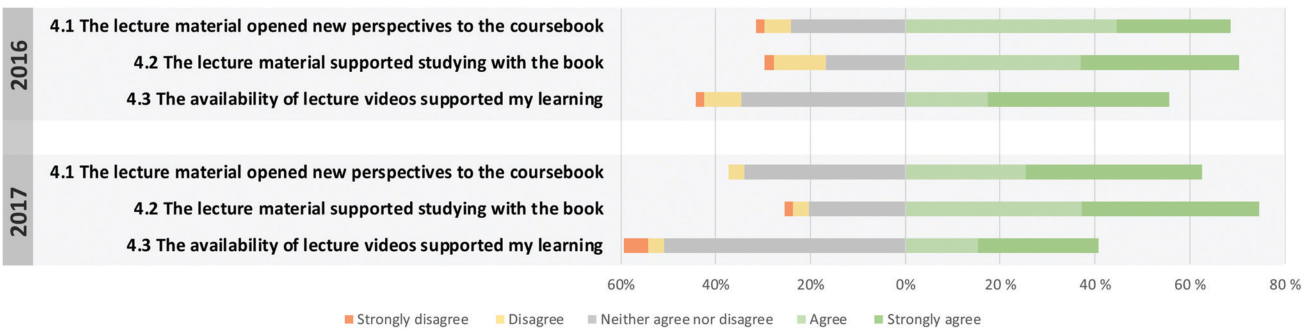

Fig. 4 Student responses to Likert questions regarding the lecture material between 2016 and 2017.

approachability of and ease of access to the lecturer together with the low barrier to asking questions that most benefitted learning. Overall, this demonstrates how even after the adoption of a student centred-learning framework, there remains a lot that the teacher can do to support learning.

The third and most frequent explanation for the utility of the lectures to learning was the use of activating learning tasks. As described in Section 3, these included discussion questions and voting activities, example exercises, and revision questions at the end of each module. All these tasks were highly social in nature, requiring the students to work in small groups. As part of the feedback questionnaire, the students were asked to estimate how the three different components impacted their learning and the results are shown in Fig. 5. While in both years all types are seen as highly beneficial, especially in 2017 the use of discussion questions and voting activities are interestingly experienced as less beneficial than the example exercises and review questions. Several factors might play into this phenomenon. For example, the positive effect of familiar lecture features like example calculations and revision of material is well known to the students beforehand, and was explicitly mentioned by many during the interview. This might cause them to favour these types of activities over novel ones like peer discussion and voting where the benefits are less familiar. In addition, it is possible that the students do not judge these methods based on their impact on learning but rather on some extrinsic criteria. They

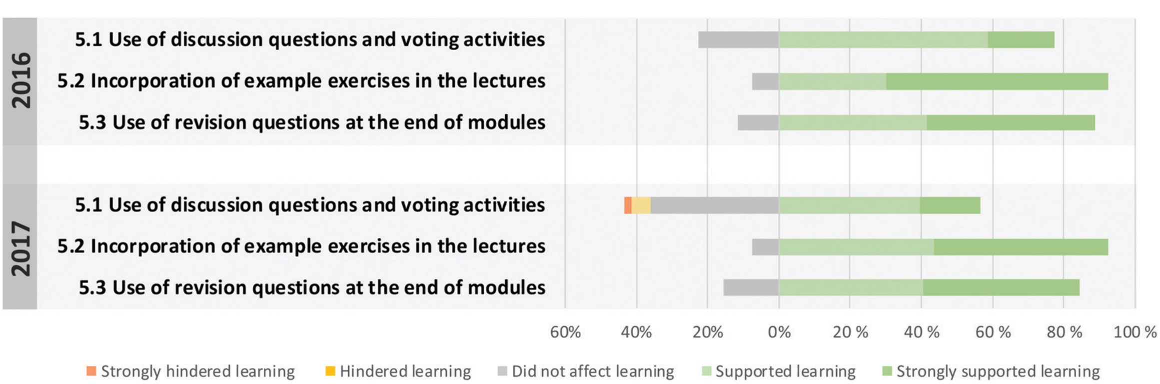

Fig. 5 Student responses to Likert questions on the impact of different lecture practices on learning.

might intrinsically prefer example calculations, for instance, since these are ostensibly more linked to the weekly problems and the course grade. An indication that this kind of expectation might be present was offered by student B4, who described how her peers had expressed discontent that the examples were, in their mind, too removed from the course problems.

What was it about the different active learning components that made them feel as effective as Fig. 5 indicates? According to the interviews, the lecture examples, end of module questions, and discussions helped review the already taught material, provided students with a way to test their learning, and obtain feedback regarding their understanding of the key concepts. It also helped them recognize the most important concepts of each module. These reasons align with findings from the Peer Instruction (Mazur, 1997; Crouch and Mazur, 2001; Meltzer and Mannivannan, 2002; Lasry *et al.*, 2008; Smith *et al.*, 2009, 2011; Turpen and Finkelstein, 2009) and active learning (Prince, 2004; Knight and Wood, 2005; Bunce *et al.*, 2010; Miller *et al.*, 2013) literatures and underscore the importance of moving the student from the role of a bystander to the centre of activity.

One student was frustrated that the benefits from group work depended on the readiness of one's partner to participate in the discussion, while others circumvented this problem by working in larger groups or with close friends during the lectures. As the topics were experienced as challenging and the students' perceived competence in quantum mechanics was rather low, anonymity in the voting tasks was identified as an important factor in facilitating participation, in line with the findings by Freeman *et al.* (2006). According to Ainsworth *et al.* (2011) anonymity can have the added benefit of making it easier for the students to change their minds after discussion, and conform less to group norms.

Lecture videos (2016–2017)

As is evident from question 4.3 in Fig. 4, there was more of a division of opinion regarding the usefulness of the lecture videos with approximately 50–60% of students reporting having utilised them. According to a correlational analysis of the items on the feedback questionnaire, the tendency to watch videos correlated with reporting that the availability of lecture videos supported learning in both years (question 4.3 in Fig. 4) with correlation coefficients of $r = 0.591$ in 2016 and $r = 0.645$ in 2017. In 2017, it was furthermore negatively correlated with both extempore and lecture attendance ($r = -0.351$ and $r = -0.406$ for questions 3.4 and 3.1 in Fig. 3, respectively). Similar connections were encountered in the interviews: four interviewees had watched lecture videos, typically after being unable to attend the lectures for some reason. The students who had watched them generally felt that they had been very beneficial for learning. Thus, even though each of the videos in SMS received only about 10–20 views, they may have helped students who were at risk of dropping out of the course due to logistical issues to hang on. Furthermore, merely enabling students to watch on lectures at their own time and pace should support their sense of autonomy, positively contributing to their motivation.

4.2.3 Extempore exercises 2017. Like the lectures, the extempore exercises were experienced as one of the most important tools for learning. As question 6.1 of Fig. 6 demonstrates, the majority of students felt that the tasks improved learning for the central course topics, and correspondingly in Fig. 3 student attendance was very high. In the correlation analysis of the feedback questionnaire items, student participation in the extempores (question 3.4 in Fig. 3) was generally connected to positive attitudes towards the exercises: students who frequently attempted exercises not only agreed that the tasks deepened understanding of central concepts (item 6.1 in Fig. 6, $r = 0.509$), but also showed how to apply the material in practical contexts (item 6.2 in Fig. 6, $r = 0.339$). In addition, according to a questionnaire item asking students whether they had primarily calculated the extempore exercises in groups or alone, these students preferred group work ($r = 0.327$).

When asked to explain what made the extempore exercises beneficial for learning, a number of interviewed students described how they bridged the gap between the weekly problems and the lectures. For others, the practical nature of the extempore exercises helped link the abstract lecture material to course problems and real-world phenomena. As shown in question 6.2 of Fig. 6, this view that the extempore exercises were practical was shared by the majority. Furthermore, the extempore exercises helped students identify and align their efforts towards central learning goals, guiding their preparation for the exam. For example, Student B4 commented

At times I wondered whether all the exercises were worth the effort because the things were already covered in the lectures through examples and repeated again and again but then again through that you could see which topics were the most important and which ones you really have to learn... so they had their own purpose and definitely helped.

Three out of the nine students interviewed in 2017 highlighted the role of the extempore exercises in forcing them to revise some of the most crucial and difficult parts of the lecture material. Student B1 also felt that the exercises brought together material from distant parts of the course, saying

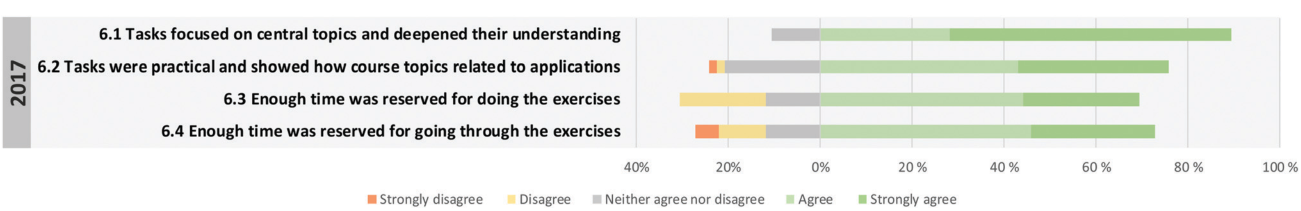

Fig. 6 Student responses to Likert questions regarding the extempore exercises in 2017.

(The extempore exercises) also helped me to revise so that in the last extempore you might have formulae that you encountered during the first lectures so that you had to think how did this thing go again and it was just that you really understood where these things are needed in practice or that what the formulae covered in the lectures really tell us in practice…so the extempores helped me to connect them with something which increased understanding.

Interestingly, student B8 reported that the extempore exercises prepared her for the exam by simulating an environment where you had to learn to interpret a set of questions and work out solutions in a very limited time frame.

Akin to the lectures, the social aspects of the extempore exercises were experienced as particularly important for both learning and motivation. For example, explaining the material to someone else is one of the most effective means of cognitive elaboration (Slavin, 1996) as illustrated by student B7 when describing the role of peers in her interview:

(The other students) have helped my learning…when you thought that you understand something and you start to explain it to a friend then you notice you have either understood it correctly originally but you understand it better after you have explained it or while you're explaining you figure out that oh this is incorrect,…so it really helps you understand.

In addition to validating understanding, the other students also facilitated learning through discussions and social support. Therefore, it is no wonder that the extempore exercises reportedly also enhanced motivation, probably by buttressing students' feelings of both competency and relatedness.

Even though most interviewed students had a positive outlook towards their extempore group, in some cases the interpersonal dynamics proved more challenging. For example, according to student B8's experience, the extempore sessions were very quiet with most people working by themselves. When prompted on, she affirmed that the TA had tried to get them to work in a group with only temporary success. The fear of losing face and revealing her lack of knowledge in front of other students made her withdraw. However, as the course progressed she got to know her peers better and her feelings of competence increased together with her willingness to participate. In this light, it might be beneficial to include activities that build group cohesion and help the students get acquainted during the first extempore exercise. Furthermore, consciously trying to preserve the same extempore groups from one week to the next might also help create a more safe environment for group discussions and enhance feelings of relatedness.

The course staff again played a role in student understanding. Several students in the open sections of the feedback form and in the interviews lauded the encouraging style of the TAs where they tried to nudge students in the right direction by asking questions and prompting them to explain their reasoning, instead of providing ready solutions. As described in Section 4.1, by promoting both student autonomy and competence, this behaviour could be one of the factors underlying the observed shifts in motivation. Indeed, there was a conscious effort to teach the TAs these types of instructional strategies through weekly pedagogical training sessions where different aspects of the extempore exercises were discussed together with the principal instructor.

Finally, some aspects of the extempore exercises were viewed as negatively impacting learning. A couple of interviewees complained that for one of the weekly sessions, the material needed was at times not yet covered in the lectures. This underscores the difficulty of combining the student-centred lecture structure with the extempore session's goals of timely practise and feedback, which are necessary ingredients of high-quality learning (Chickering and Gamson, 1989; Freeman and Lewis, 1998; Tee and Pervaiz, 2014). Other students experienced issues with the internal logistics of the extempore sessions with students running out of time or reporting that the time reserved for going through the exercises was insufficient. However, as demonstrated by the responses to questions 6.3 and 6.4 of Fig. 6, most did not share these views.

4.2.4 Course problems 2016–2017. The course problems were generally experienced as significantly more challenging than the extempore exercises and the course exam. Regardless, in the interviews, and as indicated by questions 7.1 and 7.2 of Fig. 7, students saw them as crucial for learning and preparing for the exam. For many, the problems provided the principal means of learning the quantitative side of quantum mechanics, helping to tie theory to computation. For example, student B6 commented

Yes, they (the problems) felt challenging when you saw them for the first time but when you studied for the exam and reviewed the problems you understood that they asked for the important basic topics in a way and were very concrete, even though in the beginning when you were trying to do them you felt like how am I supposed to understand and then, huh, why does it go like this again but then afterwards you noticed that they were quite simple.

This quote also illustrates the students' struggle with the conceptual overhaul when moving from classical mechanics to the quantum domain which according to Marshman and Singh is one of the key contributors to student difficulties when learning quantum mechanics (Marshman and Singh, 2015). Accordingly, several students reported that the beginning of the course where the fundamentals of quantum mechanics were first introduced felt particularly challenging. After the students had incorporated the new concepts into their knowledge structure, their application in subsequent problems became easier. As mentioned in Section 4.1, by bolstering competence, these experiences of achievement and understanding significantly increased motivation for a number of students, in line with the predictions from SDT. However, some experienced the problems as extremely difficult at first, which undercut their feelings of competence and manifested as a drop in motivation.

One way to help students overcome some of the challenges at the beginning of the course would be to incorporate instruction also in problem-solving strategy. A number of different approaches have been developed to problem-solving over the years (see, for example, Hsu *et al.* (2004) and Gok (2011), and the references therein), but in general this type of education clearly improves students' ability to tackle problems (Çalişkan *et al.*, 2010; Gok, 2015). Naturally, students also need to practice the problem-solving strategy, but this could be achieved by specifically guiding them to provide a portion of the exercise points during the peer- and self-assessment on the basis of whether the students follow the suggested model or not.

The social features of the course problems again played a crucial role in learning. Specifically, the weekly workshops were experienced as essential because they made it possible to receive immediate feedback on problem solutions. Similarly to the extempore exercises, many interviewees highlighted the autonomy and competence building actions of the course staff such as providing pointers to relevant parts of the coursebook, asking questions that helped students solve the problems themselves, and encouraging group work. This is important, as according to Heller *et al.* (1992) student collaboration results in better solutions regardless of ability level, especially in the case of content-rich problems (Heller and Hollabaugh, 1992).

There were also elements in the workshops that did not support learning. While most students in both years agreed that the explanations provided by the workshop staff were understandable according to question 7.4 of Fig. 7, this type of instruction required more time from the TAs. As a result, several students felt that they had to wait to receive aid, as evidenced by their responses to question 7.5 in Fig. 7. Student B5 aptly summarised the situation: the tasks have to be challenging to be beneficial for learning and motivation, but if they are, you also have to provide the students with a way to succeed by providing sufficient support.

Despite the issues with workshop crowding, as shown by question 7.6 in Fig. 7, a little over half the students in both years either agreed or strongly agreed that they had received enough support for the course problems in both years. Based on the correlational analysis of the feedback questionnaire in 2017, students who agreed that they had received sufficient support (item 7.6 in Fig. 7) also actively took part in the extempore exercises (item 3.4 in Fig. 3, $r = 0.424$), indicated that the discussion and voting activities were beneficial to their learning (item 5.1 in Fig. 5, $r = 0.355$), attempted a large percentage of the course problems (item 3.2 in Fig. 3, $r = 0.365$), frequently attended the workshop (item 3.3 in Fig. 3, $r = 0.641$), and felt that the TAs in the workshop were able to explain the course topics in an understandable fashion (item 7.4 in Fig. 7, $r = 0.756$). In short, they actively participated in course tasks, readily sought help, and felt that the help they received was useful. Other significant correlations indicated that the tasks also seemed meaningful and relevant to their learning. This could help explain a previous finding that despite the substantial learning gains observed between 2016 and 2017, a significant minority of students showed virtually no improvement in their conceptual test score between pre- and post-course tests (Partanen, 2018). The current results suggest that there might be a portion of students who remain on the fringes of the course, disengaged and not actively participating in the various group activities.

4.2.5 Self- and peer-assessment 2017. According to question 8.1 in Fig. 8, most students felt that the peer- and self-assessment system supported their learning. This is in broad agreement with the findings of Moneypenny *et al.* (2018) and Wen and Tsai (2006) that most students hold positive attitudes toward peer-assessment and find it to be both effective and helpful to learning.

As for the other course components, what exactly was experienced as beneficial for learning varied from student to student, but some commonalities emerged. For example, six out of the nine interviewed students cited the importance of the self- and peer-assessment in promoting reflection and facilitating revision of the course material. For example, when asked about the role of self- and peer-assessment in her learning, student B1 said

For me it was mostly revision of what I had done in the problems and reminding yourself how the calculations went…and maybe it was also easier to understand how you did it the way you did after a short break and seeing the model solutions, so it was helpful and the peer-assessment as well so that you could get an idea of how other people had done the same exercise was pretty good in my opinion.

Indeed, according to several studies (Topping, 1998; Dochy *et al.*, 1999; Pereira *et al.*, 2016) with a careful choice of the assessed tasks, increased exposure can improve student learning and reflection. However, unless the peer- and self-assessment process is summative in nature, students are unlikely to engage

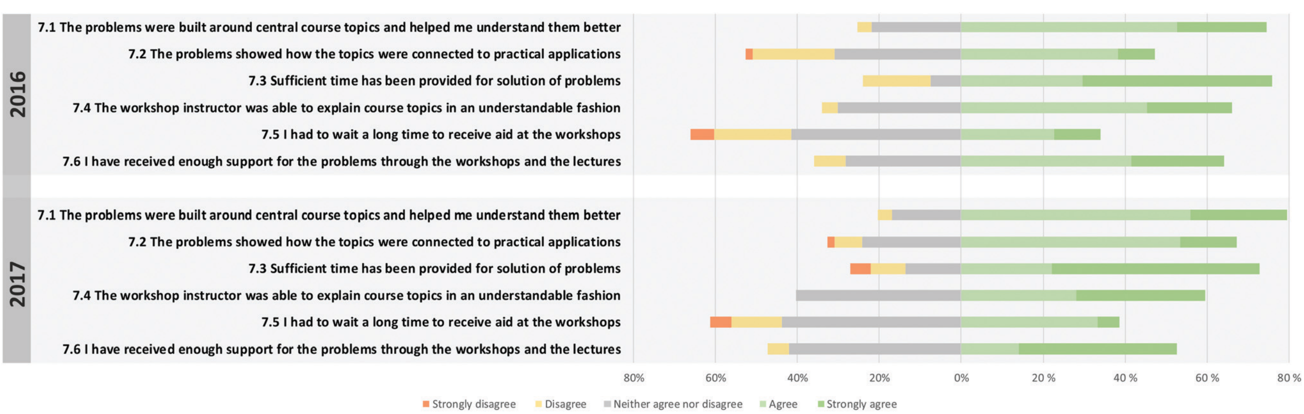

Fig. 7 Student responses to Likert questions regarding the course problems and workshops in 2016 and 2017.

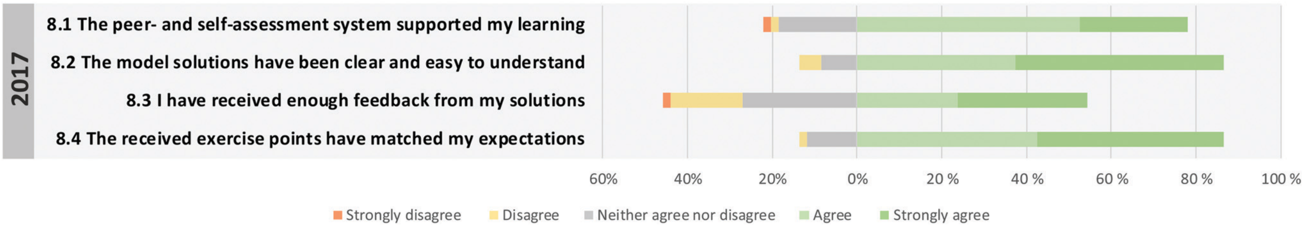

Fig. 8 Student responses to Likert questions regarding the self- and peer-assessment in 2017.

in the same way they otherwise would (Boud, 1990). For instance, student B5 specifically highlighted the motivating effect of the exercise points awarded for completing the peer- and self-assessment. Furthermore, student B5 felt that comparing her solutions with the model ones helped identify areas where more training was needed, making it easier to direct her learning efforts.

Two interviewed students described how seeing alternative solutions to exercises through the peer-assessment system benefitted their learning. In contrast, student B4 felt that the act of grading promoted reflection and learning in itself:

. . .also when you think about whether to give points or not you have to think about the problem itself and that also multiplied the learning so that when you had already twice gone through the problems before (in first doing them yourself and then self-assessing) you didn't really have to return to them when studying for the exam because they were already in your memory.

These student reports conform to the finding of Nicol *et al.* (2014) that both the production and reception of peer feedback enhances student learning. More generally, as indicated by previous studies (Topping, 1998; Dochy *et al.*, 1999; Pereira *et al.*, 2016), active participation in the assessment process can help develop critical thinking, assessment, and reflection skills. By helping students become more realistic judges of performance, self- and peer-assessment may guide them to better monitor their learning (McDowell *et al.*, 2006).

Regarding factors negatively impacting learning, many students felt that the full potential of the peer-assessment component was not reached. While according to question 8.2 in Fig. 8, most students agreed that the model solutions were easy to follow, six out of nine interviewed students together with a number of respondents to the electronic feedback form found the written feedback they received short and non-specific. For example, student B4 berated others for subtracting points with no justification even when the solution followed the provided model. She was also discontent with the general lack of constructive feedback from her fellow students. These negative sentiments are reflected in question 8.3 in Fig. 8 where one sees a relatively large variation in student responses compared to the other questions. Indeed, only five students in the interviewed sample reported providing others with extensive feedback in at least some cases. Of those who did, one student struggled with providing constructive feedback especially when the other student's solutions were either completely correct or incorrect.

In addition to issues pertaining to the production of open feedback, some students also found grading difficult when the other's solution differed substantially from their own or the model. As commented by student B6, a stringent reading of the grading matrix often left students bereft of any exercise points, so a certain degree of flexibility in reading the model solutions and the grading matrix was necessary. One student responding to the electronic feedback form felt that the grading matrix was overly specific and criticised the large differences in the level of detail required in the solutions in some cases. In their study on first-year undergraduate students, Cassidy and Weinberg found that while the majority of students were in favour of introducing peer-assessment for both formal and formative assessment, a number of students expressed concerns about their own and peers' ability to assess (Cassidy, 2006). In light of the positive attitudes of most interviewed students, and the evidence that even inexperienced students can be competent self- and peer evaluators (Cassidy, 2007; Kearney *et al.*, 2016), this is not a problem *per se*. Indeed, some interviewed students described how the ambiguous cases forced them to delve into the model solutions and figure out what was essential in light of the learning goals set by the grading matrix. This they experienced as beneficial for learning.

To deal with the identified challenges of insufficient peer feedback and problems utilising the grading matrix, sample student submissions with instructor grading and feedback could be made available for the first few sets of problems. The scaffolding for providing open feedback could also be improved by explicitly stating what factors the peer assessors should consider when reading through the other student's solutions and by providing concrete examples of constructive feedback.

Several aspects of the self- and peer-assessment system could impact students' feelings of competence, autonomy, and connectedness and hence their intrinsic and extrinsic motivation. Most importantly, inviting students to participate in the assessment process likely contributes to their sense of autonomy. Moreover, student B8 disclosed that seeing other people's solutions increased her sense of competence by providing a more realistic image of course expectations and skills possessed by the other students. As this more lucid view of other students made it easier to collaborate and socialize with others, it could be argued that it also contributed to her feelings of connectedness.

Although most students perceived the assessment system as just and felt that the points they received matched their expectations as indicated by question 8.4 in Fig. 8, two interviewed students consistently undermarked their own solutions.

As this tended to drag down their point average, it created frustration which negatively impacted their motivation. Correspondingly, a number of studies have indicated that higher ability students tend to undermark themselves, whereas lower ability students are more prone to overmarking (Boud and Falchikov, 1989; Dochy *et al.*, 1999). According to Kearney *et al.*, there is seldom a conscious effort to inflate the students' marks, but rather the differences emerge from issues in judgment, and would disappear as the students became more competent assessors (Kearney *et al.*, 2016).

4.3 Summary of the contributions of different course tasks to learning and motivation

Two central themes emerge from Sections 4.2.1–4.2.5 in response to research question 2. First, the social features including student–peer and student–staff interactions played a central role in learning for all the course components where they were present. While some mechanisms for how the social features of a particular course component supported student's perceptions of learning were universal, such as the ability to obtain feedback and validate one's understanding, others were more specific. For example, the social support from the other students was mentioned only in the context of the more challenging course tasks like the extempore exercises and course problems.

Second, according to the interviews, the different components supported learning in distinct ways. Consequently, the previously observed learning gains (Partanen, 2018) might arise more from the positive interplay between the new course components with the old ones rather than the new components in isolation. This is illustrated in the following quote from student B1 when she was asked to describe what factors were central to the attainment of her own learning goals.

Just how the course was, like, structured and everything that it involved. The prelecture tasks helped me understand. Then also understanding at the lectures and then we went through the extempore exercises and the course problems then supported it even more because they were still a bit deeper than the extempore's. So a lot of things had been built around the lectures and you had to do quite a bit yourself so you couldn't help but learn as long as you did things.

While similar sentiments were found in other interviews in 2017, they were notably absent in 2016. In further support for this explanation, as shown in Fig. 2, 4, 5, and 7 and in the discussions of the relevant subsections, student experiences of the impact of the shared components in learning were similar throughout the years. As shown in Sections 4.2.3 and 4.2.5, the extempore exercises and self- and peer-assessment essentially supported the already existing components: The extempore exercises served as a stepping stone between the lectures and the course problems, whereas the self- and peer-assessment forced students to revisit and reflect on their solutions of these problems.

With regard to research question 1, clear improvements were observed in student motivation as explained in Section 4.1. However, there were variations in the impact of different course components on motivation through the satisfaction of the basic psychological needs, as predicted by the SDT. All components seemed to support students' feelings of competence, which was important as many students entered the course with low expectations of success. While the social features were also connected to perceived competence, they further supported motivation by bolstering feelings of relatedness and a sense of community between the course participants and staff.

Finally, while staff–student interactions that focused on supporting the student's learning process, and student participation in the grading process through self- and peer-assessment may have enhanced feelings of autonomy, the adopted course structure may have negatively impacted motivation. For instance, it made student B3 feel overwhelmed with the amount of different deadlines:

It was a little bit that there were so many deadlines and all that and for me that caused a lot of extra stress. Especially when you had to collect some points and you are in a hurry it makes you panic that if you wont get these points you will not pass the exam.

Indeed, deadlines and concrete rewards are known to negatively impact intrinsic motivation (Amabile *et al.*, 1976; Deci *et al.*, 1999), whereas autonomy support is crucial for both intrinsic and the more internalised forms of extrinsic motivation. As others experienced the course structure as beneficial precisely because it scaffolded and helped organise their learning, it might be better to try to support autonomy in a way that maintains these positive features of the current structure. The students could, for example, be offered choices within their weekly tasks like pre-lecture exercises and problems. Alternatively, they could play an even more active role in the assessment process by participating in the creation of the grading matrix.

5 Conclusions and implications for teaching

The quantitative analysis presented in my previous publication (Partanen, 2018) and the complementary analysis of student experiences presented here demonstrate that the incorporation of active learning principles outside course lectures improves both student learning and motivation. These findings reveal the benefits of adopting a multifaceted and integrated approach to both exercises and lecturing in challenging subjects like quantum chemistry and thermodynamics, where quantitative and qualitative understanding are equally important.

One significant barrier to student learning in physical chemistry arises from the initial negative attitudes and low motivation possessed by the students. Using self-determination theory, this study indicates that these can be effectively counteracted by increasing the social features of the course such as group work and peer–peer and peer–staff interactions to support the fulfillment of student's basic psychological needs. The importance of the social components also highlights the importance of pedagogical training for the course staff, and underscores the importance of not selecting staff solely based on the applicants' academic merits but also on the ability to act encouragingly and in a positive fashion towards the students.

In fields like quantum mechanics, it is important to construct the course tasks so that both quantitative and qualitative understanding is supported. As demonstrated by Byun and Lee (2014) and Kim and Pak (2002), just solving a large number of traditional physics problems does not guarantee conceptual understanding. In particular, the qualitative components should be designed so that they are interconnected and gradually force students to challenge their flawed conceptions. The progression of course tasks from easier to more challenging ones is useful for providing external regulation for learning and guiding students to distribute their learning efforts evenly throughout the course. It also forces students to build upon their previous knowledge, in line with the constructivist theory of learning. However, educators should ensure that the amounts of time and support increase in proportion to task difficulty. Especially with a strict set of deadlines, it is important to also provide students with sufficient autonomy so that they can make meaningful choices and employ study strategies that work for them. In the current model, for example, all the lectures were available in video-format, and the students were active participants in the assessment process through self- and peer-assessment.

Finally, because timely feedback is a crucial component of learning and the development of problem-solving skills, personalised feedback should be readily available to students. In the adopted model, feedback was obtained at various stages throughout the weekly cycle, starting from the automated feedback to the pre-lecture exercises and the various voting-activities and revision questions in the lectures. This was followed by the process-oriented feedback of both staff and peers during the extempore and workhop sessions and finally the outcome-oriented feedback from peer- and self-assessment of the problem solutions.

Conflicts of interest

There are no conflicts of interest to declare.

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