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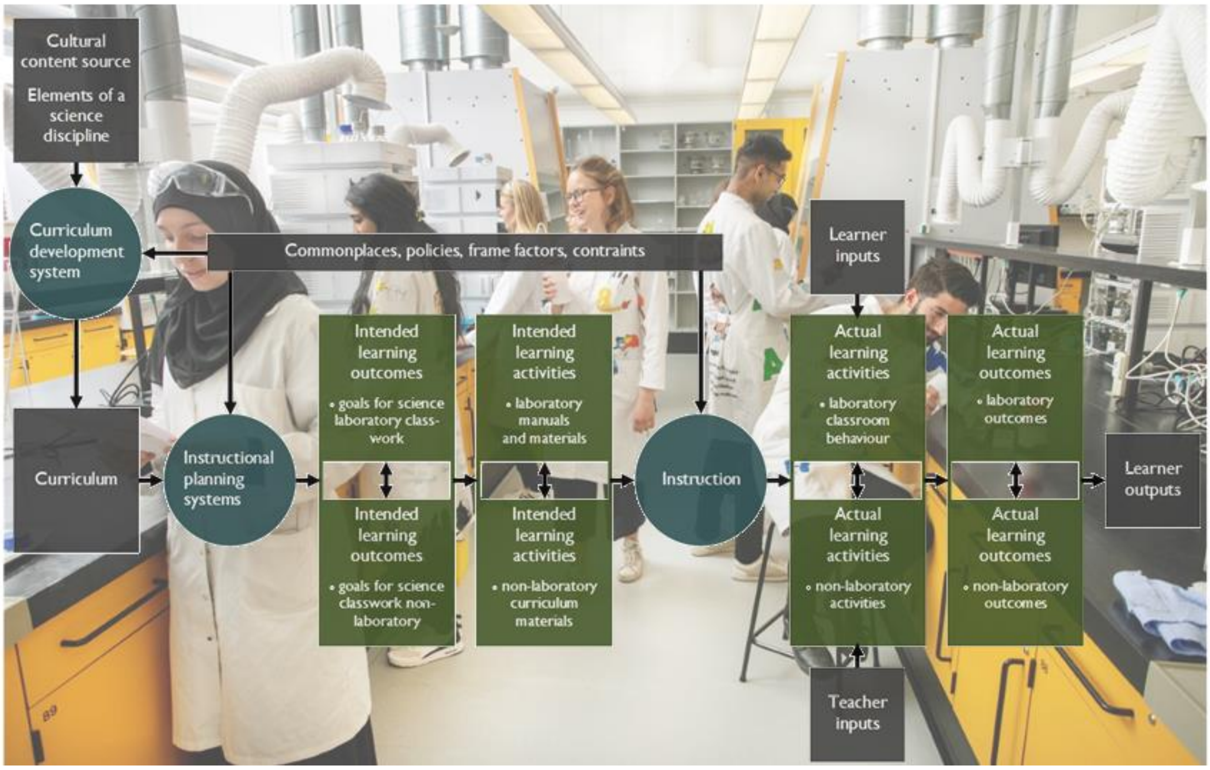

PhD Thesis

Jonas Tarp Jørgensen

Longitudinal Development of Pharmaceutical Students' Laboratory Learning Outcomes

This thesis has been submitted to the PhD School of The Faculty of Science

Longitudinal development of pharmaceutical students’ laboratory learning outcomes

A PhD thesis by

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[T]hey [students] can meet together for the practical study of the various departments of science, where they will be brought together to use their eyes and hands - their eyes otherwise than in merely reading books and looking at pictures or drawings; their eyes to observe accurately, and their hands to experiment, in order to learn more than can be learned by mere observation. To teach students to so work and so learn is the object of a scientific students' laboratory.

W. Thomson aka Lord Kelvin (1885) in Nature

Resume

Praktisk arbejde udgør en vigtig del af undervisningen i naturvidenskabelige fag. Laboratorieundervisning er en omfattende del af kemiske og farmaceutiske universitetsuddannelser. Laboratoriet tillader særegne undervisningsformer og læringsudbytter, men vores viden om den longitudinelle udvikling af studerendes læringsudbytter af laboratorieundervisning er begrænset. Nærværende kvalitative forskningsprojekt brugte undersøgte hvordan disse læringsudbytter kan karakteriseres og hvordan de udvikler sig over tid. Karakteriseringen af studerendes læringsudbytter af laboratorieundervisning blev foretaget gennem et systematisk litteraturstudie, der fandt at læringsudbytterne kan fordeles meningsfuldt i fem grupperinger: Eksperimentelle kompetencer, konceptuel faglig læring, højere-ordens udbytter, generelle kompetencer og affektive påvirkninger. Vigtigheden af at fokusere på læringsudbytter frem for læringsmål diskuteres. Den longitudinelle udvikling blev undersøgt på kort tidsskala gennem skriftlig feedback på laboratorierapporter inden for et enkelt kursus og på lang sigt henover det tredje år af bacheloruddannelsen i farmaci på Københavns Universitet. Data bestod a semistrukturerede interview med undervisere og studerende, studieordningen, kursusbeskrivelser og laboratorierapporter med tilhørende skriftlig feedback. Det primære analytiske værktøj var Tematisk analyse. Resultaterne viser blandt andet at feedback udgør en vigtig del af studerendes læreproces og at vigtige dele af progressionen i laboratoriearbejdet er begrænset til gennemførelsen af bachelorprojektet. Udbytterige feedbackformer og meningsfuld progression kan bidrage til at udvikle studerendes læringsudbytter fra laboratoriet, men der kan være store udfordringer forbundet med at planlægge og gennemføre aktiviteter, der udnytter dette.

Abstract

Practical work is an essential component of teaching and learning in science subjects. The laboratory is a prominent feature of chemical and pharmaceutical tertiary educational programmes. The laboratory affords specific activities and learning outcomes, but we have limited knowledge of how students' laboratory learning outcomes develop over time. To expand this knowledge, this thesis investigated how students' laboratory learning outcomes can be characterised and how they develop over time. An interpretivist approach was used with "the Student Laboratory and the Science Curriculum" and the Congruence framework as essential theoretical assumptions. The characterisation of laboratory learning outcomes was done through a systematic review of the empirical literature and a discussion of these findings against previous reviews. The result was that students' laboratory learning outcomes could be meaningfully grouped into five clusters: Experimental competences, disciplinary learning, higher-order thinking and epistemic learning, transversal competences and the affective domain. The importance of investigating actual empirically found outcomes was highlighted. The longitudinal development was explored on a short timescale, through feedback for laboratory reports and on a long timescale, during the third year of the pharmaceutical bachelor's degree programme at the University of Copenhagen. Data were collected by semi-structured interviews with teachers and students and through analysis of official programme and course documents and students' laboratory reports with teachers' written feedback. Qualitative thematic analysis was used as an analytical tool. Findings include that feedback can be a critical component of student learning and that progression of some of students' laboratory learning outcomes is limited to a few critical experiences of independent problem-solving, most notably, the Bachelor's projects. Helpful feedback formats and deliberate progression can develop students' laboratory learning outcomes over time, but there is difficulty in planning and executing activities that leverage this power.

Preface

The PhD degree is another educational and academic achievement. However, receiving that official paper in the mail is not a an adequate representation of the PhD experience. I inititated this project by leaving Greenland and my job at GUX Aasiaat. Being a teacher in secondary education has been such a valuable experience. Teaching is a fast-paced job with weekly, daily and hourly deadlines. Research has other demands, and it was a big adjustment to change my mindset into work with knowledge production that takes years to complete.

This project has been conducted at various locations. I set out in the beautiful observatory, enjoying the botanical garden and celebrating my wedding. Then, with the rest of the world, I worked from home. Then moving in to the (forever) almost finished Niels Bohr Building. I wish for future inhabitants to be allowed to use the gardens and the stairs. Along the way, many more places have served as temporary office space including course venues, beach hotels, family basements and camping sites. I hope that this thesis will stand as an addition to the important work that is being done on laboratory teaching and learning. If you want to experience more excellent research and dissemination from the IQ-Lab research group, I recommend the IQ-Lab website: *https://lablearning.ku.dk/*

In the end, I have compiled three papers and these accompanying chapters, but I would never have done so without the help of many giving and caring people. The changing need for input and support characterises my PhD journey. I acknowledge this, and want to thank you.

I am grateful to my supervisors, Frederik and Bente, who have continuously worked with me throughout this project, especially with extra support towards the end, and who, together with Jan, gave me the opportunity to commence the project in the first place.

The rest of the IQ-Lab group is a constant force in pushing forward our knowledge of laboratory teaching and learning and you have all been important to me: Maja, for helping me learn qualitative methods. Hendra, for relentlessly pushing the research forward. Rie, for providing insightful clarity just when I needed it. Laura, for constant cooperation and for great company in our visit to the Netherlands, which was unfortunately too brief.

In the Netherlands, I want to thank Hylkje, Freek, colleagues and students at TU Delft and University of Utrecht, for opening your contexts to let us see how you conduct things and to let us try our own teaching ideas.

Thank you, writing groups of varying combinations, sizes and formats, whether live or on Zoom, at home or on a trip, you have been a great way to just keep writing. Thank you, PhD students at the department of Science Education, always continue to join each other in laughing and snacking, you have all been wonderful company, but I must give special praise to my office mates. Line and Henry at the observatory. Rongrong, Mayu and Aswin at NBB.

The Department of Science Education shows how research and teaching can become excellent. Lene, for sharing your teaching of future secondary school teachers. Christine, for bringing me on the path towards better teaching for laboratory technicians. Marie, for that extra insight into research fields that were new to me. A full thank you to the lunch group.

The role of administrative staff cannot be underestimated. Christina and Nadja at DSE as well as Ida, Louise and Laila with IQ-Lab.

This leaves the contribution of friends and family. You have kept my in the real world and yes, I will get back to you soon, I just need to write a bit more. I am fortunate enough that my daughter has four grandparents who willingly spend time with her every week. Lilje, your cry, laughter and face-paint is a constant reminder that working is relatively unimportant, thank you. Finally, the single most important acknowledgement to Christine, all of this is enjoyable because of you, we got this, thank you, I love you.

November 2022

Jonas

The thesis is based on these three papers and they are referred to as Papers 1-3 throughout the thesis.

Paper 1

Agustian, H. Y., Finne, L. T., Jørgensen, J. T., Pedersen, M. I., Christiansen, F. V., Gammelgaard, B., & Nielsen, J. A. (2022). Learning outcomes of university chemistry teaching in laboratories: A systematic review of empirical literature. *Review of Education*, *10*(2), 1–95. https://doi.org/10.1002/rev3.3360

Paper 2

Jørgensen, J. T., Gammelgaard, B., Christiansen, F. V.
Teacher Intentions vs Student Perception of Feedback on Laboratory Reports
Submitted to Journal of Chemical Education

Paper 3

Jørgensen, J. T., Malm, R. H., Gammelgaard, B., Christiansen, F. V.
Progression of laboratory learning outcomes in the third year of pharmaceutical education
Submitted to Scandinavian Journal of Educational Research

In addition, I have co-authored the below paper which is not included in the thesis, though some findings from the study are considered. I will refer to this article as Paper 4.

Paper 4

Agustian, H. Y., Pedersen, M. I., Finne, L. T., Jørgensen, J. T., Nielsen, J. A., & Gammelgaard, B. (2022). Danish University Faculty Perspectives on Student Learning Outcomes in the Teaching Laboratories of a Pharmaceutical Sciences Education. *Journal of Chemical Education*, 99(11), 3633–3643. https://doi.org/10.1021/acs.jchemed.2c00212

Contents

1 Introduction

There is a long tradition of practical work in science education, both in the field and, as is the focus here, the laboratory. Many have presented research on the laboratory with recommendations on how to conduct laboratory teaching (Hofstein, 2017; Lazarowitz & Tamir, 1994; Reid & Shah, 2007). The laboratory is a unique venue that affords itself to teaching situations different from lectures or classroom-based teaching. Most science subjects involve engaging students in practical work with lab-coats, chemicals, and apparatus in laboratory settings. It is fair to say that in the chemical and pharmaceutical sciences, the practical work in the laboratory is the signature pedagogy involved (Shulman, 2005). However, despite extensive and ongoing research on pedagogy and teaching in science, there is still a need for useful evidence for the impact of laboratory courses on student learning in higher education (Bretz, 2019).

In-depth and longitudinal studies into chemistry education can serve two important purposes: To develop an understanding of teaching and learning processes and outcomes concerning chemistry and to develop guidelines for course development informed by research (De Jong & Taber, 2007). This project investigated teaching and learning by combining a teacher and a student perspective. The results can inform development in the local context and global contexts.

In tertiary education, there is limited insight into the students' learning outcomes of laboratory work and how this learning develops over time. This project aimed to provide teachers and researchers with in-depth knowledge about which learning outcomes students acquire from laboratory work and a perspective on how students develop these competences longitudinally.

1.1 The overall project: IQ-Lab

This PhD project was part of a larger project on laboratory teaching and learning called Improving Quality of Laboratory learning at university level or IQ-Lab (see www.lablearning.ku.dk).

The IQ-Lab project comprised several researchers who aim to build knowledge about laboratory teaching and learning in the chemical laboratory in the university setting.

The IQ-lab project is a collaboration between the Department of Science Education and the Department of Pharmacy, and the project steering group had strong connections in the pharmaceutical programme, with one being a professor at the Department of Pharmacy.

Other than myself, the research members of the IQ-lab group were PhD student Laura Teinholt Finne, Assistant Professor Hendra Agustian, Associate Professor Frederik Voetmann Christiansen, Professor Bente Gammelgaard (PI), Professor Jan Alexis Nielsen, and Research Assistant Maja Ingerslev Petersen. Frederik Christiansen and Bente Gammelgaard supervised my PhD study.

In the project's first stage, we reviewed empirical literature to explore what students learn in the chemical laboratory. The project's research question was "How can laboratory-related competences in a university pharmaceutical education context be described and characterised?" Papers 1 and 4 contributed to the answer to this question.

The other stages explored how learning in the laboratory unfolds in the context of a pharmaceutical degree programme, more specifically how "Which factors influence pharmaceutical students' acquisition of laboratory-related competences, and how can such competences be assessed?" and "In which contexts and how are acquired laboratory-related competences activated at later stages in a pharmaceutical program?". These questions influenced my study, and Papers 2 and 3 contributed to answering them.

1.2 Research questions of the thesis

This thesis investigated how laboratory learning outcomes develop over time by analysing and discussing the findings across the attached papers and against existing literature. I used the existing literature to evaluate the current understanding of students' chemical laboratory learning outcomes. Following this, I have tracked students' laboratory learning outcomes in a longitudinal study in the third year of the pharmaceutical bachelor's degree programme at UCPH. I investigated the feedback process in a course and the progression and taxonomical development of laboratory learning outcomes in the programme. Thus, the thesis seeks to answer the following overall question:

- How do students' laboratory learning outcomes develop over time?

In seeking the answer to that question, I have broken it down into these sub-questions:

- How can students' laboratory learning outcomes be characterised?
- What is the role of feedback in developing students' laboratory learning outcomes?
- What is the progression of students' laboratory learning outcomes?

1.3 Structure of thesis

Chapter 2 takes its outset in Paper 1 and discusses how previous influential reviews in chemistry education relate to the findings in Paper 1. This chapter answers the first sub-question of this thesis as it describes how student learning outcomes in the laboratory have been characterised.

Chapter 3 is situated in the specific pharmaceutical context at the University of Copenhagen (UCPH). In IQ-Lab, we have researched the pharmaceutical context from three perspectives: The teachers', the students', and the programme's perspective. The distinctions between these perspectives are unfolded further in Section 3.1.

I have investigated students' longitudinal development of laboratory learning outcomes through a qualitative study that explored learning processes in relation to laboratory work. Thus, Papers 2-3 have the same qualitative data study as their foundation. Section 3.2 lays out the details of this study.

The results of the study are presented in Section 3.3 and Section 3.4. Section 3.3 relates to feedback processes in connection to laboratory reports, Paper 2 and the second sub-question of this thesis. Section 3.4 relates to the progression of students' learning outcomes, Paper 3 and the third sub-question of this thesis.

In chapter 4, I will conclude the thesis by showing the connections between the papers and the answers given to the three sub-questions and the overall research question.

The thesis aims to continue the discussions from the papers, and I recommend reading the attached papers prior to reading the thesis.

2 Characterising students' laboratory learning outcomes: Paper 1

This chapter introduces the main findings from Paper 1 and discusses the paper's results against recent literature and influential publications about laboratory learning from the preceding decades. This discussion seeks to answer how students' laboratory learning outcomes can be characterised.

Paper 1 synthesised its results by analysis of empirical studies of laboratory learning outcomes in higher chemical education. This approach distinguishes it from many other publications presented in this chapter, which have a more conceptual rather than empirical approach.

The main result from Paper 1 was that student learning outcomes from laboratory work could be grouped into five distinct clusters of learning: Experimental competences, disciplinary learning, higher-order thinking and epistemic learning, transversal competences and the affective domain (Table 1). Table 1 lists the overall clusters of learning outcomes from tertiary education chemical laboratory work and specifies some constructs associated with each cluster. Thus, learning in the laboratory is multi-dimensional and should be viewed from a holistic perspective. Therefore, teaching development and curriculum planning must consider the complexity of laboratory learning to realise the outcomes of the planned activities better.

Table 1 Clusters of learning outcomes identified in Paper 1.

Cluster	Constructs
Experimental competences	Practical skills Conducting experiments Data analysis and interpretation Experiment design
Disciplinary learning	Conceptual understanding Theory-practice connection Academic achievement Mastery
Higher-order thinking skills and epistemic learning	Problem-solving Critical thinking Argumentation Metacognition Reasoning and reflection Epistemic learning
Transversal competences	Collaboration Communication (oral and written)
Affective domain	Expectations Interest, enjoyment, and engagement Self-efficacy Laboratory anxiety Motivation Self-regulation Professional identity

In the following, I will turn to some influential papers on laboratory learning and consider their relation to our findings from Paper 1.

Within the field of laboratory learning, an unavoidable reference is the paper Hofstein & Lunetta (1982). This important review on the role of the laboratory in science courses at the introductory level of science education, primarily at the secondary level, concluded that research must provide more quality information about the role of laboratory education. As we have seen, this call is still echoed today (Bretz, 2019). The premise of the review was that the laboratory was a distinctive feature of science education but that some research questioned its effectiveness. The review showed that the goals of laboratory learning outcomes were multiple and complex, and it discussed and presented this list of what they called variables of learning that needed further research (Hofstein & Lunetta, 1982):

- Understanding of concepts: The review showed that previous research had focused on this learning outcome but concluded that learning outcomes were interrelated and that all other variables warranted further research.
- Creative thinking and problem-solving: The review described this as underexplored and pointed to some evidence of positive results when students were engaged in problem-solving activities

- Scientific thinking: The review defined scientific thinking as whether students could understand how scientists work and if they could apply inquiry methods to expand their knowledge, and described it as an “important probable outcome of laboratory instruction”.
- Intellectual development: Prior research based on Piagetian stage theory pointed to the relevance of learning by manipulating concrete materials and objects. However, the empirical basis for this assumption regarding laboratory instruction was questioned.
- Practical skills and abilities: Research into practical skills and abilities suggested that the laboratory provided a venue where motor and intellectual skills could develop simultaneously because the laboratory situation contained both performance and feedback. However, teachers often failed to include practical skills in assessments.
- The affective domain: This was described as including attitudes, interest and curiosity, and the review found that these variables could greatly influence learning but concluded that there was a need for further research.
- Social variables: The review referred to the interpersonal and structural aspects of the learning environment, for instance, relations between students or between teachers and students or the specific type of instruction. Prior research on social variables had indicated the power of the laboratory learning environment, particularly how relationships and positive interactions could strengthen collaboration and learning within other variables.

At the time of the review (1982), it was clear that the laboratory learning situation was complex. Nevertheless, the study pointed to central areas of learning from laboratory instruction and highlighted the need for further research and the scarcity of empirical studies exploring these areas.

When comparing the list from Hofstein & Lunetta (1982) with Table 1, there are obvious similarities but a central difference. The items described by Hofstein & Lunetta (1982) were described as: “[R]esearch areas with potential for contemporary study”. In the ensuing years, researchers started producing much of the research called for in 1982, including empirical studies of laboratory instruction outcomes. Paper 1 is a rigorous analysis and presentation of learning outcomes found to have been acquired by students rather than assumptions about what the outcomes might be. This empirical foundation differs from presenting a list of goals for laboratory learning with intended learning outcomes.

Even if research at the time tended to focus on goals of instruction rather than student outcomes, there was no universal agreement on the objectives of laboratory activities. Thus, a review by Kirschner & Meester (1988) identified 120 objectives of practical work at the tertiary level, many of which were considered either too specific to be widely used or too general to be informative. Nevertheless, based on the multitude of objectives, the study identified eight general objectives:

- To formulate hypotheses.
- To solve problems.
- To use knowledge and skills in unfamiliar situations.
- To design simple experiments to test hypotheses.
- To use laboratory skills in performing (simple) experiments.
- To interpret experimental data.
- To describe the experiment clearly.
- To remember the central idea of an experiment over a significantly long period.

The eight objectives were purposefully formulated with action verbs and agreed with a standardised experimental procedure: Problem formulation, model generation, verification/falsification, results, adjustment of model, new results, interpretation, and evaluation (Kirschner & Meester, 1988). In the terminology of Hofstein & Lunetta (1982), the objectives were within the cognitive domain, creative thinking, problem-solving, scientific thinking and practical skills, but disregarded learning outcomes in intellectual development, affective domain and social variables. Concerning intellectual development, Kirschner & Meester (1988) do not unfold the argument in depth but point to studies showing that many university students are not in a formal reasoning stage. If this is true, it is argued: "At best then, these experiments are a waste of time and money, at worst they are a demotivating experience for the student". Thus, the argument seems to be that intellectual development should not be aimed at by laboratory instruction. As for the affective and cognitive outcomes of learning, the study by Kirschner & Meester (1988) also has some critical comments on whether and how laboratory instruction could relevantly contribute to such development, more specifically it was questioned whether attitudes towards science are acquired as part of: "'[L]earning by doing' or just magically happens”. Thus, the argument seems to be that other types of instruction might more directly and effectively aim at such outcomes.

Paper 1 shows that neither cognitive nor affective learning in laboratory work should be disregarded as important outcomes of laboratory instruction, although these objectives can be pursued by other means. Furthermore, research on intellectual development might require other types of studies. Most of the studies included in Paper 1 were on short timescales, whereas an investigation into intellectual development would require longer studies aiming specifically at this.

The study by Kirschner & Meester (1988) demonstrated a lack of consensus on what students learn in the laboratory, further underscoring a need for quality research, as pointed out in the first review (Hofstein & Lunetta, 1982).

In a later epistemological discussion of the motives for doing practical work in tertiary education, Kirschner (1992) concluded that practicals were not suitable for teaching substantive structures of science but were important if students should learn the syntactical structure of science, roughly, learning how knowledge is established rather than learning the established knowledge. The conclusion was that the goals of practical work are threefold:

- Specific skills. E.g. discrimination, observation, measurement, estimation, manipulation, planning, execution, and interpretation.
- Academic approach. E.g., studying a situation, defining a problem, seeking, evaluating and choosing solutions.
- Experience phenomena. Tacit, implicit, indescribable *Fingerspitzengefühl*.

This outline of the learning outcomes in categories like problem-solving and scientific thinking put much less emphasis on conceptual learning than previous research. That was also a significant critique of earlier frameworks: Having students do the work does not necessarily result in them understanding the applied methods or the related theory. As scientific concepts are abstract, and given that laboratory exercises are necessarily concrete and specific – laboratory work cannot do justice to the general nature of science (Kirschner, 1992). To make things worse, as was also argued in Kirschner & Meester (1988), not all students can make the connections between the specific and the abstract, given their “cognitive level of reasoning”.

Regarding manipulative skills, Kirschner (1992) recognises that laboratory teaching, unlike other teaching formats, can teach such skills but dismisses them as relevant learning outcomes for students in tertiary education (Kirschner, 1992, p. 295, note 3).

The studies Kirschner & Meester (1988) and Kirschner (1992) thus, in some ways, recommended a narrowing down of the goals for laboratory instruction compared to what was outlined in Hofstein & Lunetta (1982), downplaying the conceptual domain, practical skills, intellectual development and the affective domain as relevant goals for laboratory instruction.

Discussing the goals and purposes of laboratory instruction from a conceptual or epistemological perspective provides important insights, and it may shape what to research and what goals to pursue in teaching. However, it is also important to consider what is actually going on in student learning in the laboratory, as we have sought to do in Paper 1. Even if the laboratory is planned with certain learning goals, students may have different outcomes. Such studies may even find that the students obtain types of outcomes that the conceptual analysis has ruled out.

A meta-review from 1994 also reached that conclusion. It analysed 37 reviews published between 1954 and 1990 and stated four goals that laboratory teaching should address in all science education (Lazarowitz & Tamir, 1994): Confronting misconceptions, data manipulation, logical thinking about science-technology-society and building values concerning the nature of science. There was no focus on practical skills, but cognitive skills were at the forefront. The chance to experience phenomena was highlighted as worthwhile, and complex learning outcomes like the nature of science or logical thinking skills were emphasised. The Lazarowitz & Tamir (1994) meta-review carried many nuances but had limited focus on learning outcomes within the social variables and affective domain. This meta-review also presented the conclusions as goals for learning and not as learning outcomes for students.

A significant development in the understanding of laboratory learning outcomes was that laboratory instruction encompasses several different styles of instruction (expository, inquiry, discovery, problem-based), which may lead to very different outcomes. Domin (1999) focused on general chemistry laboratories in secondary and early tertiary education. This publication put forward the critique that research often investigated student achievement but failed to acknowledge the diversity of instructional styles employed under the heading of laboratory instruction and argued that different styles of instruction should be researched regarding general outcomes claimed for laboratory learning. This review explicitly mentions manipulative skills, conceptual learning, and understanding of the nature of science as central desired outcomes. Furthermore, it included affective learning outcomes in the form of attitudes and had higher-order cognition, scientific reasoning and understanding nature of science as separate outcomes (Domin, 1999).

A literature review on tertiary-level laboratory instruction commented that explicit assessment methods and criteria should accompany the aims of laboratory work and concluded that this often was not the case. With this in mind, it presented a list of skills, abilities and affective outcomes for students to obtain (Johnstone & Al-Shuaili, 2001):

- Manipulative skills
- Observational skills
- Ability to interpret experimental data
- Ability to plan experiments
- Interest in the subject
- Enjoyment of the subject
- A feeling of reality of the phenomena

That list begins with explicitly putting manipulative skills as an outcome in tertiary education. It described no less than three different affective outcomes, including: "A feeling the reality of phenomena", which was not found in the reviews mentioned above. Interest and enjoyment were presented as separate affective outcomes, which acknowledged the complexity of this domain. This list gives little attention to conceptual learning. However, it is clear that this type of outcome was not disregarded; the cognitive skills were instead considered to relate to observational and interpretative skills, as these rely on conceptual understanding. As Domin (1999), this review also considers different laboratory instructional styles or types and distinguishes between expository, inquiry, discovery and problem-based. Moreover, Johnstone & Al-Shuaili (2001) considers the relationship between desired outcomes and the assessment methods and point to the necessity of aligning these.

Johnstone & Al-Shuaili (2001) exposed a difficulty in laboratory activities, though it does not discuss it explicitly. The review clarifies that assessment criteria should align with aims and the mode of instruction, but on the other hand, describes interest in and enjoyment of a subject as important aims. These types of affective aims do not lend themselves easily to summative assessment; perhaps they are somewhat irrelevant for assessment. This difficulty highlights that perhaps we should consider the role of the affective domain of learning differently than the other aims of learning.

In 2004, Hofstein & Lunetta published an updated review (Hofstein & Lunetta, 2004), published more than twenty years after the initial review. This new review aimed at exploring the development that had occurred in the interim and still mainly focused on secondary education. It reiterated the laboratory's distinctive role and stated that educators claim rich benefits from it. The review presented an updated list of goals for learning in the laboratory that aimed at enhancing the students':

- Understanding of scientific concepts
- Interest and motivation
- Scientific practical skills and problem-solving abilities
- Scientific habits of mind
- Understanding the nature of science
- Methods of scientific inquiry and reasoning
- Application of scientific knowledge to everyday life

Hofstein & Lunetta (2004) claimed that a changed view of the learner was one of the significant developments that had occurred in the 20 passing years. In the new review period, teachers and researchers had increasingly come to view students as having a subjective experience when building their scientific understanding, described as a shift towards more constructivist understandings. The description of outcomes contained interest, motivation, and connection to everyday life. Employing new teaching formats, such as inquiry learning, was part of this change. Laboratory teaching was identified as an area that promoted learning by encouraging a focus on engaging students with varying motivations and abilities and making them apply evidence to justify assertions, preferably through inquiry techniques (Hofstein & Lunetta, 2004).

Hofstein & Lunetta (2004) explicitly stated that goals for students' learning outcomes should drive curriculum development and, in line with Johnstone & Al-Shuaili (2001), assessment formats should align with the stipulated learning outcomes. Furthermore, it concluded that research and development should include a classroom-based approach anchored in the local context and that teachers should participate in professional development informed by scholarship.

We delimitated Paper 1 to the tertiary level. Given that delimitation, the final comprehensive review article I will discuss in some depth is "the role of the laboratory in university chemistry" (Reid & Shah, 2007). In Reid & Shah (2007), the reasons for doing laboratory work in tertiary chemical education were reviewed and synthesised into aims as four types of skills:

- Skills relating to learning chemistry. Learning ideas and concepts, learning chemical theory.
- Practical skills. Learning techniques and procedures. Handle equipment, measurement and observation.
- Scientific skills. Learning interpretation of experimental results. Devising experiments with empirical insights.
- General skills. Learning ways to solve problems, teamwork, report production.

Even though they were formulated differently, there are overlaps and differences between this list of aims and the list presented by Hofstein & Lunetta (2004). For example, they agree that students learn chemical concepts, practical skills, and scientific inquiry, and there is an acknowledgement of the multitude of possible laboratory learning goals.

A notable difference is that the affective outcomes are absent in the list of aims described in Reid & Shah (2007). An explanation could be that the researchers of the underlying papers view secondary and tertiary education differently in this regard. However, Reid & Shah (2007) seem to recognise at least one type of affective outcome. In their discussion of whether the learning goals could be met without practicals, it is asked: "would the students have any 'feel' for chemistry, for chemicals, for instrumentation, or for the way experimentation is conducted or reported?" Depending on the definition of this 'feel' for chemistry, this hints that the practical work has additional learning outcomes. These outcomes could be affective outcomes such as enjoyment of the subject or identity development. Nevertheless, Reid & Shah (2007) did not attribute this enough importance to warrant am aim in itself.

Researchers published excellent papers in the following years, but publications focused on a single or a few learning domains or a specific teaching mode. Research and reviews did not attempt to encapsulate or understand the variety of learning outcomes but focused on compartmentalised features (Sandi-Urena, 2018), with many publications being about conceptions and conceptual change in 2004-2013 (Teo et al., 2014). Other examples are Galloway & Bretz (2015), that focused on the cognitive and affective domains, comparing students' expectations and experiences, Zacharia et al. (2015), that focused on guidance in virtual and remote laboratories and Agustian & Seery (2017) that focused on the role of pre-lab activities. Finally, studies within multiple learning domains were often small-scale, such as Emenike et al. (2011).

Flaherty (2020) was about affective learning in chemistry education and was a comprehensive review delimited to a single domain. Here I compare some findings from

Flaherty (2020) with Paper 1, as they both attempt to characterise learning outcomes empirically. The scope of Flaherty (2020) differs from Paper 1 as it includes all levels of education and delimits its paper to this millennium. In contrast, Paper 1 focuses only on laboratory instruction in tertiary education and has no age limit on included papers.

Research into affective constructs of laboratory learning could benefit from an increased focused on methodological rigour. In Paper 1, we argued that research into the affective domain would benefit from a more substantial theoretical grounding, as studies often draw conclusions into the affective dimension, albeit in layman's terminology and lacking methodological rigour. Likewise, Flaherty (2020) questions the use of the range of measurement tools used to investigate affect and puts forward the critique that: "[N]o evidence of considerable critical reflection" about the nature of the collected data was present in any of the reviewed articles.

Flaherty (2020) shows that measurement of affect using scales has been a core result from previous research but recommends that assessment of affect has a complexity that affords alternative research approaches. Flaherty (2020) concludes that research into the affective domain might give us better answers to why "an individual student would seek to learn at all". In Paper 1, we concluded that the affective domain was perhaps best understood as a component in the learning process, e.g., as motivational constructs. Both of these conclusions hint at the affective being distinct from other types of learning.

In learning theory, the affective domain has been presented as a learning driver rather than a learning outcome. For example, consider the model of two learning processes, acquisition and interaction, and three dimensions of learning; content, environment and incentive (Illeris, 2018). In that model, the incentive dimension is also referred to as emotion, motivation, volition or mental balance (Illeris, 2003). In that view, the affective domain becomes part of the learning process, which is perhaps more in line with learners' experience than it being presented as intended learning outcomes. This alternative definition of the affective can help explain why the publications presented in this chapter sometimes disregard it, e.g., when enthusiasm, motivation and confidence were present in the reviewed literature but not in the aggregated synthesis (Reid & Shah, 2007, pp. 176–177). Understanding the affective domain as an incentive component of learning rather than a learning outcome thus encapsulates that it influences learning and that there is an importance of indescribable learning.

This is not to say that components in the affective are irrelevant in the assessment of learning. Indeed, both Flaherty (2020) and Paper 1 agree that research finds many affective constructs that can be measured, e.g., self-efficacy, interests, and motivation. These assessments might be well-suited as part of a future course and curriculum development and not as an assessment of students' learning outcomes in relation to course goals.

Another type of learning that is relevant to discuss in terms of assessment is learning practical skills. In the literature, the weight of practical skills in laboratory learning differs. For example, Kirschner (1992) downplayed practical skills as something worth pursuing by students in tertiary education, whereas Paper 1 showed that learning experimental skills is one of the laboratory's core outcomes. Of course, in Paper 1, experimental skills encompass more, as we found conducting experiments, data analysis and designing experiments to be evident and connected learning outcomes. This is more in line with having: "Scientific practical skills and problem-solving abilities" as part of laboratory aims as Hofstein & Lunetta (2004). Whether there is a difference between secondary (and primary) and tertiary education is irrelevant, as I argue that laboratory teaching in tertiary education should acknowledge the practical dimensions of learning. Recent research also argues that chemistry is something you *do*, putting practical skills a part of chemistry identity (Seery, 2020).

The reviews in this chapter presented their results as intended learning outcomes or some stated objectives, aims or goals and not as actual achieved outcomes. This differs from learning outcomes, which students achieve during and after an activity and which was the focus of Paper 1.

In Paper 1, we have described and characterised student learning outcomes from tertiary chemical education based on empirical studies of actual student outcomes. We identified 5 clusters of outcomes, and we have seen clear evidence that students have learned many of the goals claimed to be provided by laboratory instruction. When considering the reviews in this chapter, there is not much difference in whether a list was stated as a goal or as a student outcome. The lists may look similar. However, the difference is whether the teacher's intention or students' outcomes are presented. This is part of the explanation of why Paper 1 concludes that learning in the laboratory can be complex and result in multiple outcomes, while many previous reviews sought to delimit what we aim for students to learn.

Affective and practical outcomes are part of the student experience of practical work and can be very different in this setting compared to other teaching formats. Experimental learning, disciplinary learning and learning of higher-order thinking skills are also at play in laboratory learning. I recommend that this be shown in our tertiary education institutions, as dismissing the interconnection between laboratory learning outcomes in the five clusters ignores complexity. I emphasise that the contribution of all five clusters of laboratory learning should be considered when laboratory teaching is planned and executed. All evidence points towards students' laboratory learning outcomes as complex and multiple. Notably, it has been recommended that the laboratory should have limited and specific goals so students can quickly identify meaningful learning (Nakhleh et al., 2002, p. 88). However, even when teachers state a few *intended* learning outcomes, students will still experience a complex multitude of *realised* learning outcomes. Therefore, I reiterate that learning in the laboratory is complex and that simplifying learning outcomes to less than the complexity represented by the five clusters would be an oversimplification that risks overlooking learning opportunities or boundaries.

Another development discernible in the chronological discussion of reviews is the gradual recognition that clear goals must be accompanied by appropriate instruction and assessment. This development is not unique to the laboratory learning research field. We see it as the central argument of *constructive alignment* (Biggs & Tang, 2011) and the *congruence* framework (Hounsell & Hounsell, 2007).

Hounsell & Hounsell (2007) presented congruence as a broader framework than constructive alignment because it acknowledged the complexity of the teaching-learning situation and sought to explain how multiple factors influence the learning process and learning outcomes of the students. The model has six areas in which congruence will improve students' learning process and outcome: Assessment and feedback, course organisation and management, curriculum, aims scope and structure, teaching-learning activities, learning support and finally, students' background and aspirations. The congruence framework views the learner as central to the learning process and outcomes and shows that complexity in learning demands congruence in teaching. The approach we took in Paper 1 was well aligned with this view, and the congruence model can help explain why we find such complexity in learning. The students' laboratory learning outcomes can happen in all five clusters of Paper 1 and are influenced by all six areas in the congruence framework.

I set out to answer how students' laboratory learning outcomes can be characterised. Prior definitions were full of complexity and showed many intended outcomes, aims or goals. With Paper 1, we found that the five clusters of laboratory learning outcomes, experimental competences, disciplinary learning, higher-order thinking and epistemic learning, transversal competences and affective domain could encompass the complexity of students' laboratory learning outcomes. As research and tertiary education continues to develop, these discussions continue. However, the complexity of learning in the laboratory is evident, and the amount of research on laboratory learning is growing, superseding the research underlying all the excellent reviews in this chapter. Therefore, there was a research gap to fulfil for Paper 1 as a new comprehensive systematic review of learning outcomes in the laboratory.

A relevant point of discussion is whether it even matters what clusters of learning we delimit. As shown above, there was a lot of variation in delimitations in the past decades. Nevertheless, the answer is yes if the delimitations of learning produced in the research setting show up in other settings such as curricula, course descriptions, professional development of teachers, and the prioritisation of teaching in the laboratory. The five clusters of laboratory learning outcomes from Paper 1 is a theory development and can potentially influence the discussions and understanding of laboratory learning if this research-based definition influences teaching-learning contexts with laboratories. The findings from Paper 1 influenced the next part of this research project, which investigated laboratory learning in the pharmaceutical context.

3 Learning in the pharmaceutical laboratory

A *Perspective* piece in Chemistry Education Research and Practice emphasised how educational research into laboratory teaching and learning takes place in settings with substantial differences and called for researchers to provide detailed descriptions of the laboratory's context (Hofstein & Mamlok-Naaman, 2007). In the previous chapter and in Paper 1, laboratory learning outcomes were discussed concerning all chemistry subjects in tertiary education. However, this general perspective ignores the importance of context as it risks overlooking crucial contextual implications.

This thesis continues by investigating students' laboratory learning outcomes in the context of laboratory teaching and learning in the pharmaceutical programme at the University of Copenhagen. The main research question of this thesis is how students' laboratory learning outcomes develop over time. Chapter 2 characterised laboratory learning outcomes but ignored the longitudinal component of the question. To investigate this, I conducted a study that resulted in Papers 2 and 3 and which this chapter further elaborates on.

I investigated the development of laboratory learning outcomes in two ways, as represented by the second and third sub-questions:

- What is the role of feedback in developing students' laboratory learning outcomes?
- What is the progression of students' laboratory learning outcomes?

Answering these questions show what happens in the short term, with particular consideration on feedback, and in the long term, in the programme progression. I will get back to these questions in sections 3.3 and section 3.4. First, section 3.1 presents central background information about the pharmaceutical context, while section 3.2 presents the methodology of the study that is shared between Papers 2 and 3.

3.1 The pharmaceutical context

As part of the European Higher Education Area and the Bologna process, education at Danish universities is generally organised in a 3+2 structure where students are awarded a bachelor's degree after three years of study and a master's degree after an additional two years of study. The Bologna process ensures comparability of higher education in the European Higher Education Area, resulting in staff and student mobility between member states (European Commission/EACEA/Eurydice, 2020). One main objective of the Bologna process was the member states' adaptation of the European Credit Transfer and Accumulation System (ECTS). ECTS formalises the academic workload with one full year of study corresponding to 60 ECTS credits (European Union, 2015). Another implication was the introduction of the European Qualifications Framework (EQF), which ensures systematic comparability between educational programmes. The EQF divided the intended learning outcomes of programmes into knowledge, skills and competences (European Parliament and Council of the European Union, 2008). The Danish Qualifications Framework was implemented in line with the EQF and similarly presents intended learning outcomes as knowledge, skills and competences (Danmarks Evalueringsinstitut, 2011). Since all educational programmes in Denmark are described according to the Danish Qualifications Framework, it provides transparency between educational programmes in Denmark and the European Higher Education Area via comparison to the EQF. Competences are still part of the qualifications framework in Denmark but have been replaced by responsibility and autonomy In the EQF (The Council of the European Union, 2017). The EQF distinguishes between 8 levels of education with bachelor's degrees in Denmark (including the pharmaceutical degree programme at UCPH) corresponding to level 6 (Table 2).

Table 2 Intended learning outcomes relevant to Level 6 (of 8) in the European Qualifications Framework (The Council of the European Union, 2017). A bachelor's degree in Denmark, including the pharmaceutical programme, corresponds to this level.

	Knowledge	Skills	Responsibility and autonomy
EQF Level 6	advanced knowledge of a field of work or study, involving a critical understanding of theories and principles	advanced skills, demonstrating mastery and innovation, required to solve complex and unpredictable problems in a specialised field of work or study	manage complex technical or professional activities or projects, taking responsibility for decision-making in unpredictable work or study contexts take responsibility for managing professional development of individuals and groups

The pharmaceutical bachelor's education at the University of Copenhagen is worth 180 ECTS credits over three years with 21 mandatory courses and a few electives. The courses have a workload of 7,5 ECTS credits, with the final bachelor project awarding 15 ECTS credits and completing the education awards a Bachelor of Science (BSc) in Pharmacy (Faculty of health and medical sciences, 2018). More than 200 students are admitted annually, with 238 admitted in 2018 (Københavns Universitet, 2018). A few of these students became the cohort of the study, which I conducted in their third year beginning in 2020.

Working as a pharmacist is a regulated profession, and the educational programme is under relevant European directives, including the length and the content of the programme, albeit at an overall level of description (European Commission, 2005). Therefore, the relevant regulatory documents for the analyses conducted in this research project were at the programme and course level.

Three official types of documents regulate the programme at the University of Copenhagen. First, a central document covers regulations shared for all bachelor programmes at the Faculty of Health and Medical Sciences. This document concerns, e.g., examination rules and the organisation of the year, and consequences when a student cancels an exam due to illness (Det Sundhedsvidenskabelige Fakultet, 2020). Secondly, each bachelor programme has a programme-specific document. Thus, a specific document specifies content and regulation concerning the pharmaceutical programme (Faculty of health and medical sciences, 2018). The programme description does not contain the course descriptions, as the specific course descriptions are revised and updated annually, whereas the program description is revised less often. Thus, thirdly, every course has a description containing goals, scope, content and assessment.

The overall description of the educational programme lays out the structure, the courses, the overall learning outcomes of the programme and other rules and regulations. Pharmacy is an applied discipline emphasising quality control and the biological application of chemical principles. This applied approach makes it different from chemistry and affords certain ways of thinking and practicing as well as teaching. The intended learning outcomes are presented as knowledge, skills, and competences (Table 3). The current organisation of the programme was implemented in 2016.

The pharmaceutical programme at UCPH is organised with four courses each semester for four semesters, with the third year divided into quarters (Table 4). Seventeen mandatory courses contain some laboratory components according to their course description. Whether a course has a laboratory component can range from having students engaged in practical work for one day to going through multiple exercises over multiple weeks. In aggregate, the use of time is distributed in 30% laboratory time, 35% lectures, 30% project work, and 15% class work (Københavns Universitet, 2022).

Table 3 Intended learning outcomes for the pharmaceutical bachelor programme at UCPH (Faculty of health and medical sciences, 2018). This is a subsection of the programme description. Other sections include assessment regulations and courses in the programme.

Knowledge	A bachelor in pharmacy has knowledge of theory, method and practice within the pharmaceutical profession and can understand and reflect on theories, method and practice within the natural science, health science and pharmaceutical science disciplines relevant to the profession. A bachelor in pharmacy has • general inorganic, organic, analytical, pharmaceutical and physical-chemical knowledge for description and understanding of medicinal substances, excipients, biomarkers and medicines • biological, including biochemical, microbiological, anatomical, physiological and pharmacological knowledge to describe and understand medicinal substances, excipients, biomarkers and medicines • knowledge of pharmacology, including pharmacodynamics, pharmacokinetics, pharmacotherapy, clinical pharmacy, as well as pharmacovigilance • pharmaceutical translational knowledge of the clinical relevance of in vitro, in vivo and silico studies • pharmaceutical knowledge to describe and understand the development of medicinal substances, formulation, production, assessment, regulation, and quality assurance • knowledge of pharmaceutical manufacturing technology • knowledge of pharmacognosy • societal pharmaceutical knowledge for description and understanding of pharmaceutical issues concerning drug supply and use • knowledge of natural and social scientific methods and can relate the methods to problems in the pharmaceutical profession. • knowledge of chemical safety, hygiene as well as safety aspects of biological materials in connection with laboratory work • knowledge of basic ethics and scientific theory related to the pharmaceutical profession • knowledge of pharmaceutical legislation and regulation
Skills	A bachelor in pharmacy has experimental and theoretical skills to be able to assess problems as well as justify, choose and communicate relevant solution models within the natural science, health science and pharmaceutical science disciplines relevant to the pharmaceutical profession. A bachelor in pharmacy can apply, evaluate and communicate • general inorganic, organic, analytical pharmaceutical and physical chemical methods and theory related to drug development • methods and theory for biological, including biochemical, microbiological, anatomical, physiological, pharmacological and toxicological studies related to the development of medicines • methods and theory for the identification, quality assessment and regulation of medicinal substances, biomarkers, excipients and medicinal products • pharmacognostic method and theory • specific pharmaceutical and pharmacological translational strategies and methods for characterizing and describing, e.g., Pharmacokinetics of medicinal substances (absorption, distribution, metabolism, excretion (excretion) and pharmacodynamics (effect(s) and side effects) • theory and methods for formulating/developing and producing medicines that can be approved by relevant authorities and exhibit optimal durability and effectiveness. • theory and method for registration and quality assurance/control of medicinal products, including work according to GXP • relevant theories and methods in the analysis of societal pharmaceutical (including regulatory, pharmaco-therapeutic, drug consumption and supply) issues • systematic and critical literature search, including using relevant databases in work with pharmaceutical issues • information technology to seek knowledge about fundamental aspects of medicinal substances and medicinal products
Competences	A bachelor in pharmacy can handle complex and development-oriented study project work within the natural science, health science and pharmaceutical science disciplines relevant to the pharmaceutical profession, and can independently participate in professional and interdisciplinary collaboration with a professional approach, including identifying own learning needs and structuring own learning in both laboratory-based and theoretical project work as well as combining experimental and theoretical projects. A bachelor in pharmacy can • collaborate, communicate and inform appropriately about medicinal substances and medicines from molecules to humans with colleagues, other academic and non-academic professional groups and patients • independently analyse, systematise and critically assess new problems in pharmaceutical science • reflect on your professional role in a historical, cultural and interpersonal context, with a particular perspective on the expected future work as a pharmaceutical expert • formulate goals for your professional development and continue your competence development, e.g., through relevant graduate courses • make suggestions for optimal drug treatment based on the patient's disease, clinical data and para-clinical data

*Table 4 The pharmaceutical bachelor programme at UCPH (Faculty of health and medical sciences, 2018). Year, semester and quarter show when courses take place. Courses are marked with a + if the course description has any allocated time towards laboratory work, regardless of scope. The programme is organised into four strands: Pharmaceutical (=yellow), chemical (=blue), biological (=red) and social science (=green) courses. *Context of data collection for papers 2 and 3.*

Year	Semester	Quarter	Course	Laboratory	Strand
1.	1.		Drug Development from Molecule to Man	+	yellow
			Chemical Principles	+	blue
			Cellular and Molecular Biology	+	red
			Organic Chemistry I - Physicochemical Properties	+	blue
	2.		Pharmaceutical Physical Chemistry I - Thermodynamics and Equilibrium	+	yellow
			Evaluation of Pharmaceutical Substances	+	blue
			Biology (Pharmacy)	+	red
			Organic Chemistry II - Synthesis of Drug Compounds	+	blue
2.	3.		Pharmaceutical Physical Chemistry II - Kinetics and Transport Phenomena	+	yellow
			Basic Pharmacology	+	red
			Philosophy of Science and Social Pharmacy	-	green
			Biopharmaceuticals - Bioorganic Chemistry	+	blue
	4.		Pharmaceutics I - Liquid and Semi-Solid Dosage Forms	+	yellow
			Organ Pharmacology	+	red
			Social Pharmacy - Method and Dissemination	-	green
			Pharmaceutical Analytical Chemistry	+	blue
3.	5.	1	Drugs from Nature*	+	blue
		1+2	Systems Pharmacology - Signaling Pathways	-	red
		1+2	Pharmaceutics II – Solid Dosage Forms*	+	yellow
		2	Pharmacotherapy	-	green
	6.	3/4	Elective courses	?	
		3/4	Bachelor's Project in Pharmacy*	+	yellow

The four strands delimited with colours in Table 4 are purposefully organised to contain progression through the programme. Consequently, the programme has a high proportion of courses in natural sciences and chemistry in particular and a low proportion of courses relating to other areas of the pharmaceutical profession, e.g., pharmacy practice and patient relations.

Almost all students continue into the master's programme, as is common practice for 80% of bachelor's graduates in Danish higher education (Danmarks Statistik, 2017; Hovdhaugen & Ulriksen, 2021). Students then graduate with a master's degree in pharmacy or pharmaceutical sciences, depending on their course portfolio, herein whether they have completed a six-month internship at a pharmacy during their studies. Graduates from the pharmaceutical programme have a low unemployment rate, and a majority have applied for jobs in or are already employed in the life science industry (Københavns Universitet, 2021; Lassen et al., 2016), which is somewhat in contrast to many other nations where pharmacists are predominantly employed at community pharmacies.

Comprehensive training in chemistry has been part of the pharmacy programme at UCPH for almost 200 years, precisely to supply industrial ventures with chemically educated personnel. Moreover, the industry was already an established career path for Danish pharmacists a century ago, as approximately a third of graduates would pursue such work in the decades prior to 1916 (Kruse, 2010).

Previous research on laboratory work in the Danish context has emphasised differentiating teachers' and students' perspectives. For example, one PhD project discussed a course failing to achieve the intended learning outcomes because of a misalignment between aims and teaching (Troelsen, 2003). In addition, a report from the pharmaceutical education at UCPH discussed the use of written laboratory reports, internal course constructive alignment and alignment with the bachelor's programme, concluding that learning is better supported by less but better-aligned report writing (Berthelsen, 2020).

In the IQ-Lab project, we conducted our studies in the pharmaceutical context through teacher, student, and programme perspectives. My study, which resulted in Papers 2 and 3, investigated the programme perspective through a simultaneous collection of data from teacher interviews, student interviews and the official documents of the programme. Other parts of the IQ-Lab project looked more closely at the teacher or student perspectives. Here are a few relevant findings from these investigations.

3.1.1 Teacher perspective

In the IQ-lab project, a central question has been the description of the characterisation of laboratory-related competences in a pharmaceutical setting. As described in the previous chapter, Paper 1 provided important insights into the empirically found outcomes in tertiary chemical education. However, we also contextualised the findings from Paper 1 through the teachers' perspective in the pharmaceutical programme at UCPH. Our findings have been published in Paper 4. We found that teachers recognise and can debate the multitude of laboratory learning outcomes identified in Paper 1.

The analysis in Paper 4 of the teachers' discussions provided a somewhat different view of laboratory learning outcomes than was suggested from analysing empirical literature in Paper 1. Thus, the teachers' discussions of laboratory learning outcomes centred on experimental learning. Teachers distinguished between experimental skills, such as carrying out experiments and analysing data, as distinctly different from designing the experiment. Therefore, designing experiments might be better suited as a higher-order thinking skill when seen from the pharmacy teachers' perspective. That experiment design is a higher-order thinking skill mirrors the findings presented later in this thesis – that learning outcomes related to designing experiments are situated late in the pharmaceutical programme and late in the students' laboratory learning progression. This is not surprising considering that the teachers interviewed for Paper 4 and my study are all from the pharmaceutical programme at UCPH.

In Paper 4, we applied a prescriptive approach where focus groups were presented with a summary of the results from Paper 1. This simultaneously expanded and limited the discussions. That list essentially guided all discussions and thus limited other ideas that teachers might have about laboratory learning outcomes. However, as we discuss in the paper, the multitude of laboratory learning we found in Paper 1 also presents teachers with a broad view of learning in the laboratory. For many teachers, this provided them with different ideas of laboratory learning than they might have suggested otherwise.

3.1.2 Student perspective

Other IQ-Lab group members investigated the students' perception of laboratory learning in the course Pharmaceutical Analytical Chemistry which is located prior to the context of my study at the end of the second year of the programme (Table 4).

One investigation was conducted during a pandemic lockdown period where teaching was moved online, and laboratory sessions were cancelled. This different situation provided a context for students to reflect on the influence of laboratory teaching (Finne et al., 2022b).

The analysis in that article presented two important reasons for laboratory work, as seen from the student's perspective. It described that laboratory work had both pedagogical importance and what is referred to as epistemic importance. The researchers found that students recognised the pedagogical importance of the laboratory, as the laboratory was an important venue for providing high-quality feedback and authentic dialogue with the teacher. These findings are also, to a degree, reflected in my interviews, which I will discuss in section 3.3. The epistemic merit of laboratory learning was expressed as providing a structure for and embodiment of learning. As students go through the steps of the experimental design and end up with a dataset, they understand how knowledge is created, and at the same time, the structure gives students a framework to pin their learning and clearly understand where data came from.

Another factor that the paper was the embodied learning happens as students spend time in the laboratory with multiple sensory inputs as part of the learning experience. This input provides students with a visceral experience of learning. From the students' perspective, the laboratory was a powerful venue for learning (Finne et al., 2022b).

Another investigation looked into the students' conception of the theory-practice connection (Finne et al., 2022a). That study showed how students experience the laboratory in three ways. The first way is a visual representation of the theory, where the laboratory exemplifies theoretical concepts. The second way is experiencing the laboratory as a multimodal setting where students are present in the laboratory with all their senses and the ability to act. Students experience the theory-practice connection through their actions. The third way is that student experiences the laboratory as a complementary perspective in understanding theory. With this view, students experience the differences between theory and practice in the laboratory and value the learning that comes from making mistakes and engaging in problem-solving.

This presents a relevant takeaway connection to my study. If students are ready and able to engage in problem-solving in their second year, then it should be possible to implement through fitting laboratory activities throughout the third year, as I will argue later. This leads to another relevant takeaway from the studies on the student perspective, which is that students have different views and experiences of the laboratory, which highlights why one limitation of my study pertains to having few student participants.

3.2 Methodology of the study: Programme perspective

I investigated the pharmaceutical programme's feedback processes and the progression of laboratory learning outcomes. The data was interviews with teachers and students, laboratory reports, and official documents. The work resulted in Paper 2 and Paper 3. Here I outline some methodological considerations that were relevant to the study. Some of these considerations are absent from or very limited in the papers.

3.2.1 Interviews and analysis

The primary data sources were interviews with students and teachers, student laboratory reports, bachelor's projects, and written feedback for these. Table 5 provides an overview of the data collection. Easy access to the institution under investigation can be a methodological benefit when it improves the recruitment process in qualitative research (Braun & Clarke, 2013, p. 60). Other project members of the IQ-Lab group who had close connections in the pharmaceutical programme helped me access it.

Table 5 Collected empirical material

	5th semester 2020		6th semester 2021
	Sep + Oct	Oct + Nov + Dec	June + July
	Drugs from nature	Pharmaceutics 2	Bachelor's project
Student products	16 lab reports	5 lab reports	3 bachelor's projects
Written feedback	Online feedback on lab report	Handwritten feedback on lab reports	-
Oral feedback	-	Observation of whole-class session	-
Interviews w. teachers	4	4	3
Interviews w. students	4	5	3

Other materials were collected as part of the interview preparation and served as topics in the interviews. This material included course descriptions of all the courses in the programme, the programme description, The European directive on professional qualifications, and surveys of graduates from the education. Materials on the three courses in focus were their course descriptions, schedules, laboratory protocols, lecture slides and access to their learning management system (Canvas).

In concordance with general data protection regulations, participants had signed consent forms prior to the meeting or at the beginning of the interview. The interviews were conducted according to Covid-19 restrictions at the time. Most interviews were conducted on Zoom, but one was conducted inside, in a large open space with plenty of space between the interviewee and me. Some interviews were conducted outside on park benches.

The interviews were conducted in a receptive manner as semi-structured interviews (Mik-Meyer & Järvinen, 2020, p. 11). I approached the interviews as a craft, as suggested by Kvale & Brinkmann (2008, p. 33). Their point is that the (novice) researcher can prepare extensively, show awareness of their own bias, and construct a good interview guide, but in the end, they only get better at interviewing through practical experience.

Extensive preparation before the first interview resulted in useable data from the beginning, but it is still clear that I improved my interview technique throughout the study. The good interviewer exercises active listening and uses the interviewee's responses as prompts to continue further questioning (Kvale & Brinkmann, 2008, p. 159). An example of this is asking the interviewee to elaborate. In the first interview, the conversation was fruitful, but I rarely asked for elaboration. During the final interview, nine months and more than twenty interviews later, I asked the interviewee to elaborate with specific examples five times.

The quality of a semi-structured interview is improved when the researcher can find the balance between asking questions about prepared elements and allowing participants to answer freely, and letting their answers guide further questioning. During the interviews, I would follow recommendations by McGrath et al. (2019) and focus on talking less and listening more, being aware of my wording and framing of the discussion and seeking to build trust with the interviewee.

The interview guide was constructed with open-ended questions and ample space for notes (Creswell, 2007, p. 133). It focused on the interviewee's perceptions but always with specific content to talk about, e.g., the course description, reports with feedback or clusters of laboratory learning from Paper 1.

Using the definitions by Braun & Clarke (2006), Papers 2 and 3 are based on a common data corpus but have different data sets, meaning that they are based on analysis of the same interviews, but focus on different parts of those interviews. For example, the five clusters of laboratory learning became one of the foundations for Paper 3, whereas the students' laboratory reports with feedback and the perceptions teachers and students expressed regarding it became central to Paper 2.

Interviews were recorded using a digital voice recorder or the embedded recording features of Zoom. An external transcriber transcribed interviews verbatim. Interviews were analysed in Nvivo (QSR International Pty Ltd., 2018).

Thematic analysis was applied as analytical method (Braun & Clarke, 2006). Thematic analysis is especially useful for the inexperienced researcher "as it provides core skills that will be useful for conducting many other forms of qualitative analysis." (Braun & Clarke, 2006, p. 78). Braun & Clarke (2006) lists six questions that the researcher should consider when conducting thematic analysis. First, what counts as a theme? The researcher should maintain flexibility in analysis and allow codes to develop into themes depending on whether they add meaning. This is related to the second question of whether the analysis aims at a rich description of the data set or one particular aspect, as this will help decide what is important. Papers 2 and 3 followed different research questions, and the analysis for each paper aimed at a detailed description of two different aspects (feedback or progression). The third question is if the analysis in inductive or theoretical. My analysis was theoretically driven in the way that the congruence model is the outset for analysis in Paper 2 and the five clusters of laboratory learning are the outset for analysis in Paper 3. Importantly, using theory to drive analysis forward is not in conflict with conducting the analysis with an open mind and allowing interviewees perceptions to give meaning. The fourth question is to conduct analysis at a semantic or latent level. My analysis was semantic, meaning that interviewees' accounts were identified and used with their explicit meaning. The fifth question is that the researcher should know their philosophical worldview. I will explain how this project is situated in an interpretivist worldview in section 0. The sixth question is to determine and distinguish the types of questions the researcher asks and whether they are overall research problems, research questions, interview questions or analytical questions? In this research project, the initial problem was to investigate how laboratory learning outcomes develop longitudinally. This translated into varied interview questions, such as what the aim is with the course. The analytical questions were different depending on the analysis. For Paper 2, one of the analytical questions was, for example, what all the course teachers say about the affective learning outcomes of their laboratory practicals. In the papers, there are more details on the specific analysis conducted for each.

3.2.2 Courses under investigation

Before selecting the three courses that the study focused on, I needed to familiarise myself with the programme. I did so by conducting a curriculum mapping, which compared the description of knowledge, skills and competences from the programme description (Table 3) with the corresponding description in all 21 mandatory courses. This knowledge acquainted me with the programme and improved my preparation for interviews with students and teachers, where one of the subjects was the programme and its courses.

Following the curriculum mapping and some further informal analysis of relevant courses, I settled on Drugs from Nature, Pharmaceutics 2 and the bachelor's project as the courses that would serve as the context for collecting empirical data.

The course descriptions contain content, assessment, teaching format, and course-specific intended learning outcomes, described in knowledge, skills and competences. The course-responsible teachers write these course descriptions. The study board approves them.

3.2.2.1 Drugs from Nature

This course aims to teach students how to identify and characterise drug candidates from natural sources. The course employs analytical chemistry methods like high-performance liquid chromatography, gas chromatography, mass spectrometry and high throughput screening assays. The workload of the course is 7,5 ECTS credits distributed with 24 hours in the laboratory, 25 hours of lectures, 25 hours of class-based teaching, 2 hours for the exam and an estimated 130 hours of preparation (University of Copenhagen, 2020a). Table 6 shows the intended learning outcomes of the course.

Table 6 Intended learning outcomes from the course Drugs from Nature. From University of Copenhagen (2020a)

Knowledge	• Explain the use of instrumental analytical technologies for the separation and dereplication of peptides and secondary metabolites in complex matrices - including describing the strengths and weaknesses of the various methods. • Explain the structural, physical and chemical properties of peptides and secondary/specialised metabolites - including knowledge of structure, biosynthesis and naming of selected substance classes. • Explain 1D and simple 2D NMR experiments as well as mass spectrometric methods used for structure elucidation of peptides and secondary metabolites. • Explain the use of photometric in vitro bioassays - primarily microplate-based enzyme assays - for the identification of bioactive ingredients in complex mixtures. • Master principles of the taxonomy of the plant kingdom, microorganisms and certain marine organisms. • State which characteristic ingredients are in herbal medicines, traditional medicines and nutritional supplements on the Danish market and know their indication.
Skills	• Isolate peptides and secondary metabolites from complex matrices using efficient instrumental separation techniques. • Identify or elucidate the structure of smaller polypeptides and secondary metabolites using mass spectrometry and NMR spectroscopy. • Perform, analyse, and discuss quantitative analyses of pure substances or single components in complex mixtures. • Perform 'semi high-throughput' in vitro screening of drug libraries and high-resolution assays for the identification of active single components in complex mixtures. • Describe the structure and biosynthesis of the most important types of natural substances.
Competences	• Act independently as a central person in interdisciplinary research projects that focus on drug development from nature using in vitro pharmacology, analytical chemistry and spectroscopy. • Demonstrate good and independent laboratory practice, including working safely in an experimental analytical/in vitro pharmacology laboratory in accordance with current practice for laboratory safety. • Take responsibility for the structured acquisition of theoretical knowledge within analytical instrumental chemistry, spectroscopy and in vitro pharmacology, and on the basis of this plan experimental trials in interdisciplinary research teams working with drug development based on natural sources.

3.2.2.2 Pharmaceutics 2

Pharmaceutical education’s core content that distinguishes it from related chemical and biological education is pharmaceutical development and production of medicinal products, such as tablets (Faculty of health and medical sciences, 2018). This course uses solid dosage forms to teach pharmaceutical formulation and unit operations, including granulation, drying, filling and coating. The course also covers other production areas, such as packaging and scaling. All while adhering to principles of good manufacturing processes. The workload of the course is 7,5 ECTS credits distributed as 40 hours of lectures, 21 laboratory hours, 8 hours of class-based teaching, 3 hours for the exam and 134 hours of estimated preparation time (University of Copenhagen, 2020b). Table 7 shows the intended learning outcomes of the course.

Table 7 Intended learning outcomes from the course Pharmaceutics 2. From University of Copenhagen (2020b)

Knowledge	• Explain the principles of formulating and manufacturing different solid state pharmaceuticals. • Demonstrate an overview of principles and key concepts when formulating and manufacturing different solid state pharmaceuticals using relevant work processes. • Explain formulation aspects in the selection and development of solid state formulations. • Explain the importance of the excipients in solid state formulations. • Explain stability conditions in the development of solid state formulations. • Describe principles and issues regarding pharmaceutical unit operations for solid state pharmaceuticals. • Explain the use of packaging for solid state pharmaceuticals. • Reflect on the importance of the physicochemical properties of the drug and excipients in relation to ADME properties, with a focus on oral absorption. • Reflect on the importance of the physical and physicochemical properties of raw materials for the quality of solid state pharmaceuticals. • Obtain, assess and apply knowledge of pharmaceutical unit operations, raw material quality, quality control and legislation. • Identify and describe factors that influence the quality of medicinal products. • Assess the influence of the drug formulation on the bioavailability of medicinal substances. • Summarise rules around GMP and understand GMP requirements for documentation in drug manufacturing. • Explain pharmacopoeia methods for assessing the technical properties of medicinal products.
Skills	• Operate pharmaceutical production equipment. • Calculate solutions for pharmaceutical problems. • Classify solid state pharmaceuticals. • Apply methods for the characterisation of solid pharmaceutical forms and raw materials. • Assess the properties and use of solid pharmaceutical forms. • Assess and apply methods used for characterising the physicochemical and biopharmaceutical properties of medicinal substances. • Use correct excipients. • Explain relevant tests when assessing the quality of the medicinal product. • Assess the influence of the drug formulation on the bioavailability of medicinal substances. • Use the in vitro methods that are commonly used when assessing the biopharmaceutical properties of medicines. • Assess the quality of reports in relation to GMP. • Collect available knowledge/literature on requirements for medicinal products. • Convey knowledge in writing in a scientifically correct manner and use a critical view when evaluating the results. • Transfer theory and examples from lectures in drug manufacturing to practice. • Use of word processing program, spreadsheet, formula drawing program, experiment planning program and reference management program.
Competences	• Understand the pharmaceutical aspects of drug manufacturing and formulation. • Understand the difference between solid state pharmaceuticals. • Use pharmaceutical technical terms in connection with drug manufacturing and formulation. • Reflect on how the physicochemical properties of medicinal substances and excipients influence the formulation, manufacture and quality of medicines. • Manufacture pharmaceuticals on a smaller production scale. • Summarise a clear critical report on experimental results obtained, including using IT as a work tool for data processing (e.g. spreadsheets) and reporting. • Use IT as a work tool in a professional context to obtain knowledge about medicines in subject-specific databases, electronic reference works and books (e.g. Ph.Eur., DLS and USP). • Gain familiarity with the use of computerised laboratory equipment. • Understand and apply standard operating procedures (SOPs) of pharmaceutical production and analysis equipment. • Cooperation with fellow students on planning and implementation of laboratory work and reporting of laboratory experiments. • Discuss relevant issues with fellow students, other specialists and lecturers

3.2.2.3 *Bachelor's project in pharmacy*

The bachelor's project is the final course in the three-year education. Students work in groups of four on a project, which takes them through multiple steps of pharmaceutical work, including design decisions, formulation, production, evaluation and quality assurance. The project's product is a detailed report including relevant theory on the active pharmaceutical ingredient and excipients and a description and discussion of laboratory results. Students are assessed at an individual oral exam taking its outset in the report. The project's workload is 15 ECTS credits distributed as 4 hours of lectures, 96 laboratory hours, 40 hours of class-based teaching and approximately 270 hours of additional work as preparation and report writing (University of Copenhagen, 2020c). Table 8 shows the intended learning outcomes of the bachelor's project.

It is also possible to pursue an individually planned project where a student seeks out a specific researcher. A few students do this each year, allowing them to plan their bachelor's project according to a specific interest. One student who was interviewed for this research project conducted such a project.

Table 8 Intended learning outcomes from the bachelor's project. From University of Copenhagen (2020c)

Knowledge	• Master key concepts within the formulation, manufacture and assessment of medicinal products. • Master the use of IT tools for word processing programs, spreadsheets, statistics, formula drawing programs and reference management programs. • Master the use of IT tools to obtain knowledge about medicines in subject-specific databases, electronic reference works and books (e.g. Ph.Eur, DLS and USP). • Reflect on the significance of statistical uncertainty for pharmaceutical research
Skills	• Carry out a technical manufacture and evaluation of pharmaceuticals on a small production scale using batch documentation • Carry out process control in accordance with the GMP regulations when manufacturing pharmaceuticals on a small production scale • Justify the choice of formulation, manufacturing method and assessment for a given drug. • Interpret the results of systematic planned studies. • Draw up a clear and critical report on the relevant literature and the obtained experimental results. • Present experimental and/or theoretical results clearly at an oral presentation.
Comp.	• Transfer relevant pharmaceutical theory to the solution of multidisciplinary pharmaceutical formulation/manufacturing issues. • Independently plan, design and carry out systematic studies on the formulation, manufacture and evaluation of a medicinal product. • Reflect on and take responsibility for own learning

3.2.3 Philosophical viewpoint

Different paradigms in science education research have previously been outlined as either critical theory, positivist/post-positivist or interpretivist (Treagust et al., 2014). In that delimitation, this thesis sits in the interpretivist research paradigm, where localised meanings of human experiences are the area of interest and data source. In this paradigm, analytical power comes from situated meanings, emphasising that overgeneralising human understanding removes meaning. In addition, the conclusions of the research should be transferred to other contexts with caution and are not necessarily fitting for anything more than the context under investigation. In the interpretivist paradigm, the researcher's claim is not that the obtained knowledge is complete but merely that it is a sensible interpretation of the situation. This is a fitting description of this project, where I draw conclusions on multiple topics based on subjective and thick data. In addition to the philosophical viewpoint, the researcher's viewpoint is relevant to consider.

3.2.4 Researcher's personal background

It has been argued that subjectivity is a core feature of qualitative research that cannot be easily ignored, as it is an established feature of qualitative research that the researcher's histories, assumptions and perspectives influence the process and becomes a prerequisite of the research (Braun & Clarke, 2013, p. 36).

Before this research project, I was an upper-secondary school biology and sports science teacher in Greenland. I am a graduate of the University of Copenhagen in these fields, and as a university student, I found laboratory work to differ from boring to exciting, from deep work to rushed work. As a teacher, I enjoyed using practical work to engage students and have them develop their inquiry skills.

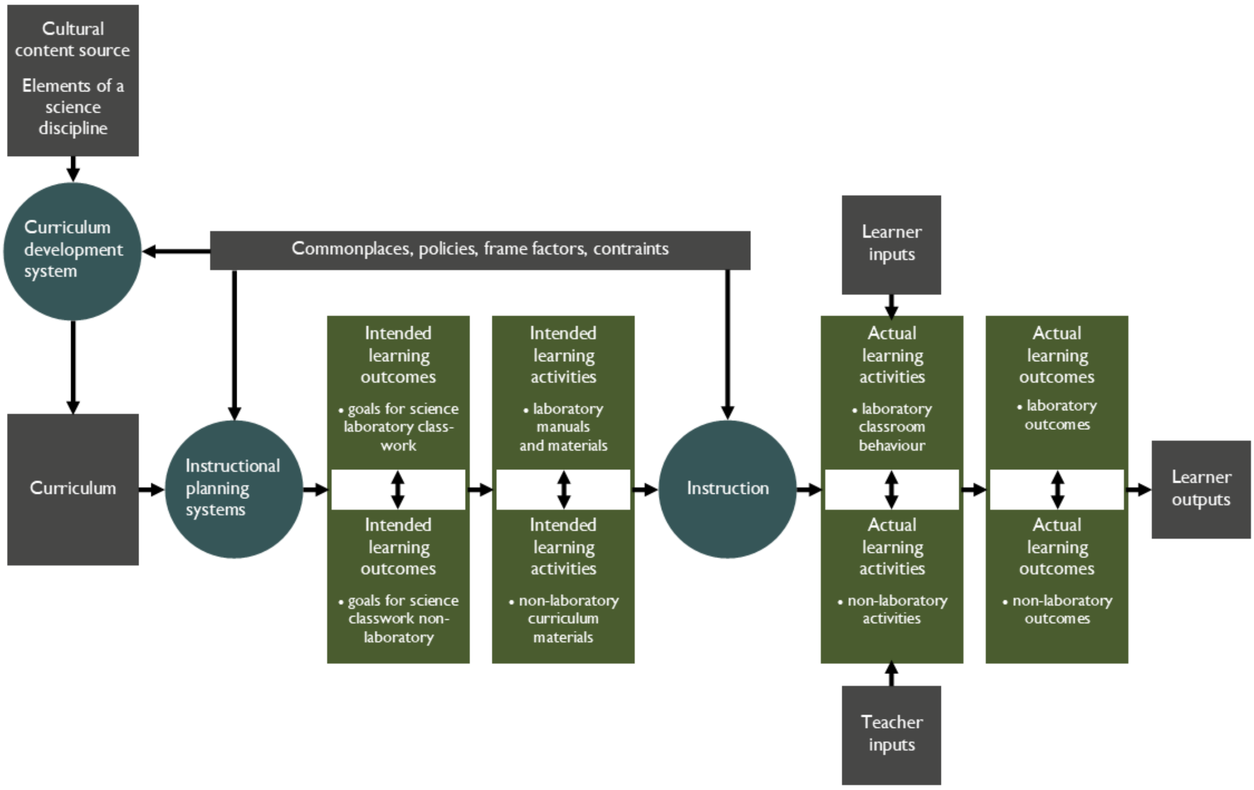
When I commenced this research project about teaching and learning in the pharmaceutical laboratory, I considered it an advantage that I had insights into science and pedagogy. Reading laboratory reports and course descriptions and interviewing teachers and students about them was more manageable when I understood the science content adequately. However, an unwanted effect of having such prior knowledge is that the researcher risks concluding from preconceptions, and the researcher should seek to limit this risk, e.g., through bracketing, which can mitigate unwanted effects of preconceptions (Mik-Meyer & Järvinen, 2020). In this project, I applied bracketing as the act of being aware of my own opinions and experiences upon commencing the interviews and analyses (Tufford & Newman, 2012).

I used my pre-existing understanding to approach the research with insight while simultaneously bracketing my interpretations and presumptions about what the laboratory should and should not do.

3.2.5 The student laboratory and the science curriculum

Researchers have emphasised that there is power in using a theoretical model that explicitly distinguishes various features of the laboratory teaching and learning situation from each other because subtle features appear and can become available as topics for planning, development of teaching and research (Mørcke & Rump, 2015). Therefore, this study is discussed against the theoretical model of the student laboratory and the science curriculum presented in Figure 1 (Hegarty-Hazel, 1990b). This model is an overview of the educational laboratory setting, and it has a clear emphasis on the curriculum perspective with its clear distinction between curriculum development, instructional planning, and the instruction itself.

Figure 1 The student laboratory and the science curriculum. From Hegarty-Hazel (1990b). Circles represent processes. Boxes represent the inputs and outputs of processes. Arrows represent connections where it is relevant to focus matches or questions. To the left is the process of curriculum development. Cultural content and elements of science are included as broader scopes of society or disciplines, which inform the curriculum development. To the far right, learner outputs are displayed as the final output stemming from the relations between laboratory learning outcomes and non-laboratory learning outcomes. The constant interaction of laboratory and non-laboratory elements is displayed with double-headed arrows.



In discussing this model, Hegarty-Hazel (1990a) acknowledged the complexity of laboratory teaching in tertiary education, where the laboratory can enhance engagement, provide students with a sense of accomplishment or technical proficiency, and be the venue where students finally grasp a concept. Course designers, teachers and students can enjoy these outcomes if the laboratory is correctly used.

Others have referenced the model and the book it was part of when researching learning outcomes to establish essential factors of the laboratory (McRobbie & Fraser, 1993) or when investigating factors that influenced students in introductory college chemistry (Tai et al., 2005). The model was applied as background theory when chemistry students and research chemists' epistemic beliefs of chemistry were compared (Samarapungavan et al., 2006).

I used documents and teacher and student interviews as data in my study. All these are present in the model: Teachers' perspectives on curriculum development, intended and actual activities, including their input here, students' perspectives on the actual activities, their input, and their learning outcomes. Furthermore, to the left is the curriculum development process, and to the far right of the model, learner outputs are displayed as the output stemming from the relations between laboratory learning outcomes and non-laboratory learning outcomes. The constant interaction of laboratory and non-laboratory elements is emphasised in the model. There is a deliberate separation of planning, intention, instruction, actual activities and outcomes in the model, which highlights why a simultaneous inclusion of teacher, learner and document data sources was relevant. Moreover, the model explicitly mentions constraints, frame factors and policies, further highlighting the need to include more than interviews with only the teachers or the students when I wanted to approach the more encompassing programme perspective

The model emphasised the conscious separation of the intended and the actual, which is also a recurring theme in my thesis. For example, chapter 2 discussed how it is essential to distinguish between goals and outcomes, and Paper 2 showed that intentions with feedback were not met in the actual experience of feedback.

3.2.6 Didactic engineering

The didactics of mathematics provided some relevant tools for planning my data collection. Didactic engineering is a model helpful in designing, conducting, evaluating and improving teaching, somewhat in the same way as action research (Brousseau, 2002; Margolinas & Drijvers, 2015). It was developed to improve teaching by bridging teaching and research and controlling and validating findings while acknowledging the complexity of a given teaching situation (Artigue & Perrin-Glorian, 1991; Barquero & Bosch, 2015). I used it for its strengths as a research tool and not as an intervention or to develop the teaching situation explicitly. Instead, the categories and distinctions employed in data collection and analysis were helpful.

Didactic engineering suggests data collection in four steps, which informed my data collection and analysis. First, preliminary analysis of documents and assignments. Second, an a priori analysis of the design of the teaching-learning situation based on the teachers' views on courses and assignments. The third step is the actual situation, where students are in the laboratory and then complete reports and receive feedback. Fourth, a posteriori analysis based on the products of the situation (reports and feedback) and the teachers' and the students' views on these (interviews).

While I have taken inspiration from didactic engineering, I have not employed it as rigorously as others have outlined (Barquero & Bosch, 2015). Instead, I applied the more flexible approach of thematic analysis. Furthermore, my data collection was not chronological in that I first interviewed teachers about intentions and then later about outcomes. This division was at the analytical end, where I coded the interviews for intentions and outcomes separately.

The connection between the theoretical model in Figure 1 and the data collection model inspired by didactic engineering lies in their mutual assumption of knowledge in the teaching situation as something that transforms. It changes from the planning, through the teaching, through the learning. It is established that knowledge changes from meant to taught to learnt, e.g., in mathematical educational research (Bauersfeld, 1979). Outside mathematics, consider the work on science communication at my own Department of Science Education, UCPH, where analysis of out-of-school educational settings use the didactic transposition (Achiam, 2014; Evans & Achiam, 2021). This is part of a tradition that emphasises the importance of the context and the knowledge at play instead of merely considering the actors, teachers and students (Chevallard, 1989), which was a relevant approach for my study.

As such, the model in Figure 1 provided a relevant theoretical separation of elements in laboratory instruction, which, together with the didactic engineering model, suggested how and where to collect data.

3.2.7 Methodological limitations

The programme perspective I have described here was an attempt at making the research process account for the complexity of teaching and learning. Researchers have long called for qualitative interpretative studies into broad aspects of learning (Sandi-Urena, 2018; Tobin, 1990). Nevertheless, it should be questioned whether the idea of the programme perspective was used in the best way here. I chose to follow a few students throughout one year and then investigate the laboratory contexts they would encounter during that year. Another strategy could be to simultaneously sample multiple data points, for example, by conducting interviews in the first, second, third, fourth and fifth year. This data would instantly provide a longer perspective. However, I found that following the same students came with advantages. It increased comparability between student interviews as some interviews will be with the same student, and it made the setting and the topics of the research interview familiar to the students, possibly improving some of the later interviews. In addition, conducting a longitudinal study can be difficult due to the time constraints that project employment as a PhD student entails. Luckily, I had an opportunity to collect longitudinal data due to a paternal leave that stretched my data collection multiple months.

Another potential critique of my research project relates to the selection of student participants. In contrast to teachers who were deliberately selected for their role in specific courses, the student participants self-selected upon invitation. This process leaves the possibility of selecting students with agendas. However, the invitation was not explicit regarding the topics covered during the interviews, and interviewing a student with opinions on laboratory learning can be viewed as a source of relevant data and an expression of participant subjectivity, which should be celebrated in qualitative research (Braun & Clarke, 2013, p. 36).

Papers 2 and 3 are the products of a small research study, and the limited size of studies was already critiqued decades ago (Hofstein & Lunetta, 1982). The risk of small studies is that important insights are not uncovered, but the researcher can overcome this by aiming for saturation, including participants, until no more relevant data appears (Braun & Clarke, 2021). Unfortunately, the finding and inclusion of participants took place under restrictions related to the Covid-19 pandemic, which somewhat limited the possibility of inclusion. The longitudinal setup of the project further limited the possibility of adjusting this, as it was impossible to go back to the first context and include more participants after ten months. Indeed, pragmatic reasoning often determines the number of included participants (Braun & Clarke, 2021). The cure is that the researcher stays reflexive and critical of the produced knowledge throughout the research process (Braun & Clarke, 2013, p. 37).

A way to rely less on interviews could be to observe teaching, which was an initial idea, but it was quickly discarded in favour of Zoom interviews when Covid-19 restrictions emphasised that we should meet as few people as possible. A single observation of a Zoom class was conducted, but I decided not to pursue it further due to a lack of clarity about how I would seek to observe.

Trustworthiness should be pursued in qualitative research through credibility, transferability, dependability and confirmability (Bryman, 2012). The examples below show how I incorporated this throughout my project:

- Credibility: Triangulation was achieved by basing results on multiple data types, such as teacher and student interviews, official documents, and laboratory reports. Respondent validation was achieved for Paper 2, where the senior teachers were invited to give comments before submission.

- Transferability: Each paper presents clear descriptions of methods and thick descriptions of data and results. These descriptions allow future researchers to evaluate this project in relevance to their context.
- Dependability: The core of the dependability criteria is an audit. Once papers are published, they have undergone peer-review. In addition, all papers that make up part of this thesis have multiple co-authors who questioned and discussed the dependability of the research during the research process.
- Confirmability: I acted in good faith and refrained from reproducing my values or swaying the research findings. The responsibility is on the individual researcher because true objectivity is not possible.

Even if the discussion above provides insights into the quality of the research, it is still only a limited take on what constitutes quality in research. Others have discussed the validity of qualitative research and concluded that validity should not necessarily be defined in terms of rules or guidelines. Measures of validity should instead follow the argumentation that is undertaken and the measures of quality are whether the claims put forward can be supported by the evidence, considering how the evidence was obtained (Dennis, 2013). I believe that the internal logic of the research project is evident throughout this thesis and that this criterion is thus fulfilled.

3.3 Role of feedback in developing students' laboratory learning outcomes: Paper 2

In Paper 2, I have considered students' learning from feedback within the course Pharmaceutics 2 in the third year of the UCPH bachelor programme, and here I will provide some additional considerations on the role of feedback in students' development. In Paper 3, I have considered teachers' and students' perspectives on their learning in the laboratory as they occurred during the 3rd year, through two exercise-oriented courses to a more problem-based and open experimental study in the bachelor's project. In this way, the two papers provide two different perspectives on how students' laboratory learning outcomes develop over time. Ongoing feedback is part of the learning process on a short timescale within a given course (or even a theme within a course), whereas the progression discernible in a programme ideally influences the learning process on a longer timescale. Thus, the two papers provide two different answers to how students' laboratory learning outcomes develop over time, one for the short term and one for the longer term.

In this section, I will consider feedback in laboratory learning and seek to answer the question:

- What is the role of feedback in developing students' laboratory learning outcomes?

When the temporal dimension is short, as in learning during a single assignment or course, feedback is a central activity and an essential component of learning. In Figure 1, the feedback process is part of the "actual learning activities". It is a meeting between the learners' and the teachers' inputs. How this meeting occurs depends, of course, on the situation. In Paper 2, we discuss several different ways in which this occurs: In the verbal and directive feedback in the laboratory as the students are doing the experiments, in written comments from the teachers on students' work and in the whole-class feedback sessions taking place in a classroom or virtual space.

The teachers have a specific progression in mind in the design of the activities: The students should read the comments and try to move forward with them prior to the whole-class exercise feedback, where the teachers will provide general feedback on common mistakes, thus closing the remaining gaps in student understanding. However, the teachers' intentions are not necessarily realised.

In the literature on feedback, the reiterated conclusion is that feedback is a powerful tool and something teachers and students can use with great benefit, especially when the focus is on formative feedback (Hattie & Timperley, 2007; Nicol & Macfarlane-Dick, 2006; Shute, 2008). Research shows that teachers and students agree that the purpose of feedback is an improvement of learning, but they disagree on whether good feedback is mainly determined by the design and timing of the feedback (teachers) or determined by the quality of the specific comments (students) (Dawson et al., 2019). Unsurprisingly, the importance of good formative feedback has also been found to be useful for written feedback. Students value written feedback for their assignments, but the comments teachers give are often challenging to understand and use for the students (Weaver, 2006).

In pharmaceutical education, studies show that students recognised feedback as necessary to their learning, but the quality of the feedback often failed to meet student expectations (Hanna et al., 2012). Tutors and students in a pharmaceutical programme have been shown to agree on the crucial influence of feedback, leading to a recommendation that tutor training in giving feedback should be prioritised (Kairuz et al., 2015).

Recently, research has shown discrepancies in teachers' and students' perceptions of the quality of feedback: Teachers were aware of the organisational aspects of feedback, like timing, but students mostly valued feedback that consisted of high-quality comments (Dawson et al., 2019). That conclusion might help explain some of the findings in Paper 2. Teachers plan for valuable feedback but provide brief comments that students fail to use. We conclude that this stems from a lack of congruence between feedback and organisation, such as allocated time for feedback or focus and the purpose of feedback.

Others showed that conducting the feedback process while focusing on working with peers could improve learning outcomes. For example, by having students give peer feedback on each other's laboratory notebooks (Donovan, 2014) or by allocating time for discussions of problems and results among students (Lyall, 2010). Previous research recommended that oral discussions be prioritised before and after laboratory work (Nakhleh et al., 2002). The results presented in Paper 2 support these conclusions, as dialogue could help students engage while simultaneously exposing any lack of congruence to the teachers. Teachers should consider the importance of dialogue in the laboratory and perhaps leverage the potential of peer feedback.

Feedback can guide student learning in the different outcomes represented by the clusters from Paper 1. For example, we found that students' affective outcomes were at play when they expressed disappointment about the received feedback. Furthermore, constructive alignment highlights that the feedback and assessment process can determine whether students take part in higher-order thinking skills (Biggs, 1996).

The complexity of teaching-learning situations is evident from the literature on higher education. As I have also discussed in Chapter 2, many different aspects of a learning environment are interrelated and determine the quality of learning outcomes, illustrated by the frameworks of constructive alignment (Biggs & Tang, 2011) and congruence (Hounsell & Hounsell, 2007). In both frameworks, feedback to the students as part of the learning activity plays a central role. However, a range of other factors in the learning environment determines the students' outcomes of formative feedback. Constructive alignment emphasises that teachers should develop student-centred teaching, be clear about what they want students to learn, and align the objectives with teaching activities (including formative assessment) and summative assessment. Biggs (1998) recognises the importance of formative feedback for learning but underlines that the effect of formative feedback can be negatively influenced by the structure of the summative assessment when the different types of assessment tasks are not aligned. Therefore, it is argued that we should see formative assessment "in a broader context, embracing a multidimensional view of the instructional process". This multidimensional view is also the basic idea in the congruence model (which takes Biggs' model several steps further). The presence and opportunity for ongoing advice and formative feedback has also been recognized as an important element in ensuring quality learning outcomes (Hounsell et al., 2008).

In the course Pharmaceutics 2, which was the course in focus in Paper 2, teachers provided feedback with good intentions for students to improve their learning and with attention to detail. Nonetheless, as we show in paper 2, students often failed to use the feedback appropriately. We employed the congruence framework and provided examples of a lack of congruence between the formative feedback practice and several other dimensions of the learning environment.

The suspicion by teachers that summative assessment elements (passed vs failed report) overshadowed the students' focus on the formative feedback they received was, to some degree, supported in the student interviews. Sometimes, the written feedback failed to communicate the needed information to students. This conclusion agrees with earlier findings stating that summative feedback may overshadow formative feedback (Shute, 2008).

A central question when considering the effectiveness of feedback is whether the students use the feedback provided. Indeed, if feedback is not used, then it is not effective. In my interviews with students, there were examples of students not having acted on the provided feedback (although they might have done it at a later point before the final examination), as has also been found in research. For example, Orsmond & Merry (2011) compared teachers' and students' perceptions and found that misalignment between tutors and students resulted in students not acting on the provided feedback.

We also saw an example of a lack of congruence between the course organisation and management because of the logistics involved in the large course: Students might receive written feedback from one teacher and meet another in the whole-class feedback session. While different perspectives from different teachers can be very important in learning, they can also make effective feedback more difficult. However, we also saw how aspects of the course organisation supported the acquisition of feedback, for instance, how students used each other in discussing the feedback in the group-based reports.

In Paper 2, we do not discuss the congruence or lack thereof between: "[S]tudents' backgrounds and aspirations" (Hounsell & Hounsell, 2007) and the feedback provided. However, we also saw examples of a lack of congruence between students' backgrounds and aspirations and the provided formative feedback, as is evident from the situation described below.

During a student interview, we went through the written feedback from the teacher and the student reflected on the different comments. At a few locations in the report, the teacher had underlined some numerical results; at one location, the teacher had marked a result and written “decimals”. When I asked the student what they thought was meant by the comment, they responded that they were pretty sure it was about significant digits. The student elaborated that this was something the teachers had focused on earlier and shared that a chemistry teacher from secondary school had also pointed out the importance of significant digits. The student said that significant digits appear to be an essential concept for teachers and acknowledged that teachers probably know more about it. The student then went on to conclude: “I just think that it is more accurate the more digits I add.”

There are two points to consider from that situation. First, there was something fundamental that this student had not understood correctly, and the situation makes clear that brief markings in the text did not help the student to understand it. An analysis can use the Piagetian terms assimilation and accommodation (Ginsburg & Opper, 2016). It appears that the comments made by the teacher were intended for assimilation, meaning the teacher’s comments encouraged the student to remember and apply their existing knowledge. However, this student needed accommodation: to change their understanding of how and why significant digits are important and why adding more than the significant digits is less precise. The feedback format did not allow for that, nor did the follow-up teaching. The misunderstanding might have been discovered in a verbal discussion between the student and a teacher or between the students who authored the report. Thus, the specific format of the feedback did not allow this student to learn from the feedback, and the report was insufficient for the teachers to realise that a more fundamental misconception was at play. The format of the feedback does not make the students confront the misconception.

The other point of this situation concerns the affective domain of learning. At this point in the student’s study, the student has already followed many laboratory courses and must have met the requirement to include only the relevant number of significant digits many times. Indeed, the student describes this. The student knows exactly that this is something teachers require. So how does this student not consider why teachers keep making that request? We cannot know for sure (as it is not expressed in the interview), but one explanation could be if the student had low self-efficacy beliefs regarding mathematics and physics and therefore focused more on giving the teacher the answer they requested rather than trying to understand why the request is made. In that way, the feedback session does not work as a meeting between the student’s and the teacher’s understanding of good scientific practices.

In Paper 2, we show how several different elements of the structure of the learning environment may inhibit the outcomes for students, even when laboratory activities were thoughtfully planned with relevant pre- and post-lab activities, precise schedules, and internal progression between practicals. Thus, Paper 2 confirmed the theoretical assumption of the congruence model as the connection of feedback with other elements was evident. The story about significant digits above and the examples in Paper 2 of the lack of congruence between the provided formative feedback and other aspects of the learning environment show why students may miss opportunities for high-quality learning processes and outcomes. Restrictions on teaching activities that were enforced as a result of Covid-19 further complicated the feedback processes of this course, e.g., when whole-class feedback sessions were conducted online and not onsite without much time to adjust or prepare for the different format.

In considering the progression of learning throughout the course, a central consideration could be how the feedback provided in the first report (and student learning from that) can find its way into subsequent report writing. For example, in Paper 2, we suggest that students provide peer feedback while in the laboratory. An alternative idea could be to formalise and scaffold the students' work with the feedback in an attempt to force reflection. In Ellegaard et al. (2018), this was done by providing students with a spreadsheet in which part of the assignment was to fill in how feedback from the prior assignment was used. This spreadsheet was used throughout the course, and each student consistently built a document of deliberate reflection on received feedback. In addition to a column containing the feedback, the spreadsheet had a column reserved for students' reflections on the received feedback and a column for students' actions regarding the following assignment. The purpose was to help students to relate consecutive assignments, and a structure like this is useful if a course contains a series of assignments or if a series of courses wish to relate their assignments to each other. In this way, such scaffolding can assist in elevating feedback from something that happens in isolation to something that has a clear function in the progression of students' learning. Teachers in the pharmaceutical programme could consider such scaffolding of feedback both in each course and in the already established strands of related courses (marked with colours in Table 4).

Feedback is an important component in the process of learning. In laboratory instruction, a large part of the student work and learning process comes from report writing. The feedback provided for laboratory reports thus facilitates student laboratory learning. Organisational choices made providing proper written formative feedback for laboratory reports are challenging, for example, when one teacher has to assess many reports or if the reports have to be summatively assessed (pass/fail). Alternatively, establishing valuable feedback practices can aid in the experience of congruence, which is valuable for achieving high-quality learning.

The practical implication is that teachers must consider multiple areas in their planning of the feedback process. Organisational structures, such as place and timing, the form of feedback, and the type of comments given, are connected to ongoing oral discussions and the laboratory work itself. Therefore, teachers should plan feedback for laboratory reports with congruence in mind, trying to aid students learning towards the intended learning outcomes. Face-to-face time in the laboratory to discuss report writing may be a way forward.

Feedback plays an essential role in the longitudinal development of students' laboratory learning outcomes. It can determine the types of learning outcomes that students achieve. For example, feedback affects students' motivation and affective perception of their work while determining whether they engage in learning that requires higher-order thinking skills. Feedback can be the deciding component for a specific assignment that determines if students learn the desired outcomes, and in the longer term, feedback can determine whether students succeed in transferring previous learning to future contexts, be it other assignments or other courses.

The role of feedback in developing students' laboratory learning outcomes depends on the nature of the feedback itself, whether it is written or oral, formative or summative, but also on the interplay of feedback with other elements of the teaching-learning environment. Thus, the role of feedback depends on the choice of activities and the course's organisation.

I discussed the implication of distinguishing between aims and outcomes in chapter 2 of this thesis. That discussion becomes relevant here as feedback becomes a meeting between teachers' aims and intentions with the assignments and students' outcomes. Students' laboratory learning outcomes can be more than what was intended, and teachers can utilise feedback to help students learn in both intended and unintended ways, e.g., in all five clusters of laboratory learning outcomes.

3.4 Progression of students' laboratory learning outcomes: Paper 3

In a degree programme, learning takes place over multiple years, and the longitudinal development of students' learning outcomes is a core purpose. Therefore, this project investigated the progression during the third year in the pharmaceutical degree programme to answer the question:

- What is the progression of students' laboratory learning outcomes?

As the previous section about feedback analysed learning in the short term within a given course, this section analyses learning in the longer term. Interestingly, the programme progression perspective is present in Figure 1 if we view it as part of curriculum development but appears to be relatively static as the curriculum development system is completely decoupled from learner outputs. In Paper 1, we focused on students' learning outcomes and argued that programmes should accommodate students' progression, but we did not provide a coherent framework for that progression. Therefore, with Paper 3 and this section, I discuss how the progression of students' laboratory learning outcomes can be part of programme development.

A general view of progression is a taxonomical classification of learning outcomes. Famous examples of this are the original publications of Bloom's taxonomy and its iterations (Anderson et al., 2001; Bloom et al., 1956; Krathwohl, 2002; Krathwohl et al., 1964). Systematically ordering student learning outcomes provides a common language and thus the ability to discuss, analyse or evaluate what type of learning outcomes a particular course or activity afforded, herein the intended progression (Krathwohl, 2002).

The first publication of Bloom's taxonomy divided learning into three domains; cognitive, affective and psychomotor, but was then delimited to constructing a taxonomy of learning outcomes for the cognitive domain (Bloom et al., 1956). That publication described that learning is complex and that theories at the time were unable to account for the complexities in defining or ordering learning outcomes. The central statement in that publication is that the presented taxonomy is a useful way to order cognitive learning outcomes because learning outcomes within a category are likely to build on outcomes from a preceding category. The categories were: Knowledge, comprehension, application, analysis, synthesis and evaluation (Bloom et al., 1956). The original Bloom's taxonomy presented progression as the ability to conduct increasingly more complex cognitive actions while employing abilities learned at previous levels.

Bloom's taxonomy was very simple in its construction but has proven useful. Klopfer (1970) introduced a two-dimensional model for developing taxonomical behavioural objectives. That model is seen in Table 9 and displays more complexity of objectives and a higher focus on inquiry processes. The behavioural objectives were related to subject-specific content, e.g., cell biology. For that content category, the student could display behaviour as knowledge, application, manual skills, attitudes, orientation and processes of scientific inquiry. The processes of scientific inquiry are further divided into observing, problem-solving, interpretation and testing models. In this model, progression was less taxonomical and probably provides a more accurate representation of student learning because introducing the two dimensions of behaviour and content resulted in progression being student behaviour directly related to subject-specific content. Students can progress, e.g., concerning observation, while not progressing concerning testing models. Furthermore, that model included more of the complexity of learning that was also part of the five clusters in Paper 1, namely that practical skills and affective changes are part of student learning outcomes.

Table 9 Two-dimensional chart of student behaviours and content (Klopfer, 1970)

		Content		
	Student behaviour	Biological sciences: Cell, organism, population	Physical sciences: Chemistry. physics, earth and space sciences	General: Nature of scientific inquiry, social aspects of science, historical development of science, biographies of scientists, mathematics in science, measurement, systems
	Knowledge and comprehension			
Processes of scientific inquiry	Observing and measuring			
Processes of scientific inquiry	Seeing a problem and seeking ways to solve it			
Processes of scientific inquiry	Interpreting data and formulating generalisations			
Processes of scientific inquiry	Building, testing, and revising theoretical model			
	Application of scientific knowledge and methods			
	Manual skills			
	Attitudes and interests			
	Orientation			

A later revision of Bloom's taxonomy replaced the one-dimensional model with two dimensions: Cognitive process and knowledge (Table 10). The cognitive processes were to remember, understand, apply, analyse, evaluate and create. The knowledge dimension contained factual, conceptual, procedural, and meta-cognitive knowledge (Anderson et al., 2001). In that view, students could learn to apply procedural knowledge and evaluate factual knowledge without defining which precedes which. Progression could happen in both dimensions, such as remembering factual knowledge early in a progression and creating meta-cognitive knowledge late in a progression.

Table 10 The taxonomy table. Published as a revision of Bloom's taxonomy (Anderson et al., 2001)

	The Cognitive Process Dimension					
The knowledge dimension	Remember	Understand	Apply	Analyse	Evaluate	Create
Factual						
Conceptual						
Procedural						
Metacognitive						

A critique of Bloom's taxonomy was the lack of empirical backing. The Structure of the Observed Learning Outcome (SOLO taxonomy), though also a theoretical model, claimed a more substantial empirical basis and was introduced with empirical studies of the model's applicability within different school subjects (e.g., math, history, and geography). The SOLO taxonomy emphasises that students could display a specific performance at a particular time and describe the learning outcomes in terms of how the student response was structured (Biggs & Collis, 1982). As a result, SOLO learning outcomes are formulated with action verbs, as suggested in Table 11. The implications of the SOLO taxonomy are quite different from Bloom's. For example, compare the action "apply" in Table 10 and Table 11. In Bloom's taxonomy, applying is a mid-level cognitive process and can be done at any level of the knowledge dimension. In SOLO, applying shows that students can consistently integrate components, putting it in the relational category, high in the taxonomy.

Table 11. The SOLO taxonomy and descriptions of the categories (Biggs, 1996; Biggs & Collis, 1982; Biggs & Tang, 2011)

Category	Description (Biggs, 1996)	Student consistency and closure (Biggs & Collis, 1982)	Relevant action verbs (Biggs & Tang, 2011)
Prestructural	The task is not attacked appropriately; the student has not understood the point.	No felt need for consistency. Closes without even seeing the problem.	-
Unistructural	One or a few aspects of the task are picked up and used.	Denial, tautology, transduction. Bound to specifics.	Memorize, identify, recognise, count, define, draw, label, match, name, quote, recall, recite, order, tell, write, imitate.
Multistructural	Several aspects of the task are learned but are treated separately.	Although has a feeling for consistency can be inconsistent because closes too soon on basis of isolated fixations on data, and so can come to different conclusions with same data.	Classify, describe, list, report, discuss, illustrate, select, narrate, compute, sequence, outline, separate.
Relational	The components are integrated into a coherent whole, with each part contributing to the overall meaning.	No inconsistency within the given system, but since closure is unique so inconsistencies may occur when student goes outside the system.	Apply, integrate, analyse, explain, predict, conclude, summarise, review, argue, transfer, make a plan, characterise, compare, contrast, differentiate, organise, debate, make a case, construct, review and rewrite, examine, translate, paraphrase, solve a problem.
Extended abstract	The integrated whole at the relational level is reconceptualised at a higher level of abstraction, which enables generalisation to a new topic or area, or is turned reflexively on oneself.	Inconsistencies resolved. No felt need to give closed decisions, conclusions held open, or qualified to allow logically possible alternatives.	Theorise, hypothesise, generalise, reflect, generate, create, compose, invent, originate, prove from first principles.

In Paper 3, we used the SOLO taxonomy in our synthesis of intended learning outcomes as it is useful for teachers to plan and assess progression at the student level, in general terms and independently of subject-specific traditions.

A challenge with formulating subject-specific progressions is often that the specific teaching situation is more complex than the intended learning outcomes and progression. Nevertheless, course development and intended learning outcomes are subject-specific and adhere to the subject’s signature pedagogies (Shulman, 2005). Literature on competence models in the EHEA and learning progression models in the USA currently discuss the balance between general and subject-specific learning outcomes (Jin et al., 2019; Upmeier zu Belzen et al., 2019). In competence development literature, there has been both a linear and continuous view of learning and a non-continuous view where the progression between steps is less explicit (Ropohl et al., 2018). The complexity of the teaching and learning situation is increased when other factors are considered, such as the individual teacher's pedagogical content knowledge and the teacher-student interaction that it can entail (Lutter et al., 2019).

3.4.1 Progression in the pharmaceutical context

A decade ago, an investigation was conducted into UCPH pharmaceutical students' reasoning when they struggled with or failed courses. That report concluded that coherence was lacking and partially related this to the programme's progression (Johannsen, 2012). This thesis explores some of the same areas, but the pharmaceutical programme at UCPH has undergone considerable changes since that report, and today, teachers are aware of the role of their course in the programme, which mitigates the risk of having courses planned in isolation, as is often a critique in higher education (Jessop & Tomas, 2017). Laboratory activities are always contextualised as they take place as part of courses and not as separate activities, which has been recommended by research (Matz et al., 2012). Furthermore, teachers plan courses with intent and structure. Nevertheless, Paper 3 concludes that there is room for further improvements in congruence and suggests that using SOLO and the five clusters of laboratory learning outcomes from Paper 1 could guide these improvements.

The third year of the pharmaceutical programme contains a lot of laboratory work and terminates with the bachelor's project. The overall finding in Paper 3 relates to students' independence. The courses are primarily teacher-directed and structured, whereas the bachelor's project requires the students to conduct work independently. In the bachelor's projects, students in groups are highly self-reliant, with some support from supervision meetings but with the actual laboratory work being planned and executed independently. In Paper 3, teachers and students agree that this independence is vital to the students' learning. This progression is purposeful as problem-solving was planned as limited in the courses but central to the bachelor's project. This thinking mirrors ideas from SOLO and Bloom's taxonomies. In Bloom's taxonomy, evaluating and creating are higher-level cognitive processes than understanding and applying. Independently planning, conducting and analysing laboratory work allows students to include relevant, implicit knowledge and interrelate it coherently, which, in SOLO terms, requires multistructural, relational and extended abstract capacities and operations. It should be expected that students experience the bachelor's project as a place for independent problem-solving when teachers plan for it. This agreement between teacher and students is a positive display of congruence in the programme.

In Paper 3, we used the SOLO taxonomy to expand findings of progression into an empirically backed, taxonomically consistent list of intended learning outcomes. Synthesising those intended learning outcomes was also a way to develop the understanding of the five clusters of learning outcomes from Paper 1. That analysis and synthesis showed how all five clusters have learning outcomes in multiple steps of the SOLO taxonomy, but that it was in the higher-order thinking skills, epistemic learning, and transversal competences where extended abstract learning outcomes were expressed. For example, we presented the intended learning outcome; *students create and critically evaluate procedures* as an extended abstract higher-order learning outcome.

Even though teachers at UCPH planned a progression in student independence towards the bachelor's project, it, unfortunately, appears that the bachelor's project is the central venue for students to build independent laboratory skills in their third year. Further programme development might consider adding opportunities for independent problem-solving in laboratory work throughout the third year. This could be done by organising more of the laboratory work as inquiry or problem-based (Domin, 1999). There should be room for this ambition through a stronger focus on project-based laboratory instruction earlier in the programme, and such a change is possible to envision and implement, considering the teachers' perspective from Paper 4, which was that learning to design experiments and problem-solving are outcomes that students should and do learn towards the end of the programme. The change is merely to expand "the end of the programme" to the entire third year and not only the final project.

As was presented in section 3.1, the Bologna process has formalised progression in the European Higher Education Area (EHEA) with the EQF (European Commission/EACEA/Eurydice, 2020). EQF distinguishes between eight levels of qualification, with the UCPH pharmaceutical programme's bachelor corresponding to level 6 (Table 2). At level 6, Responsibility and autonomy are described as managing activities and projects and taking responsibility for decisions. It is clear that the programme is situated at this level as the equivalent intended learning outcomes at level 5 ask students to conduct "exercise management", and at level 7 ask students to "manage and transform work or study contexts" (The Council of the European Union, 2017). This relates well to the type of project management with independent problem-solving that we discuss in Paper 3. In EQF terms, the relevant progression is to provide students with opportunities to go from managing exercises towards managing their study context.

As part of this research project, I visited the College of Pharmaceutical Sciences at Utrecht University, where they established a bachelor's level programme with student autonomy supported by deliberate amounts of scaffolding throughout (Meijerman et al., 2016). The description of that programme emphasises progression in autonomy, level of inquiry, and amount of teacher or student regulation, thereby achieving congruence across the programme and putting less importance on taxonomical or competence descriptions at the programme level. This approach is similar to the recommendations given in research, where progression could begin with a well-defined experiment and go through a stepwise removal of scaffolding, with unfamiliar experimental design and scientific research in the final years (Seery et al., 2019). Whether students at Utrecht University experience their programme as coherently as planned would be interesting to learn.

Other Danish context research has emphasised the advantage of finding an appropriate progression. For example, an investigation of two first-year laboratory university courses at Aarhus University found that learning outcomes improved when courses were constructed with a progressive development towards independence (Nielsen et al., 2020). In addition, that study emphasised the importance of timely feedback. Another research project at a Danish university investigated the outcomes of general laboratory training and showed that project-based general training in experimental work could benefit students in their later chemical specialisations (Josephsen, 2003).

Viewing practical work as an activity that can be coordinated across a programme appears to have benefits. In that regard, taking a view of planning at the curriculum level is essential. Viewing progression as an essential task at the curriculum level aligns well with the theoretical framework presented in Figure 1. The model was named The Student Laboratory and The Science Curriculum (Hegarty-Hazel, 1990b) and has been categorised as a curriculum-based framework (Nakhleh et al., 2002). In that model, we see that the actual learning activities and the learner output depend on the instruction, which in turn depends on the planning systems and curriculum development. Indeed, this is not surprising, but I argue that viewing students' learning output in this context aids in establishing congruence across an entire programme. However, I started this section 3.4 by criticising how progression in that model might be part of the curriculum development system but fails to adjust to the learner outputs. I argue that this is because the model lacks a longitudinal component. Therefore, the model could be developed by adding such a component, e.g., by showing curriculum development and instructional planning as iterative processes, which depend on previous learner outputs.

The Bologna process and development in EHEA have given substantial weight to central programme documents and course planning. As a result, teachers and students can identify coherence and alignment in the pharmaceutical programme at UCPH. Teachers can further leverage this coherence if they distribute progression throughout the laboratory situations in the programme's third year, e.g., by employing problem-based and inquiry instruction, thereby minimising the responsibility of the bachelor's projects to carry many essential learning outcomes. Exploring the diversity in the five clusters of laboratory learning outcomes allows laboratory instruction to contribute many benefits to student learning.

A criticism of taking the programme perspective in general and using the model in Figure 1 is that it risks overweighting the influence of documents. Simply centralising planning and writing good strategies and aims into programme descriptions is insufficient. The local interaction between students and teachers in the laboratory will always shape outcomes in the end. As discussed earlier in this thesis, students' outcomes differ from aims. In the original development of the framework in Figure 1, this was accounted for by suggesting that the development of laboratory instruction primarily focused on teacher training in the local context (Hegarty-Hazel, 1990a). A recommendation that is still present in research, e.g., when graduate students take on teaching roles (Lutter et al., 2019).

Teachers can employ an iterative approach to teaching development and consider the students learning outcomes from previous years as they plan coming iterations of a course. The complexity of laboratory learning outcomes entails that planning for longitudinal development requires cooperation and coordination in university programmes. Paper 3 shows this is also the case in the pharmaceutical programme at UCPH. That paper investigated laboratory learning throughout the third year and found significant contributions to learning through independent problem-solving, but students mostly did this in the bachelor's projects. Therefore, there is more to gain. Students and teachers agree that the type of student-led learning that happens in bachelor's projects is worth pursuing, and having more of this earlier in the third year could be beneficial. The SOLO model provided a helpful way to frame the longitudinal development of laboratory learning. Using the SOLO model could assist planners and teachers in coordinating and formulating the progression of laboratory learning outcomes. There is evidence that the progression of students' laboratory learning outcomes lies in independent problem-solving.

Progression is an intended process at the level of curriculum development but is only realised by the learners. Progression happens in all five clusters of laboratory learning outcomes, and curriculum development should continuously consider learner outputs. In Paper 3, we have shown that independent problem-solving can be a significant component of the learning process and should be deliberately planned for in the programme's progression. We show how it is helpful to use SOLO as a framework to develop this progression. In this section, I have added that focusing on independent problem-solving is well in line with the EQF and that the practical implication is that teachers should plan their type of laboratory activity according to the intended student learning outcomes. Following this, actual student outcomes must be considered and be part of the development of activities, courses and the programme.

4 Conclusion: Longitudinal development of students' laboratory learning outcomes

This project explored how students' laboratory learning outcomes develop over time. This thesis and its accompanying papers presented the results of this investigation. I investigated through three guiding questions: first, defining and characterising students' laboratory learning outcomes, then exploring the role of feedback for laboratory reports, and finally, analysing progression in the third year of the pharmaceutical programme at UCPH.

Students' laboratory learning outcomes are complex, but in Paper 1, we showed that they could be meaningfully characterised in the five clusters experimental, disciplinary, higher-order thinking skills and epistemic learning, transversal and affective outcomes. These five clusters each contain a set of constructs, which shows the multitude of laboratory learning outcomes. The novelty of the study lies not least in the fact that this characterisation of laboratory learning is based on empirical studies of students' actual learning, i.e., in actual outcomes rather than goals, aims or intentions. In this way, the study continues the shift in focus from the teacher to the learner that has characterised higher education research in recent decades. The five clusters of laboratory learning outcomes represent something students have been found to learn. However, the precise categorisations we have employed can, of course, be questioned. When we gauged the teachers' perspective on the identified clusters in Paper 4, it became clear that perhaps a more fitting categorisation would be to put experimental learning outcomes as the central component on which all other learning outcomes could be associated. Another way to characterise laboratory learning outcomes differently could be to view the affective cluster in line with learning theory. The affective could then be part of an incentive dimension and help explain why students' take part in laboratory work and engage with the practicals in a way that leads to learning outcomes. Nonetheless, Paper 1 has provided us with a more precise characterisation of the actual outcomes students may obtain in tertiary education chemistry laboratory teaching than previously.

This characterisation of outcomes, however, does not tell anything about the development of outcomes over time. Through feedback for laboratory reports, I investigated the longitudinal development of laboratory learning outcomes on a short time scale. Feedback is essential to laboratory learning, especially when students produce a written report. Paper 2 showed that written feedback adds to learning when it is helpful, understandable and formative, but students do not reach their learning potential when comments are brief or overshadowed by summative assessment or other central factors at play in the learning environment. Looking into the use of feedback was like looking into the learning process itself. Education is a continuous interaction with context and content; when this interaction provides students with information on their work, we call it feedback. From a planning perspective, teachers can scaffold specific parts of the laboratory experience through feedback and guide students' towards meaningful learning. Teachers can choose what students should focus on and help them be engaged in these areas. Some feedback types are perhaps better suited than others. For example, teachers and students value face-to-face dialogue in the laboratory, and students in groups talk to each other about their report work. Both feedback types could be supported by planning and allocating time to scaffold dialogue, and peer feedback could aid in developing students' laboratory learning outcomes.

I investigated a longer time scale of longitudinal development through the third year of the pharmaceutical programme at UCPH. Paper 3 showed that teachers and students are aware of connections between courses and experience coherence in the programme. It is good that teachers deliberately plan for progression, but the bachelor's project was the main venue for independent problem-solving and was the driver of some important laboratory learning outcomes. Progression of students' laboratory learning outcomes can be defined by combining the five clusters of laboratory learning outcomes from Paper 1 with a taxonomical view of progression, such as SOLO. In Paper 3, we presented the intended learning outcomes in this regard. Presenting intended laboratory learning outcomes in each of the five clusters displays a complexity, which is empirically backed in the context of the UCPH programme. Presenting intended laboratory learning outcomes based on SOLO gives specific actions of varying relational complexity that teachers can use to plan and assess their laboratory activities. Furthermore, students will be able to evaluate their laboratory experience against statements that are true to the student experience, even if built on a limited number of interviews.

Students' laboratory learning outcomes develop over time in the way the context affords. The context affords to a large degree, what teachers plan for. If teachers conduct summative assessments on laboratory reports, students prepare the reports to be approved and glance past further formative feedback. If teachers plan for designing experiments, higher-order thinking and independent problem-solving in the bachelor's project, students learn it then. Students' laboratory learning outcomes are affected by feedback and organisational choices in the short term and programme structures in the long term. The consequence is that teachers have the power to construct the laboratory learning environments in a way that is meaningful for students. The implications for teaching are that teachers should:

- Consider the complexity of laboratory learning and plan for outcomes in different clusters and at varying SOLO levels.
- Plan for formative feedback and ensure teachers and students have a time and place to conduct and use feedback.
- Consider the strength of teacher-student and student-student dialogue that the laboratory setting provides.
- Provide appropriate opportunities for independent problem-solving in laboratory work by employing different types of laboratory activities throughout the programme.

Future research could be intervention studies, finding ways to implement and evaluate the teaching recommendations above. Other implications for research include that more studies with multiple perspectives are needed. Combining data from the teachers, the students, and the programme documents proved a benefit in this research project. However, the study was limited in scope, and research in other contexts, with more participants, will expand our knowledge about the progression of outcomes within the different identified laboratory learning clusters. Varying the longitudinal component should also be considered. In this study, written feedback processes defined the short component and three contexts in the third year defined the long component. Future research might consider elements other than written feedback to investigate the development of learning outcomes in laboratory instruction, e.g., the teacher-student and student-student interactions. More extended investigations of longitudinal development should consider expanding beyond one year of study. Even longer cohort studies might give further insights into student development. Another option could be to develop research that simultaneously investigated the beginning and end of a programme, e.g., through first-year and final-year courses. Results from such studies will bring us closer to a thorough understanding of how students' laboratory learning outcomes develop over time.

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6 Appendices

Appendix 1 Consent form (in Danish)

Samtykke til behandling af dine persondata i forskningsprojekt

Studerende

I forbindelse med din deltagelse i et forsøg, som indgår i et forskningsprojekt på Københavns Universitet, har vi brug for dit samtykke til, at vi må behandle dine persondata. Vi beder om dit samtykke efter reglerne i Databeskyttelsesforordningen. Du kan læse mere om projektet og behandlingen af dine persondata i oplysningsskemaet, du har fået udleveret.

Forskningsprojektets titel: **Improving Quality of Laboratory Learning at University Level, IQ-LAB**
Kort fortalt er formålet med projektet at skaffe ny viden om:

- Hvilke kompetencer studerende tilegner sig ved laboratoriearbejde
- Hvordan de studerende bedst opnår disse kompetencer
- Hvordan kompetencerne bruges og udvikles ud over laboratoriekurser

Flere oplysninger kan findes på projektets hjemmeside: https://lablearning.ku.dk/

Jeg bekræfter at have læst oplysningsskemaet som baggrund for mit samtykke til behandling af mine persondata i projektet.
Jeg giver hermed samtykke til, at Københavns Universitet må registrere og behandle mine persondata i ovennævnte forskningsprojekt.

Navn: ______________________________________

Dato og underskrift: ____________________________

- ☐ Jeg giver samtykke til, at mine persondata må gemmes i en database med henblik på nye forskningsprojekter efter projektets afslutning.
- ☐ Jeg giver samtykke til, at mine persondata må gives i anonymiseret form til studerende til brug for undervisning, projekter eller specialer på Københavns Universitet.
- ☐ Jeg giver samtykke til, at mine persondata i anonymiseret form må deles med andre forskningsinstitutioner i Danmark eller et andet land inden for EU/EØS.

Samtykket er frivilligt, og du kan til enhver tid trække dit samtykke til behandlingen af persondata tilbage. Du kan trække dit samtykke tilbage ved at kontakte Bente.Gammelgaard@sund.ku.dk.

Hvis du trækker dit samtykke tilbage, får det først virkning fra dette tidspunkt og påvirker ikke lovligheden af vores arbejde med dine data i projektet indtil dette tidspunkt. Dine data vil således fortsat indgå i det arbejde, som er gennemført i projektet, indtil du har trukket din samtykke tilbage.

Nærmere beskrivelse på KUnet:
Forside > Arbejdsområder > Forskningsportal > Databehandling > Behandling af personoplysninger > Samtykke og oplysningspligt

07/11/2019

Appendix 2 Information regarding protection of personal data (in Danish)

Oplysninger om behandling af persondata til deltagere i forskningsprojekter på Københavns Universitet

Forskningsprojektets titel	**Improving Quality of Laboratory Learning at University Level, IQ-LAB**
Hvad handler projektet om og hvorfor indsamler vi personoplysninger	Projektet handler om at skaffe ny viden om: • Hvilke kompetencer studerende tilegner sig ved laboratoriearbejde • Hvordan de studerende bedst opnår disse kompetencer • Hvordan kompetencerne bruges og udvikles ud over laboratoriekurser Flere oplysninger kan findes på projektets hjemmeside: https://lablearning.ku.dk/
Hvilke personoplysninger behandles i projektet	I projektet behandles følgende oplysninger om deltagerne: • Navn • Studienummer • Alder • Køn • Studieår på interviewets eller observationens tidspunkt • Rapporter og feedback • Stillingsbetegnelse (undervisere)
Hvor længe opbevares persondata	Dine data opbevares på Københavns Universitet i personhenførbar stand indtil 01/12/2027. Efter denne dato vil dine persondata blive slettet.
Vil persondata blive videregivet til andre, fx forskere på andre universiteter?	Dine data, som er indsamlet til projektet, vil primært blive anvendt i dette forskningsprojekt, men vil i tilfælde af fremtidigt forskningssamarbejde med andre forskningsinstitutioner muligvis blive delt med disse, hvis du giver tilladelse til dette. Desuden vil de muligvis blive anvendt i undervisningen af studerende, hvis du giver tilladelse til dette. I alle tilfælde vil dine data være fuldstændig anonymiseret.
Persondata er indhentet fra	Vi har kun indhentet data fra dig personligt.
Vi har lov til at behandle dine data efter regler i Databeskyttelses-forordningen, GDPR. Vi skal oplyse dig om, hvilke regler, der gælder for vores arbejde med dine data.	Kapitel 2, Artikel 6, punkt 1a i Databeskyttelsesforordningen giver Københavns Universitet ret til at behandle ikke-følsomme persondata om dig på baggrund af dit samtykke. (Du vil blive bedt om at afgive samtykke i forbindelse med indsamlingen af data)
Deltagernes rettigheder efter persondataforordningen	Som deltager i et forskningsprojekt har du en række rettigheder efter persondataforordningen. Du kan læse om dine rettigheder i Københavns Universitets privatlivspolitik. https://informationssikkerhed.ku.dk/persondatabeskyttelse/privatlivspolitik/
Ansvarlig for opbevaring og behandling af persondata	Københavns Universitet, CVR nummer 29 97 98 12 er dataansvarlig for behandlingen af persondata i forskningsprojektet. Forskningsprojektet er ledet af professor Bente Gammelgaard, Institut for Farmaci, som kan kontaktes på Institut for Farmaci, Universitetsparken 2, 2100 København Ø E-mail: bente.gammelgaard@sund.ku.dk Tlf: 3533 6415

Version Nov. 2020 Jonas Tarp Jørgensen

Date: Name:

Subject	**Question.** Materials Notes. Items to get back to (note time of answer)
Part 1 Course aims	**What is the aim of this course?** - **What have you learnt at this course?** Course description
Before and after this course	**What have you learnt earlier that you can apply at this course?** - **Where did you learn it?** - **What about lab work and report writing?** Overview of programme **What can you take away from this course?** - **For your bachelor's project** - **For your master education** - **For your future career** Overview of programme
Part 2 – approx. after 20 min Exercises in the course	**You have these exercises in the course. What is their role?** - **What are your takeaways of these exercises?** Course overview with exercises
About one of the students' reports and feedback	**Here is one of your reports and the comments you received** - **How did you approach this exercise?** - **What was the takeaway of this exercise?** - **What was easy/difficult for you in this exercise?** Reports and comments **Let us take a look at some of the comments you have received** - **What do think of the comments?** - **How did you use the comments?** - **How could the comments be more useful?** Reports and comments **Repeat with additional report (depends)** **Literature points to these possible laboratory leaning outcomes. What is especially relevant your exercises and reports in [this course]?** Lab outcomes from WP2

Date: Name:

Subject	**Question.** Materials Notes. Items to get back to (note time of answer)
Part 1 Course aims	**What is the aim of this course?** (Course description)
This course in the programme	**Please describe the purpose of this course in the programme** - **Why is the course now?** Overview of programme
Before and after this course	**What do you expect the students can do prior to this course?** **What can the students take away from this course?** - **For their bachelor's project** - **For their master education** - **For their future career** Overview of education
Part 2 – approx. after 30 min Exercises in the course	**You have these exercises in the course. What is their role?** - **What are the students' takeaways of these exercises?** - **The literature points to these possible outcomes of laboratory learning. Wht is particularly relevant for your exercises?** Course overview with exercises Laboratory learning outcomes for WP2
About one exercise	**Which of these exercises especially contribute to developing the students' laboratory skills?** - **What is the learning outcomes of this exercise?** - **How do the students approach this exercise?** - **What is easy/difficult for the students in this exercise?** Laboratory learning outcomes from WP2
Feedback for exercise	**How is feedback organised?** - **How can the students use the feedback?**

Date: Name:

Subject	**Question.** Materials Notes. Items to get back to (note time of answer)
Part 1 Course aims	**What is the aim of this course?** - **What have you learnt at this course?** Course description
Before and after this course	**What have you learnt earlier that you can apply at this course?** - **Where did you learn it?** - **What about lab work and report writing?** Overview of programme **What can you take away from this course?** - **For your bachelor's project** - **For your master education** - **For your future career** Overview of programme
Part 2 – approx. after 20 min Exercises in the course	**You have these exercises in the course. What is their role?** - **What are your takeaways of these exercises?** Course overview with exercises
About one of the students' reports and feedback	**Here is one of your reports and the comments you received** - **How did you approach this exercise?** - **What was the takeaway of this exercise?** - **What was easy/difficult for you in this exercise?** Reports and comments **Let us take a look at some of the comments you have received** - **What do think of the comments?** - **How did you use the comments?** - **How could the comments be more useful?** Reports and comments **Repeat with additional report (depends)** **Literature points to these possible laboratory leaning outcomes. What is especially relevant your exercises and reports in [this course]?** Lab outcomes from WP2

Appendix 6 Interview guide teacher Drugs from Nature

Date: Name:

Subject	Question. Materials Notes. Items to get back to (note time of answer)
Part 1 Course aims	**What is the aim of this course?** Course description
This course in the programme	**Please describe the purpose of this course in the programme** - **Why is the course now?** Overview of programme
Before and after this course	**What do you expect the students can do prior to this course?** **What can the students take away from this course?** - **For their bachelor's project** - **For their master education** - **For their future career** Overview of education
Part 2 – approx. after 30 min Exercises in the course	**You have these exercises in the course. What is their role?** - **What are the students' takeaways of these exercises?** - **The literature points to these possible outcomes of laboratory learning. Wht is particularly relevant for your exercises?** Course overview with exercises Laboratory learning outcomes for WP2
About one exercise	**Which of these exercises especially contribute to developing the students' laboratory skills?** - **What is the learning outcomes of this exercise?** - **How do the students approach this exercise?** - **What is easy/difficult for the students in this exercise?** Laboratory learning outcomes from WP2

Appendix 7 Interview guide students bachelor's projects

Date: Name:

Subject	**Question.** Materials Notes. Items to get back to (note time of answer)
Part 1 Bachelor's project's aims	**What is the aim of the bachelor's project?** - **Please elaborate from the course description** Course description
Before and after the bachelor's project	**What have you previously learned that you can use in this project?** - **Where did you learn it?** - **What about labwork and report writing?** Overview of programme **What can you take away from this project?** - **For your master education** - **For your future career** Overview of programme
Part 2 – approx. after 30 min Labwork in the bachelor's project	**You have laboratory work in the project. What role does that play?** - **What is your take away from labwork?** - **What if you did not have labwork?**
ABout the student's own bachelor's project	**Here is your bachelor's project.** - **How did you approach it?** - **What was easy/difficult for you in the project/lab?** Bachelorprojekt **What comments did you receive during the project?** - **What do you think of the comments?** - **How did you use the comments?** - **How could supervision be more useful?** **The literature points to these possible outcomes of laboratory learning. What is particularly relevant for your laboratory work un the bachelor's project?** Laboratory learning outcomes from WP2

Appendix 8 Interview guide teachers bachelor's project

Date: Name:

Subject	**Question.** Materials Notes. Items to get back to (note time of answer)
Part 1 Bachelor's project's aims	**What is the aim of the bachelor's project?** - **Please elaborate from the course description** Course description
Bachelor's project in the programme	**Please describe the purpose of the bachelor's project in the programme** Overview of programme
Before and after the bachelor's project	**What do you expect the students can do prior to the bachelor's project?** - **What about the types of work the project demands?** **What can the students take away from this course?** - **For their master education** - **For their future career** Overview of programme
Part 2 – approx. after 30 min Exercises in the course	**You have laboratory work in the project. What role does that play?** - **What are the students' takeaways of the laboratory work?** - **What if there were no lab work in the project?** - **How do the students approach the bachelor's project?** - **How do the students approach the laboratory work?** - **What is easy/difficult for the students in the bachelor's project**
The litterature	**The literature points to these possible outcomes of laboratory learning. What is particularly relevant for the bachelor's project?** Laboratory learning outcomes from WP2
Supervision and feedback	**How do you conduct supervision?** - **What feedback did the students get throughout?** - **What can the students do with the feedback?** - **How do you think supervision could be improved?**

7 Papers

Paper 1

Agustian, H. Y., Finne, L. T., Jørgensen, J. T., Pedersen, M. I., Christiansen, F. V., Gammelgaard, B., & Nielsen, J. A. (2022). Learning outcomes of university chemistry teaching in laboratories: A systematic review of empirical literature. *Review of Education*, *10*(2), 1–95. https://doi.org/10.1002/rev3.3360

Paper 2

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Teacher Intentions vs Student Perception of Feedback on Laboratory Reports

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Paper 3

Jørgensen, J. T., Malm, R. H., Gammelgaard, B., Christiansen, F. V.

Progression of laboratory learning outcomes in the third year of pharmaceutical education

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Paper I

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SYNTHESIS

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Learning outcomes of university chemistry teaching in laboratories: A systematic review of empirical literature

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Abstract

Laboratory work has been a common element of science courses at university level for around two centuries, but its practice has been criticised by scholars in the field and related stakeholders. Mainly on a rationale of financial justification and educational efficacy, more evidence for learning has been called for. The aims of this systematic review were to characterise learning in the laboratory and substantiate learning outcomes associated with laboratory instructions in university chemistry. Analysis of 355 empirical studies revealed that students develop five clusters of laboratory-related competences pertaining to *experimental competences*, *disciplinary learning*, *higher-order thinking and epistemic learning*, *transversal competences* as well as *affective domain*. These competences were specified into related constructs measured in the studies. Synthesis of published studies led to a substantiated view on multidimensional learning in the laboratory and its implications for research, practice and theory are suggested. Representations of research areas that deserve appraisals and further investigations are also proposed. The video abstract for this article is available at https://video.ku.dk/secret/76185334/73665cb966315601404b793ffc234a77.

KEYWORDS
chemistry education, goals, higher education laboratory work, objectives and outcomes of laboratory instruction

Context and implications

Rationale for this study

To provide comprehensive evidence for learning outcomes associated with laboratory work.

Why the new findings matter

Our research synthesis substantiates a multidimensional view of laboratory learning. There is a large scope for empirical and theoretical development in this complex setting.

Implications for researchers and practitioners

Future research should be directed towards a more comprehensive and rigorous inquiry into student learning that considers a more holistic view. Focus on higher-order competences is needed. Practice wise, laboratory curricula should better accommodate students' learning progression throughout their higher education. Assessment and feedback practices should be revisited.

INTRODUCTION

Experimental work is an indispensable element of post-secondary science curricula. However, with the increasing enrolment in STEM (Science, Technology, Engineering and Mathematics) programmes, individual laboratory work that caters for hundreds of students a year has become a challenge in terms of viability, logistic and resource distribution. Consequently, most of the modern laboratory instruction is often verificatory (also referred to as traditional, expository, or loosely termed 'cookbook'), such that more students can fit in a rotation system comprising several prescribed experiments for them to conduct.

Two of the pioneering reviews of laboratory education are Hofstein and Lunetta (1982, 2003). While these reviews pertain to school science rather than higher education science, some of the basic distinctions and findings are relevant for and have informed the current review. Thus, Hofstein and Lunetta (1982) provide an operational definition of laboratory work, which is also employed in this review. It defines laboratory work as 'contrived learning experiences in which students interact with materials to observe phenomena' (p. 201).

Taken together, the two reviews by Hofstein and Lunetta demonstrate the unrealised potentials of school laboratory work with a widespread failure in turning learning goals of school laboratory instruction into actual learning outcomes for students. They argue that in order to realise the potentials of laboratory instruction, there is a continued need for the examination of goals, and how specific laboratory activities and assessment formats can be designed to support these (Hofstein & Lunetta, 2003, p. 46). The reviews also argue that past research has tended to focus on a narrow conceptualisation of skills, which limited the application of the findings.

In terms of teacher's implementation of the curriculum, they argue that research also failed to substantiate teacher-student interactions in the laboratory, and how these reflected the intended curricula. In the context of undergraduate science education, Bradforth et al. (2015) argue that excellent teachers do so by linking their pedagogy to their own research. Focusing on teachers' teaching practices may substantially contribute to their professional learning, by means of researcher-practitioner collaboration and reflective activities (Ping et al., 2018).

Some of the arguments from research mentioned above have led to curriculum reforms, aimed primarily at improving student learning, including learning in laboratory settings. For instance, in the United Kingdom, *Good Practical Science* was published in 2017, providing a framework for schools to develop science curricula around practical work (Gatsby Foundation, 2017). One of the recommendations in the reform document states that the 'school should have laboratory facilities such that students can carry out extended practical science investigations' (p. 13). The reference to extended investigations can be interpreted as laboratory exercises that require a longer trajectory beyond a single period, presumably with a higher level of inquiry. However, students are yet to benefit from this type of laboratory work, as the report claims that many schools 'are not making full use of [the available laboratory facilities]' (p. 14). When they are, the extent to which students actually learn from laboratory work also needs to be substantiated.

A decade earlier, *America's Lab Report* presented similar findings (The National Academies of Sciences, 2006). At least in the context of school science education, their findings point to the lack of clarity in defining 'the laboratory' and 'laboratory work', which 'make[s] it difficult to reach precise conclusions on the best approaches to laboratory teaching and learning' (p. 2). Informed by research and curriculum reform recommendations, efforts have been made to improve learning in the laboratory by designing new curricula that reflect scientific inquiry, incorporate more investigative elements, authenticity, or some form of problem orientation.

As mentioned, Hofstein and Lunetta's reviews were concerned with school science education. An important article by Reid and Shah (2007) reviews some key studies of university chemistry education, but there is no systematic review of learning in the university teaching laboratories.

In higher science education, especially in physical science courses like chemistry, laboratory work occupies significantly more space in the curriculum, which can amount up to 400 h in an entire undergraduate chemistry degree (American Chemical Society, 2015). Accordingly, the role of laboratory in university chemistry is more structurally integrated within the curriculum (Reid & Shah, 2007). This prominence may indicate higher importance, but scholars have been very critical about assumptions and taken-for-granted practices associated with experimental work in university science (Buck et al., 2008; Hodson, 2005; Reid & Shah, 2007). Recent editorials on learning in the laboratory by Bretz (2019) and Seery (2020) point to the same concern from which we embarked on this major review. Both editorials assert the importance of providing comprehensive evidence for learning in the laboratory, particularly in its pivotal function as a place to do science. While their call for substantiation of learning may be read as a call for additional primary studies, we argue that a major secondary study will provide a timely overview of knowledge about learning from laboratory work. In the decades after the Hofstein and Lunetta (2003) review, digital technology has become pervasive in teaching laboratories both in measurement, data collection and interpretation. Virtual laboratories and simulations are becoming increasingly sophisticated and are used in conjunction with laboratory activities or, occasionally, replacing the laboratory activities altogether. Thus, as Hofstein and Lunetta argue for school laboratory instruction, Bretz and Seery argue for higher chemistry education: There is a strong need for research on goals of laboratory work and evidence of how teaching and learning activities can support student outcomes.

The present review aims to shed light on what empirical research has to say about evidence for learning in the laboratory. We focus on learning outcomes, representing the attained level of curriculum representations (Thijs & van den Akker, 2009). In doing so, we strive to consider coherence between *the intended* (learning goals, perceived roles of laboratory work), *the implemented* (laboratory instructions, pedagogical approaches), and *the attained* curriculum (learning outcomes, assessment results). In the discourse of curriculum development, coherence between these levels is considered paramount to successful teaching and learning (Porter et al., 2011; Voogt & Roblin, 2012), by ensuring that learning goals in the laboratory curricula are translated into appropriate pedagogies in the laboratory, including pre- and post-laboratory activities (Buck et al., 2008). But also, assessment of student learning should reflect the formulation of learning goals and mirror feedback practices in the laboratory. Our focus on learning outcomes is an attempt to trace this coherence back into the learning goals in university laboratories, as published in previous works (Buck et al., 2008; Mack & Towns, 2016), and in response to the aforementioned Bretz and Seery's editorials.

Unlike previous works, the present review also attempts to provide a comprehensive mapping, by incorporating a systematic review methodology. Essentially, we seek to address the following questions:

- How can learning in the laboratory be described and characterised?
- What are the learning outcomes associated with laboratory instruction at university level?

METHODS

Identification: search methods

Two electronic databases—ERIC and Web of Science—were searched using topical keyword searches of entire publications. The combination of ERIC and Web of Science allowed for a comprehensive coverage of peer reviewed English literature on the overall topic of our study. ERIC is widely recognised as the largest full-text database of education-related literature.[1] One possible drawback to use ERIC is the automated nature of ERIC's indexing. This can be offset with the parallel use of a person-curated database such as Web of Science. Deciding not to include more databases of course carries some limitations. Furthermore, other databases may for example catalogue non-English literature, however, it was not feasible for us to cover non-English literature systematically in this study. Other databases may catalogue more general literature that would not be indexed as educational—for example, studies of how persons behave in psychology laboratory research settings. But we were from the beginning focused on the learning potential for students in the educational setting of laboratories.

Search terms and search logic was selected to define essential elements of the object of the review aim. The search string for the Web of Science database search was: (TS = (laboratory OR lab OR laboratories OR "practical work" OR "experimental work") AND TS = (teacher OR student OR education OR learning OR learn OR teach OR teaching)) *AND* LANGUAGE: (English) *AND* DOCUMENT TYPES: (Article OR Book OR Book Chapter) Timespan: All years. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC. The search string for the ERIC database search was: (laboratory OR lab OR laboratories OR “practical work” OR “experimental work”) AND (teacher OR student OR learning OR learn OR teach OR teaching).

Screening: inclusion and exclusion criteria

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow chart of search and screening process for systematic reviews (Moher et al., 2009) acted as a guide for the current study. PRISMA provides an evidence-based minimal list of aspects to report in systematic reviews. Following PRISMA in no way ensures high fidelity, validity and reliability of a study; but as any widely accepted procedure, it makes it easier for readers to audit the decisions made in the review process.

The exclusion and inclusion of publications was a part of the so-called *screening phase* in the PRISMA statement (Moher et al., 2009)—that is, based on screening titles and abstracts. After these steps, in the *eligibility phase*, full-text readings were the basis for quality assessment. Publications were included if they were English language educational peer-reviewed research publications within the STEM disciplines that employed empirical studies to report on student learning outcomes related to chemistry education at the post-secondary level. Only journal papers and book chapters that were peer reviewed and written in English were included. This was instructed in the database searches, and so not a part of the screening per se. As stated above, it was not feasible to cover non-English literature systematically in this review. It is a limitation only to focus on English literature, but we do think that our vast scope in terms of time and area may offset some of the blind spots resulting in the narrow language coverage. Similarly, only focusing on book chapters and journal papers omits the substantial amount of ‘grey literature’ such as conference papers, white papers, government reports and so on. It was important for us to focus only on peer reviewed material to ensure a minimal compliance with research reporting criteria.

While the current review is particularly concerned with chemistry teaching in the university laboratory, we opted to include educational research within the STEM teaching gamut because it was hypothesised that a range of laboratory activities could be contextualised in the teaching of several STEM disciplines. Therefore, the term ‘chemistry’ was not a part of the database search. This strategy allows the authors at a later stage also to consider a comparative review of educational literature on laboratory learning within the different STEM disciplines. This decision is discussed below. Some inclusion criteria had to be refined iteratively within the group of coders who excluded and included publications. In the case of all but one of the inclusion criteria, we calculated the interrater reliability among the individual coders on a subset of the publications. The eventual list of inclusion criteria is presented in Figure 1, while the exclusion criteria are described with the inclusion criteria description in the following.

Regarding *inclusion criterion 1*, we required that the publications had to be on a topic within education research. This meant excluding titles such as ‘Electrocardiographic and blood pressure effects of the ephedra-containing TrimSpa thermogenic herbal compound in healthy volunteers’ (Caron et al., 2006), while retaining titles such as ‘Electrocardiogram interpretation training and competence assessment in emergency medicine residency programs’ (Pines et al., 2004). The coders only excluded a publication if they could rule out that the publication reported on a topic within education research. If the publication was published in an educational research journal, the coders automatically included it in the criterion, even if the title did not suggest it was concerned with educational research (e.g., ‘History of hepatic bile formation: Old problems, new approaches’ [Javitt, 2014]).

Regarding *inclusion criterion 2*, only publications on a topic within the field of STEM education were retained. This excluded titles such as ‘A journey towards self-directed

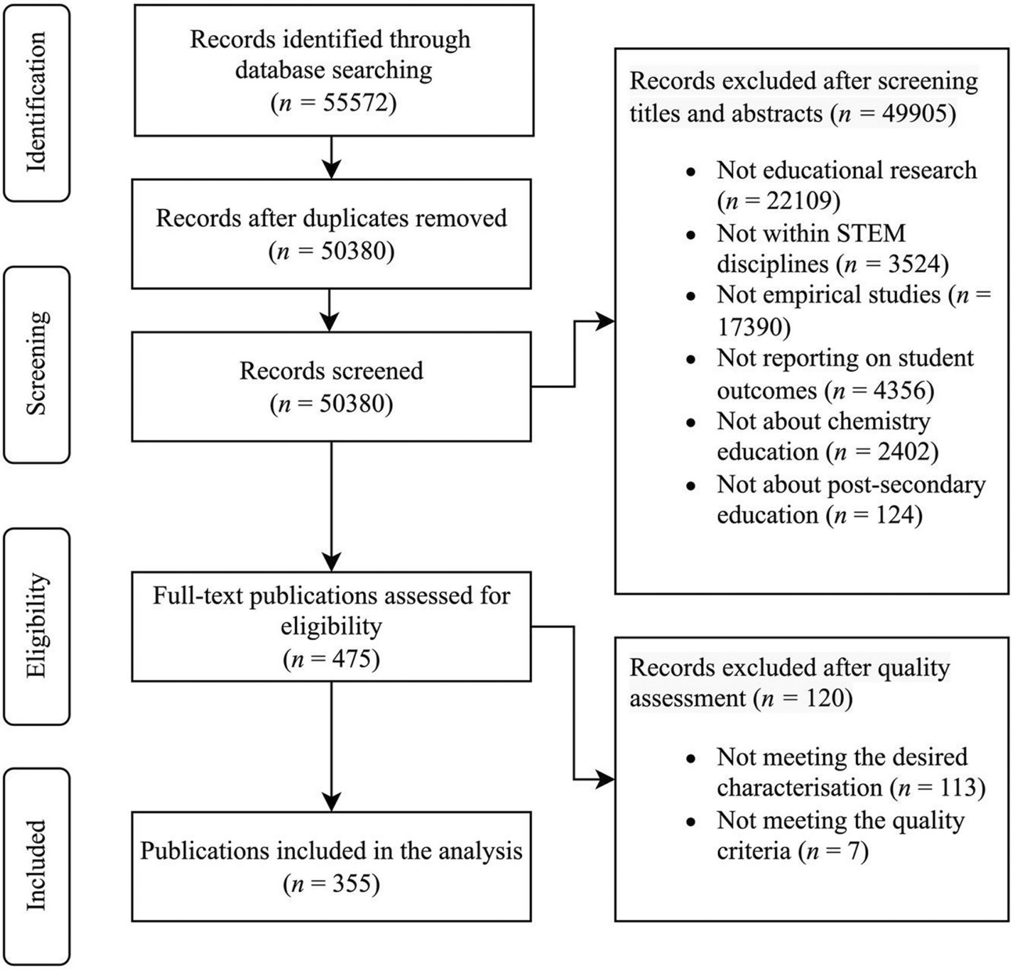

FIGURE 1 PRISMA (preferred reporting items for systematic reviews and meta-analyses) flow diagram of the search and screening process (including exclusion criteria) for the current systematic review (cf. Moher et al., 2009)

writing: A longitudinal study of undergraduate language students writing' (Olivier, 2016). The coders used a wide understanding of what constitutes STEM. Publications concerning areas of a more biological or chemical nature would be included, whereas publications concerning other areas of health care were excluded (e.g., 'The use of peer leadership to teach fundamental nursing skills' [Bensfield et al., 2008]).

Regarding *inclusion criterion 3*, only publications that reported on an empirical study were retained. Thus, literature reviews as well as course descriptions and descriptions of laboratory activities without collection of evaluative data were excluded. This excluded otherwise interesting publications that have informed our work in other ways (e.g., 'The role of laboratory in university chemistry' [Reid & Shah, 2007]). It also excluded detailed descriptions of well-made laboratory activities with little to no mention of empirical assessment, such as 'Peptide mass fingerprinting of egg white proteins' (Alty & LaRiviera, 2016). Course evaluations is a widespread tool for assessment of teaching and learning. In this criterion, articles were excluded if the course evaluation appeared to be the only assessment or data-point and if it appeared to constitute a minor part of the articles (e.g., 'Community-based presentations in the unit OPS laboratory' [Mitchell & Law, 2005]). This is not to say that course evaluations were discounted as empirical data, and articles where it appeared to have a more prominent role were included (e.g., 'Showing the true face of chemistry in a service-learning outreach course' [LaRiviere et al., 2007]).

Regarding *inclusion criterion 4*, only publications that focused on student outcomes were retained. This meant excluding studies that focused, for example, only on teachers/educators. We required that the publication included an investigation of the student outcome, and that this investigation was a primary focal point in the publication. Student outcome was taken to be all cognitive, affective, psychomotor, and epistemic proxies for learning. In order to operationalise this criterion, we aimed to include publications that had a stated aim or a research question about student outcome. But in order to gauge this from the abstract and title we used as a proxy the following coding criterion: In the abstract, the description of the empirical study of the student outcome gives reason for the coder to assume that the publication contains (i) a research question about student outcome, (ii) a sufficient description of research methods and (iii) an appropriate and coherent description of data analysis, regarding student outcome.

Regarding *inclusion criterion 5*, only publications that reported on studies that were explicitly about chemistry education were retained. This was done by searching for "chem" in the worksheet, excluding records that did not contain this element. Thus, the remaining publications containing "biochemistry" were included, but not "schema". Regarding *inclusion criterion 6*, only publications that reported on studies about post-secondary education were retained, excluding papers such as 'Secondary school students' attitudes to practical work in biology, chemistry and physics in England' (Sharpe & Abrahams, 2020), but including papers like 'Helping students understand formal chemical concepts' (Ward & Herron, 1980). We do believe that research on secondary level can inform the didactics and pedagogies in higher education, but we wanted to narrow our focus in this paper.

While it may seem ineffective to first code for the criterion about STEM-education (inclusion criterion 2) and then later code for the criterion about chemistry education (inclusion criterion 5), we wanted to keep open the possibility that we at a later stage can make a comparative review of educational literature on laboratory learning within the different STEM disciplines. Had we included 'chemistry' at the level of database search, we would have to retrace our screening steps up to this step in order to make comparisons between the findings on chemistry education and, for instance, physics education. Each screening step is labour intensive, so not having to retrace steps is preferable.

Eligibility: study selection

Publications identified through the Web of Science database search were exported as BibTeX entries and combined in a *.bib file. Publications identified through the ERIC database search were exported as PubMed nbib entries and imported as entries into an EndNote X9 library using the PubMed (NLM) filter; then the library was exported as a *.bib file. The two *.bib files containing all entries were converted into *.csv files using JabRef version 4 and were made to have uniform column titles and then subsequently combined in Excel version 16. Each entry was given a unique identifier on the format AXXXXXX. Many entries stemming from the ERIC database, were not retained in this process. Therefore a python script was made which retrieved the missing abstracts on the basis of the ERIC Accession Numbers of the publications.

This information (Accession Number and Abstract) was saved in a spreadsheet file and the data were imported into the master *.xlsx file containing all publications using Excel's VLOOKUP function using the Accession Number as the lookup value. Duplicate entries in master *.xlsx file were identified; first by using the conditional formatting in Excel to highlight cells (containing the title of a publication) with duplicate values; second, additional duplicates were found manually by going through entries with titles that contain special characters (these titles were often not found through the conditional formatting); third, in a few cases duplicate entries were identified in the screening phase.

For inclusion criteria 1–4 and 6, the exclusion procedure in the screening phase consisted of stepwise iterations of coding attempts with interrater reliability checks. In all cases, the process was as follows: (1) The group of coders discussed how a given criteria could be operationalised; this included discussing examples and finalising the formulation of the inclusion criteria. (2) Then the coders independently coded the same subset of randomly selected publications according to the criteria. (3) After all coders finished their coding, the data were compiled in Excel and interrater reliability score (Fleiss's kappa) was calculated. (4a) If the interrater reliability score was at least moderate (i.e., Fleiss's kappa above 0.41 (Altman, 1990), all publications to be coded in this step (including those used for interrater reliability analysis) were randomly and evenly distributed among the coders. (4b) If the interrater reliability was not satisfactory, the procedure restarted at point (1) above with the change in iteration that examples of disagreements in coding were discussed. Inclusion criterion 5 (explicitly chemistry education) was so closely tied to data in the database entries that no interrater reliability tests were needed. The interrater reliability scores for inclusion criteria 1–4 and 6 are presented in Table 1.

Inclusion criteria 4 and 6 were coded in *Abstrackr* (Wallace et al., 2012) using their machine learning tool, that sorted the articles as 'most likely to be relevant'. The coders preferred the tool, which had good search functions to highlight in green colour words that were indicators for inclusion, such as 'Student outcome', 'Students', 'Undergrad', and highlight in red colour words that were indicators for exclusion such as 'K-12' or 'high school'. At the end of the coding process, 1663 publications previously undecided because of doubts about whether to include or exclude were coded in a similar process to the main process. At the end of this screening process 475 publications remained.

Eligibility and assessment

Referring to the flowchart of systematic review as recommended by PRISMA (see Figure 1), the selected studies were subsequently evaluated in a two-step procedure. The first step of this procedure was characterisation of each study according to the following elements:

a. aims of the study, as formulated by the authors;
b. theoretical or pedagogical frameworks, which may refer to theories underlying the conceptualisation of learning or pedagogical approaches used in the study;
c. overarching methodology that guides the investigation;
d. methods pertaining to the nature of data collection (quantitative, qualitative or mixed methods) and the strategies thereof;

TABLE 1 Interrater reliability scores for inclusion criteria 1–4 and 6

Inclusion criteria	n_{coders}	n_{papers}	κ	95% CI	p
1. Including only educational research	3	101	0.65	[0.53, 0.76]	<0.0001
2. Including only studies concerning science, technology, engineering and/or mathematics education	3	197	0.95	[0.87, 1.00]	<0.0001
3. Including only empirical studies	3	268	0.79	[0.72, 0.86]	<0.0001
4. Including only studies with focus on student outcomes	4	100	0.60	[0.49, 0.72]	<0.0001
5. Including only studies related to post-secondary education	3	29	0.88	[0.67, 0.1.00]	<0.0001

e. research instruments to collect data, with some specification whenever available;
f. number of participants, with some specifications if there are control and treatment groups;
g. intervention, if available, with a brief specification; and
h. results, as a list of main findings, including negative findings if reported by the authors.

Thorough discussions between the reviewers consolidated the interpretation of the elements and corresponding findings, in order to warrant reliability. During this characterisation, several studies were excluded as they did not fulfil the inclusion criteria in the screening process—for example, the study was not conducted at post-secondary level, not related to chemistry laboratory, not pertaining to student learning outcomes, not an empirical study, and there was no access to the full text. The exclusion of these studies brought the number of selected articles down to 362.

The second step of the procedure was critical appraisal of the quality of each study in which the following aspects were considered (Alderson, 2016; Zawacki-Richter et al., 2020):

- quality of the study design
- quality of the results of the study
- relevance and applicability in the context of our review questions.

The main purpose of this step was to identify the most important studies and interesting findings for our following analysis. In this procedure, each aspect was rated on a scale from 1 to 3, whereby 3 was the highest rate. The quality assessment of the study design (elements a–g in the list above) was based on proxies such as a formulation of research questions or hypotheses as well as an explicit theoretical/pedagogical framework. It was also specified whether the methodology and methods were appropriate to address the aims of the study. This information could also indicate to what extent the study was conducted in a rigorous fashion. The following questions guided our analysis for quantitative studies: Is the sampling representative of the population? Is there a control group? Is the intervention relevant to the aims? For qualitative studies, the guiding questions were: Are the instruments appropriate to address the aims? Are the numbers of participants observed/interviewed adequate?

To address the quality of the results of the studies, we focused on the aims and results of the study and if the results were triangulated to support the claims made by the authors. But most importantly, we were particularly interested in the competences related to learning in the laboratory that could be identified from the study. We were looking for constructs related to learning that were explicitly mentioned by the authors, such as problem solving, critical thinking, understanding of the nature of science, and the like. We use the term ‘competence’ instead of ‘competency’ on a rationale that the nuanced difference in defining both terms from a research perspective points to the former being more specific in scope than the latter, contrary to a generalist perspective, as argued elsewhere (Agustian, 2022).

Lastly, we assessed the extent to which each study was relevant for our research questions on the laboratory-related competences and the extent to which the findings were applicable to other contexts, such as pre-university science context or other science disciplines that may offer laboratory courses. At the end of the second part of the critical appraisal, 355 studies remained for subsequent analysis and synthesis.

Data extraction and analysis

The remaining studies were coded with a focus on key competences related to laboratory instructions. In cases where authors did not report their findings in terms of competences or complex skills, we also looked at all proxies of student learning outcomes, including constructs pertaining to the affective or conative domains.

To capture every substantiated outcome, an inductive, bottom-up approach was applied. This process resulted in 424 descriptors ranging from 'analytical skills' to 'environmental literacy'. These were combined, restructured and recombined in several steps to become 117 descriptors, 85 descriptors and eventually 32 codes, ranging from 'experimental design' to 'understanding of the nature of science'.

Using these new 32 codes, all publications were coded by looking primarily at the results sections. Whenever necessary, other sections such as discussion and methods sections were also consulted for clarification. This process led to five large themes, experimental competences, disciplinary learning, higher-order thinking skills and epistemic learning, transversal competences, and affective outcomes. Each theme was associated with more than 100 articles, with overlaps between them. Multiple themes could be present in a single publication if it reported more than one aspect of student learning.

The writing of the entire analysis was based on the 32 codes and key information from the critical appraisal (quality and relevance). Corresponding full texts were continually consulted for clarification and specification. During the writing process and the analysis, the codes were reduced to 22.

RESULTS

Summary of included studies

The aggregate of included studies in our systematic review covers publications from 1972 to 2019, as shown in Figure 2. The oldest record is Uricheck (1972), on using interaction analysis as a tool to identify patterns of laboratory instruction which differentiate effective and ineffective teaching. The study demonstrates that students learn most when they are allowed some freedom to discover and clarify the learning goals for themselves. As such, they grow independent of the teacher, by developing the habit of thinking through a problem on their own initiative. Five decades have elapsed since this early work and some of the issues investigated are still relevant. As Figure 2 indicates, 2016 was the year with most publications with 49 studies identified. These cover topics as, for instance, assessment of authentic research experience (Evans et al., 2016; Harsh, 2016) or investigation into the role of physical environment in the learning process from a perspective of basic psychological needs (Sjöblom et al., 2016). Several published studies from this year also provide evidence for the positive impact of inquiry laboratory on student learning (e.g., Brown, 2016; Goodey & Talgar, 2016; Ural, 2016).

The included studies were published in a wide range of journals (Figure 3), from subject-specific journals in chemistry education such as *Chemistry Education Research and Practice* and *Biochemistry and Molecular Biology Education* to those with broader scope in science and engineering such as *International Journal of Science Education* and *Journal of Research in Science Teaching*. In terms of frequency, *Journal of Chemical Education* is by far the most popular medium with 105 publications, followed by *Chemistry Education Research and Practice* with 50 publications.

A large group of studies (more than 70) were conducted as an evaluation study of a laboratory course or an intervention. Around 50 studies described measurements of the difference in students' learning outcomes between participating students and a control group. It is also noteworthy that qualitative research methods such as phenomenology, ethnography, and grounded theory are also represented. The majority of studies were quantitative,

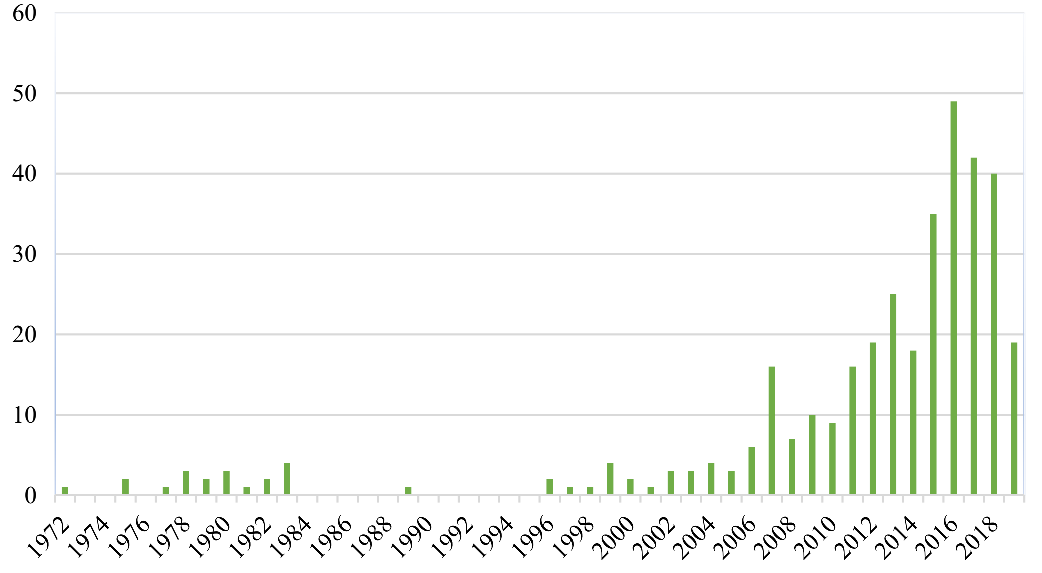

FIGURE 2 Number of publications per year

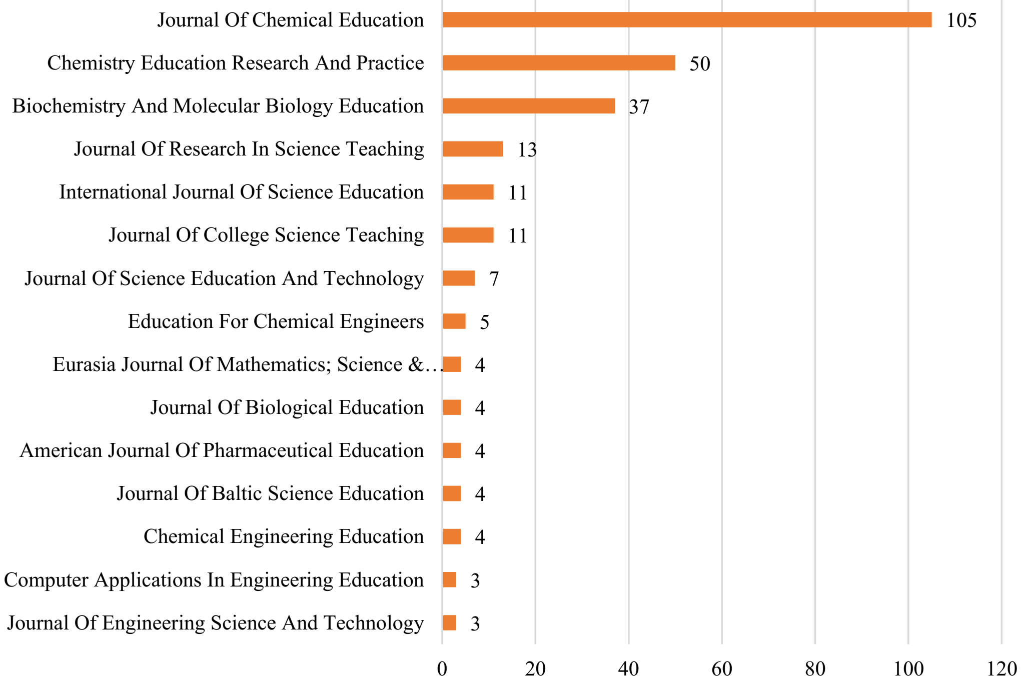

FIGURE 3 Frequency of publications (3 and more) in science education journals

as shown in Figure 4, mostly using questionnaires to collect data. As a whole, more than 110,000 students participated in the 355 studies we have reviewed.

The characterisation of the empirical studies in our review demonstrates that about three-fourths (263 out of 355) of the published studies have been conducted with a theoretical and/or pedagogical framework in mind. The extent to which the framework is stated and elaborated varies, but these studies have fulfilled the basic requirements for educational research, as widely established in science (and in particular, chemistry) education research (Abell & Lederman, 2007; Bunce & Cole, 2008, 2014). It is beyond the scope of this review to specify whether the theories or pedagogical frameworks espoused are the best choice for the intended research focus, but at the present level of analysis, the majority of the studies meet the quality criteria, from a viewpoint of this particular characteristic. The remaining 92 articles could benefit from a theoretical/pedagogical framework, in order to ensure that other elements of inquiry are illuminated by the recent development in the corresponding area of scholarship. For instance, the framework can and should be used to formulate 'theory-based [research] questions' (Bunce, 2008).

On that note, explicit formulation of research questions was missing in 222 studies (62.5%). Although these studies were still conducted with aims in mind (and stated in the article), they may benefit from an appropriate and explicit formulation of research questions, as it will drive the overall study and determine the course of direction the entire investigation is set to take, as argued by Bunce and Cole in their work on chemistry education research methodology (Bunce & Cole, 2008, 2014). Interestingly, our data show that most of these studies (170 studies, or about 75%) were published in the last decade (since 2010 up to the end of the search process in 2019). This signifies a room for improvement in the framing of the research problems, which could benefit from a clearer positioning with regards to the extant literature. Accordingly, we have identified that 181 studies did not incorporate triangulation of measurements. For instance, Hall et al. (2018) use the Course-based Undergraduate Research Experience (CURE) survey as the sole instrument to measure learning outcomes of interdisciplinary, inquiry-based medicinal chemistry laboratory.

The synthesis of 355 empirical studies on student learning outcomes associated with laboratory instructions is summarised in Table 2. As mentioned previously, five distinctive clusters have been identified, namely experimental competences, disciplinary learning, higher-order thinking skills and epistemic learning, transversal competences, and affective outcomes. Each of these clusters were further specified into related constructs that are mostly operationalised as research parameters measured in the studies.

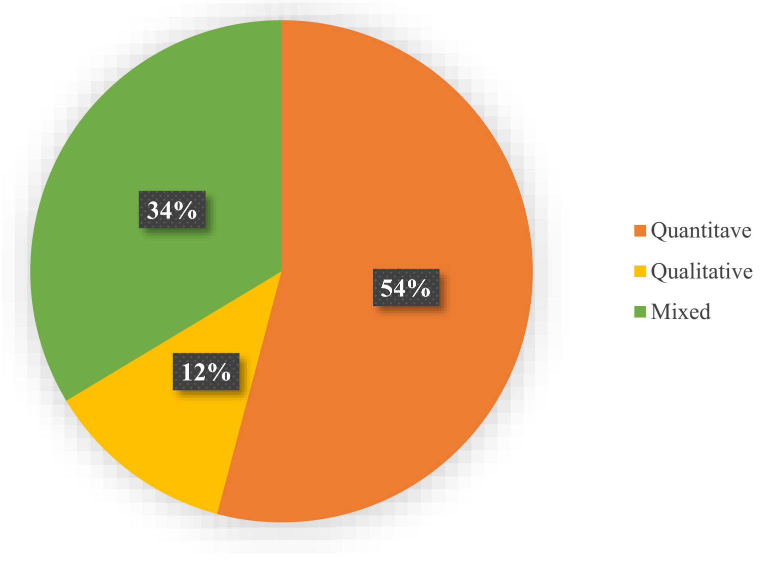

FIGURE 4 Data collection methods used in the studies

TABLE 2 Student learning outcomes associated with laboratory instructions

Clusters of learning outcomes	Substantiated constructs
Experimental competences	• Practical skills • Conducting experiments • Data analysis and interpretation • Experiment design
Disciplinary learning	• Conceptual understanding • Theory-practice connection • Academic achievement and mastery
Higher-order thinking skills and epistemic learning	• Problem solving • Critical thinking • Argumentation • Metacognition • Reasoning and reflection • Epistemic learning
Transversal competences	• Collaboration • Communication (oral and written)
Affective domain	• Expectations • Interest, enjoyment, and engagement • Self-efficacy • Laboratory anxiety • Motivation • Self-regulation • Professional identity

In the following sections, we will describe their key aims, interventions and results. Studies which are deemed highly relevant, rigorous, representable or interesting are described in greater detail and additional studies are referenced throughout to give a perspective on the depth and breadth of the corpus.

Experimental competences

In our review, 136 articles report student outcome with regards to the procedural process of the laboratory experiments, either by performing laboratory techniques, handling instruments, analysis and interpretation of data, or designing experiments. These constructs are synthesised and described as experimental competences, which we define as students' ability to plan, design and carry out a scientific inquiry efficiently and safely. Mastering this cluster of constructs requires that students understand the purpose of the investigation, are able to carry out relevant manipulative skills, analyse and interpret data, and understand criteria and arguments for evaluation of the quality of empirical data.

Practical skills

The act of doing chemistry and working in the laboratory is an important part of students' personal experience and development of their procedural knowledge of chemistry and experimental competences. Seung, Choi and Pestel (2016) examine 100 students' written argumentation for experimental procedures in laboratory reports from a process-oriented laboratory curriculum. In the process-oriented curriculum, experiments were progressing from training observation, over collecting data, synthesising findings, and employing technology to gain experimental claims. One of their major findings was that students' personal experience in practising chemical procedures helped the students to achieve epistemic knowledge.

The repetitive nature and ample room for practice in the laboratory are important for gaining valuable experiences and confidence in performing experimental work. This was demonstrated in a study of Warner et al. (2016) reporting that students' technical skills and perceived technical competences are correlated to their exposure to practical work in the laboratory. They surveyed the students' perceived technical competence (n = 876) compared to their exposure to instruments in the laboratory over 5 years and demonstrated that students scored themselves higher with more hands-on and direct exposure to the instruments. A similar increase in student's performance and confidence was reported by Erdmann and March (2014) when students were completing an assignment to make a video of performing a laboratory technique. The students (233 participating, 509 in total) increased their confidence and final grade significantly. Other examples of experimental design studies with control groups showing improvements in students' experimental skills have been reported (Gallion, Samide, & Wilson, 2015; Hass, 2000).

Of the 136 studies, 19 document that pre-laboratory activities such as videos, mental practice or synopses of the laboratory session improve students' practical skills (Box et al., 2017; Cavin & Lagowski, 1978; Jordan et al., 2016; Seery et al., 2019). For example, Beasley and Heikkinen (1983), compared practical preparation with mental preparation for experiments. In the experimental research study, students' performance (360 participants with 96 in control group) of specific practical skills as using the balance or a pipette were compared when one group practised the procedure in the laboratory, whereas another group practised mentally studying one of two pictorial illustrations with written instructions. The outcome was that practice helped the students perform the experimental tasks, regardless of whether it was the mental practice or the actual laboratory performance. In another study on pre-laboratory activities from 2001, Rollnick et al. performed an action research study with two iterations by changing pre-laboratory activity from questions to synopsis writing. Both studies are examples of the importance of engaging in meaningful pre-laboratory activities. Students' learning outcome is poorer when engaging in laboratory work without proper preparation, which is prevalent in our review findings (Box et al., 2017; Cavin & Lagowski, 1978; Darby-White, Wicker, & Diack, 2019; Jordan et al., 2016; Veiga et al., 2019).

Conducting experiments

Inquiry- or problem-based teaching approaches seem to be particularly effective in developing students' experimental skills. In our review, 48 of the 136 articles report pedagogical or theoretical frameworks that are problem-based or inquiry-driven. Essentially, these studies substantiate that inquiry-based laboratory activities increase the quality of students' experimental work. An example is a quasi-experimental design study by Goodey and Talgar (2016), where they compare inquiry-based laboratory exercises with a cookbook approach (103 students in total, 36 in treatment group) and report that students doing the inquiry-based experiments performed significantly better in the Experimental Design Ability Test. Furthermore, inquiry-based laboratories improved students' independence and experimental competences—for example, as reported by Silva and Galembeck (2017), that increasing autonomy in the laboratory exercises stimulated students' experimental planning skills; this was assessed through the quality of 180 students' laboratory reports. Likewise, the discourse in inquiry-based laboratory activities has been documented to change from mere expository guidance to procedural knowledge reflections. An example of this is a study by Xu and Talanquer (2013a, 2013b) who demonstrated that inquiry settings in the laboratory prompted students to pose ideas, test hypotheses, and explore more compared to non-inquiry settings through observation of 20 students. Similar findings were also reported by Krystyniak and Heikkinen (2007).

Awareness of safety in the laboratory is very crucial to student learning processes and outcomes. This may be associated with their psychomotor domain of learning (Flaherty et al., 2017), and we argue that this is a part of experimental competences. In our review, attention to safety issues as a part of learning outcomes has also been reported by, among others, Inguva et al. (2018) in their design and development of a chemical engineering course and Walters, Lawrence and Jalsa (2017), focusing on laboratory safety awareness. However, the latter found that although awareness among students of hazard identification, emergency response and waste disposal was high, they did not necessarily read safety documents. This was found to be a predictor of laboratory accidents, which suggests that safety awareness should be incorporated into laboratory curricula.

Authentic research experiences such as Course-based Undergraduate Research Experiences (CURE) or Undergraduate Research Experiences (URE) seem to positively influence the development of students' practical skills and experimental competence (Chase et al., 2017; Nadelson, Warner, & Brown, 2015; Williams & Reddish, 2018). In a large-scale mixed-methods study with 116 interviewees and 4285 survey respondents, Harsh et al. (2011) reported that students considered 'exposure to genuine, authentic research experience' most important (49%), followed by 'building confidence to conduct research' (16%), and 'development of experimental skills' (15%). Thus, it is evident from our review that such experiences increase students' understanding of the process of research and what scientists actually do. In another study on 33 students in a CURE setting, the outcome, based on a survey and interviews, was an improved understanding of the research process and readiness for future research (Williams & Reddish, 2018).

Data analysis and interpretation

Data analysis and interpretation are crucial in university science. In this regard, 26 articles report student outcomes of laboratory learning related to data-analysis and interpretation (Díaz-Vázquez et al., 2012; Hall et al., 2018; Iler et al., 2012; Johanson & Watt, 2015; Kappler, Rowland, & Pedwell, 2017; Kowalski, Hoops, & Johnson, 2016). Two studies demonstrate that an effective way of developing these skills is by allowing students to encounter real and raw data, instead of curated or computer-simulated data (Hill & Nicholson, 2017; Witherow & Carson, 2011).

Experiment design

An important part of being a scientist is the ability to design an experiment. Twenty-one studies in our review provide evidence that students learn some form of experiment design from the laboratory experiences (Alneyadi, Shah, & Ashraf, 2019; Cacciatore & Sevian, 2009; Turner, Jr. & Hoffman, 2018; Winkelmann et al., 2017). In a project-based learning setting, where students followed a year-long course, where they in groups explored a new, undescribed protein through five research phases, they improved their ability to design experiments (Li et al., 2019). Third-party assessment scores from 0–10 assessed the improvement and the involved students scored at least one point more compared to a control group at the same level not participating in the same learning setting.

The overall impression of the literature is that evidence for describing experimental design as a learning outcome of laboratory courses is not very strong. But at least five studies suggested a specific method, template or structure to scaffold the students' understanding of experimental design that increased their designing skills (Anwar, Senam, & Laksono, 2018a; Arias, Lazo, & Cañas, 2014; Coleman, Lam, & Soowal, 2015; Goodey & Talgar, 2016; Willoughby, Logothetis, & Frey, 2016).

Disciplinary learning

More than 190 of the articles in this review focus on either conceptual understanding, theory-practice connection, academic achievement, or students' mastery of a discipline. These constructs include learning outcomes such as theoretical or curricular knowledge, understanding of the connection between the experiment and the underlying theory, higher grades or other improvement in assessment, and progression in their higher education. For this review, these articles are labelled as investigations on various aspects of *disciplinary learning*.

Conceptual understanding

Conceptual understanding in this context is defined as understanding the underlying accepted theories and methods in the experiment. Content-based assessment is the most common approach to measuring student learning in the laboratory, as reflected in research questions exploring the extent to which students 'learned more' as a result of an intervention. Those studies are often based on course evaluations, which is generally considered somewhat weaker evidence, but not without merit as it can be very close to the actual context, and in some cases, considerable rigour is applied in the evaluation. About a third of the reviewed studies mention conceptual understanding as a central student outcome from the laboratory work.

Implementations of a more open-ended, investigative and inquiry nature of laboratory experiences have shown to increase students' conceptual knowledge. For instance, Díaz-Vázquez et al. (2012) conducted an intervention study with 400 students by introducing interdisciplinary experiments and student-driven research projects. Students learned concepts better when the laboratory teaching was investigative, with peer-review and cooperative learning. Likewise, Iler et al. (2012) developed and implemented guided inquiry laboratories in a second semester general chemistry course with 50–60 students. In this setup, students were challenged to rediscover basic theoretical principles by looking for patterns in data and testing their own explanations. Their course evaluation showed that students improved their ability to explain and correct their own misconceptions. In another course evaluation study based on interviews and pre- and post-tests, Weinlander, Hall, and de Stasio (2010) assessed two open-ended laboratory investigations and concluded that students could learn abstract concepts when the teaching incorporates real-life applications.

The benefit of problem-based learning and inquiry-driven experiments in development of conceptual understanding is supported by the work of Domin (2007) who used questionnaires and interviews to compare the learning experiences of 17 students in problem-based learning and traditional expository approaches to laboratory experiments. The findings indicate that problem-based learning approaches led to students' conceptual development *during* the experiment, while the conceptual development that arose from the expository approach occurred *after* the experimental activities. From other studies, it appears that students' conceptual understanding *during* the laboratory activity can be supported through various scaffolding interventions such as concept reinforcement (Pierce & Pierce, 2007), the use of analogies (Avargil et al., 2015), problem-based learning (Günter et al., 2017), or guided-inquiry experiment demonstration sessions (McKee et al., 2007).

Kiste et al. (2017) investigated the implementation of four integrated lecture/laboratory (studio) classrooms for engineering students taking general chemistry. Students' work in these studios alternated between laboratory work, group discussions, problem solving, lectures, computer simulations and assessment. The study was theoretically and methodologically rigorous, investigating 684 students split in treatment and control groups. The data were triangulated by combining content knowledge in pre- and post-tests, learning attitude surveys and students' course evaluations. They found that students' content knowledge, measured at final exams, improved significantly compared to traditional teaching. Taken together, these studies tell us that interventions using active, open-ended, investigative, inquiry-based, or similar teaching can lead to an increase in conceptual understanding gained from a laboratory course.

Students' prior knowledge can determine the success of their preparation for a laboratory activity, as confirmed with an action research study by Rollnick et al. (2001) and with a detailed mixed-methods approach by Winberg and Berg (2007). Furthermore, by interviewing six students three times during a semester, Emenike, Danielson and Bretz (2011) documented that students' prior knowledge has effects on how they experience and narrate their conceptual learning.

A very important finding is that conceptual discussions should accompany laboratory work, for students to reflect and refine their conceptions. By observing and interviewing 13 students, Galloway and Bretz (2016) demonstrated that without explicit conceptual discussion activities, students may develop psychomotor skills, but not cognitive skills in the laboratory. The students they followed typically held off on conceptual reflections until writing of a report, and the first time students reflected on the conceptual parts of the laboratory activities was often in the research interview. These findings resonate with the experimental study of Saribas et al. (2013), which substantiates that including metacognition tasks in laboratory work (e.g., discussing design and implications of experiment) led to better conceptual understanding. Evidence based on the collection and analysis of 36 laboratory reports showed that higher levels of inquiry resulted in a higher proportion of metacognitive questions from students, but that there was no correlation between the level of inquiry and student reflection on chemical concepts (Xu & Talanquer, 2013a).

Some studies report on the use of IT for scaffolding conceptual learning. Koretsky et al. (2008) recommend virtual laboratories as complementary to physical laboratories, and interestingly found that a virtual laboratory may be more efficient for learning concepts than physical laboratories. This recommendation was based on development and implementation of a virtual laboratory, which they assessed in an experimental setup using a think-aloud data collection method with 119 students in 46 groups. However, this finding was only based on surveys at the end of the course. Others find no significant difference between the two types of learning settings (Carvalho-Knighton & Keen-Rocha, 2007; Dalgarno et al., 2009). Finally, one study showed that the use of interactive videos did not enable students to overcome higher-level conceptual difficulties (Granjo & Rasteiro, 2018).

Theory-practice connection

Understanding the practices and processes of laboratory work can lead to a better understanding of relevant concepts and theory (Seung et al., 2016). One of the most common justifications for laboratory teaching is the theory-practice connection, and more than 10 studies have focused on students' ability to connect theory to practice and the impact of different laboratory activities on this ability. Student appreciation of theory-practice connection was confirmed by Borrmann (2008) who showed that students appreciated linkages between theory and observations and valued laboratory education more if it is highly connected to theory from lectures. This study included more than 370 students and accounted for biases in student opinions. In two studies, authors developed local teaching practices, and both emphasise the link between theory and practice. Chaytor, Al Mughalaq and Butler (2017) found that use of pre-laboratory videos facilitated students' learning of the concepts presented in an experiment (gauged with post-laboratory surveys). Warner, Brown and Shadle (2016) reported that students acquire more knowledge of instrumentation, when they spend laboratory time producing their own data as opposed to merely learning indirectly about the data collection (gauged with surveys and test scores).

In contrast, there are examples of rigorous studies which report negative or neutral findings of the theory-practice connection, all because the primary foci of the students or the interventions were elsewhere. In one pre-test post-test control group study, a new learning situation was assessed inferior to the old one, and authors suspect that an upcoming exam interfered with their data collection (Liang & Gabel, 2005). In a large project converting all laboratory teaching in the entire study programme to context-based inquiry teaching, the researcher investigated the students' perceived skills development through a survey containing closed as well as open questions. The result was an increased focus on practical and transferable skills, but focus on theoretical understanding did not change (George-Williams, Ziebell, et al., 2018).

Academic achievement and mastery

More than 50 studies in our review investigated students' academic achievement by metrics as depicted in grades or scores in final exams, tests or quizzes. Academic achievement is of course tightly related to conceptual development, but in contrast to the studies reviewed in the previous section, the studies reviewed in this section predominantly foreground academic metrics about the attainment of intended learning outcomes more broadly and use changes in those metrics to make conclusions about the efficacy of specific approaches or conditions.

Grading is the simplest and most common instrument for measuring achievement, and students place high importance on grades as a measure of their achievements in laboratory course work. This was the result of a survey among students about their goals for laboratory work and thorough analysis of more than 600 responses (Santos-Díaz et al., 2019). Similar strong evidence for the importance of grades as an extrinsic motivational factor was found by Mazlo et al. (2002) in their experimental setup where students ($n = 400$) were better prepared for the laboratory activities when their pre-laboratory quiz scores affected their grades. The importance and the accessibility of grades led to many studies using grades and final exams as a measure of outcome, often in combination with other measures (Ferrer-Vinent et al., 2015; Islim & Cagiltay, 2016; Small & Morton, 1983).

Various interventions have been found to successfully improve students' academic achievement, such as guided inquiry (Akkuzu & Uyulgan, 2017; Ural, 2016), cooperative learning (Saleh, 2011), and context- and problem-based learning (Baran & Sozbilir, 2018). As additional examples, academic achievement improved in studies, where they exposed students to a variety of interventions, such as an authentic performance project (Wilson & Wilson, 2017), use of a laboratory manual that promotes visual information processing (Dechsri et al., 1997) and use of concept maps (Ghani et al., 2017). Also, an entirely redesigned course that combined contextual, collaborative and inquiry-based learning in the laboratory and sought to give students a sense of ownership of their education, had a positive impact on academic achievement (e.g., Pezzementi & Johnson, 2002).

It can be beneficial to develop laboratory teaching that includes both a physical and a virtual part. This may manifest in big setups with live and virtual laboratories (Goudsouzian et al., 2018; Johnston et al., 2014). Also, at least six studies show that multimedia, video or online interactive preparation resources can positively influence student performance (Chaytor et al., 2017; Nadelson et al., 2015; Stieff et al., 2018; Veiga et al., 2019; Whittle & Bickerdike, 2015), which corresponds well with the finding that delegating some work from post-laboratory to pre-laboratory can improve performance at the final exam (Pogačnik & Cigić, 2006). In this study, the authors changed a course, conducted questionnaires, interviews, observations and collected exam scores from more than 200 students pre- and post-intervention. Another important finding is that laboratory teaching in combination with lectures leads to better academic achievement compared to lectures alone, as found by Matz et al. (2012) and Rowe et al. (2018) when 386 students responded to their survey about courses with or without laboratory components.

So far, we have focused on the evidence in the literature on students' content learning. In addition to content learning and performance (as reflected in grades and scores), at least 19 studies investigate more complex types of disciplinary learning. An overarching interpretation of these studies as a body of research is how students develop as they get closer to mastering a discipline.

For students to master the discipline of scientific laboratory work, Dillner et al. (2011) restructured their laboratory curriculum into integrated laboratories, rather than division in traditional chemical sub-disciplines and found through course evaluations and focus group interviews, that integration facilitated students' ability to work on research-like projects. When Harsh (2016) developed the instrument Performance Assessment of Undergraduate Research Experiences (PURE), it was found that mastering a discipline entails that students develop both laboratory skills and scientific thinking skills. Similarly, Szteinberg and Weaver (2013) introduced research experiences early in the laboratory course and found that mastering a discipline entails improvement in an array of learning outcomes. They did a three-year longitudinal study where they surveyed more than 500 students and interviewed 23 students to track students' perception of laboratory courses.

When students do work that resembles the scientific process, with self-design, problem-solving and creativity, it strengthens their independence and growth as a scientist (Gao, 2015). In a large mixed-methods longitudinal study with 116 interviewed individuals and 4300 survey respondents, Harsh, Maltese and Tai (2011) found that exposure to Undergraduate Research Experiences (URE) was highly valued by students. This underscores the point that feeling competent in the laboratory and being able to work independently leads to a positive view of chemistry as concluded by Lyall (2010) after introducing independent work and a less organised environment in a course. We will return to these last examples also in the section on affective outcomes below.

Higher-order thinking skills and epistemic learning

The selected empirical research literature in our review demonstrates that university students learn higher-order thinking skills through laboratory work (Díaz-Vázquez et al., 2012; Krystyniak & Heikkinen, 2007; Oliver-Hoyo et al., 2004). One of these studies was dedicated to investigating the use of an inquiry-based laboratory to foster higher-order thinking skills in particular (Madhuri et al., 2012). Higher-order cognition refers to a host of critical, systemic, creative and evaluative cognitive processes that lend themselves to more complex tasks such as problem solving and critical thinking. The concept is often compared to lower-order cognition, which refers to manual or algorithmic manipulation of cognitive process such as memorisation and rote learning. In our review, the following constructs have been substantiated, namely problem solving, critical thinking, argumentation, metacognition, reasoning and reflection, and epistemic learning.

Problem solving

According to OECD (2004), problem-solving competence refers to students' capacities to identify a problem and its constraints, present possible alternatives to solution, select solution strategies to solve the problem, reflect on the solutions, and communicate the results. In our review, at least 14 studies found that laboratory exercise facilitates the acquisition of problem-solving competence (Amante et al., 2011; Hill et al., 2019; Li et al., 2019). Some of these findings also suggest an association between problem-solving competence acquisition with undergraduate research experience (Burt, 2017; Shadle et al., 2012) and problem-based laboratory curriculum (Gürses et al., 2007; Lanigan, 2008; Shultz & Zemke, 2019). Analyses of student responses to surveys and interviews from these studies indicate that problem-solving competence acquisition involves an integration of many types of knowledge and necessitates self-regulation of learning.

Evidence from research shows that certain types of laboratory curriculum and pedagogical approaches such as problem-based and industrially situated laboratories (Koretsky et al., 2011; Zoller & Pushkin, 2007) could help students think at higher cognitive levels by allowing them to work on authentic experimental tasks, even in a virtual setting. These studies provide recent evidence of the effect of problem-based laboratory instruction on student learning, in comparison to other non-laboratory instructional contexts such as lectures and classroom demonstrations. Accordingly, other studies conducted by Díaz-Vázquez et al. (2012) and Kaberman and Dori (2009) are particularly interesting, as they used longitudinal case studies and experimental design methodology involving more than 1000 students, with appropriate triangulation of data analysis and interpretation. They found that student learning outcomes pertaining to higher-order thinking skills also manifested as an increase in critical thinking, question posing of a more substantial and theoretical nature, and sense-making of 3D molecular models.

Critical thinking

Critical thinking has been lauded as one of the most important goals of higher education that can benefit students in their personal and professional life beyond university. Various attempts have been made to define critical thinking, among others, by categorising the construct into skills and disposition (Huber & Kuncel, 2016). Others, like Moon (2007), strive to synthesise how learners, teachers and laypersons perceive what it means. In our review, 15 studies have found that laboratory instruction led to critical thinking (Chase et al., 2017; Knutson et al., 2010; Vitek et al., 2014). Chase et al. (2017) examined 86 students taking a course-based authentic research experience and measured their critical thinking using the Critical-thinking Assessment Test (CAT). Although they used a small sample and the study lacked a control group, they found that students' critical thinking improved upon taking such a laboratory course. As a comparison, Vitek et al. (2014) developed a grading rubric to measure critical thinking of 11 students enrolled in clinical chemistry. They, too, reported learning gains in this higher-order cognitive skill. Both publications properly described limitations of their study. However, from a viewpoint of research synthesis, there is a lack of clear definition of what the construct 'critical thinking' means. In Chase et al.'s study above, they define the construct in terms of other constructs that we also synthesise in this review, that is, creative thinking, problem solving, data interpretation and analysis, and communication. In comparison, Stephenson and Sadler-McKnight (2016) define it as self-regulatory judgement that is based on evaluation of evidence, context and methodology. In most of the other that reported critical thinking as a learning outcome, the construct was not defined. Considering the widely popular use of the construct, it is relevant to clarify what it means in the context of laboratory teaching and learning.

In general, critical thinking in the laboratory was acquired through research experience at undergraduate (Chase et al., 2017) and doctoral level (Philip et al., 2015), team-based learning approach (Belanger, 2016; Carrasco et al., 2019), problem-based curriculum (Koretsky et al., 2011), and science writing heuristics (Stephenson & Sadler-McKnight, 2016). In their analyses, researchers often report this outcome along with acquisition of other competences such as problem solving, scientific reasoning, self-directed learning, as well as collaboration and communication skills. This mirrors the development of the conceptualisation of critical thinking in the literature.

Argumentation

As an educational construct pertaining to higher-order cognition, argumentation is central to science education, as reflected in curriculum reform documents and leading science education journals (Erduran et al., 2015; Osborne et al., 2016). It emphasises the evidence-based justification of knowledge claims and draws on a mix of content knowledge, procedural knowledge and epistemic knowledge. We have analysed at least eight studies that may provide evidence for learning related to argumentation in science (Kadayifci & Yalcin-Celik, 2016; Seung et al., 2016; Walker & Sampson, 2013). Of these, Walker's research group has been consistently producing empirical work of considerably high quality focusing on students' ability to use the core ideas presented in the laboratory to explain a phenomenon and solve a problem (Walker et al., 2016), students' difficulties with elements of argumentation (Walker et al., 2019), and students' development of argumentative competence (Walker & Sampson, 2013). One of the rather striking findings from their studies is that students do not seem to change their reasoning even when provided with contradictory evidence. It is also noteworthy that the empirical findings relating to the acquisition of argumentation competence may provide a support for inquiry-type experiments, as opposed to confirmatory experiments (Katchevich et al., 2013), as the discourse during such laboratory exercise has been found to be rich in arguments.

Metacognition

As a construct, higher-order thinking skills are closely related to metacognition, which belongs to an established corpus of research in its own. Metacognition refers to an awareness of one's own learning and thinking process. In their edited work 'Handbook of Metacognition in Education', Hacker et al. (2009) maintain that metacognition consists of basic components applicable to almost any learning tasks, including laboratory work. These basic metacognitive components are often described as constructs related to knowledge and beliefs about cognition, monitoring cognition and regulating cognition. In our reviews, at least seven studies make an explicit reference to metacognition in their analysis and findings, either as a focus of investigation (Mathabathe & Potgieter, 2017; Sandi-Urena et al., 2011) or as a part of learning assessment results emerging from the data (Teichert et al., 2017; Xu & Talanquer, 2013a). Some of these quantitative findings indicated that students increased their ability and metacognitive strategies in solving online ill-structured chemistry problems. Meanwhile, others succeeded in characterising metacognition in terms of regulation of learning and corresponding strategies. The fine-grained coding system developed by Mathabathe and Potgieter (2017) allowed for a theoretical elucidation of the social nature of metacognition at play in collaborative laboratory work. As with higher-order thinking skills, the substantiation of metacognitive learning outcomes in our review also resulted in other related outcomes, such as problem solving, modelling skills, and understanding the nature of science (Sandi-Urena et al., 2011, 2012; Saribas et al., 2013).

Reasoning and reflection

Reasoning and reflection are considered as important competences that transcend disciplinary boundaries, especially in educational contexts where self-regulated learning is required (Tillema, 2000). Likewise, both of these constructs have been around for centuries in philosophical writing, often manifesting in the notion of dual processes of thinking: one fast and intuitive, the other slow and reflective (Evans, 2019). In the context of laboratory education, researchers often refer to these terms in various degrees of analyses and conceptual elaboration. This is captured in at least 13 studies in our review (Coleman et al., 2015; Furlan, 2009; Xu & Talanquer, 2013a). The study conducted by Galloway and Bretz (2016) is particularly insightful as it inquired into the cognitive processing that took place while students were watching themselves in the video recording of their laboratory work. The retrospective interviews afforded them an opportunity to stop and think about the chemistry behind the experiment they did. Varying degrees of understanding were revealed and only a few students could explain the purpose of the steps they carried out, albeit laden with inaccurate chemical ideas. Accordingly, another study by Gopal et al. (2004) also shows how reflection on laboratory work allows students to identify and change misconceptions so they can further refine their conceptions. The acquisition of reasoning and reflective competences through laboratory exercise can seemingly be facilitated with writing tasks that go beyond standard laboratory report formats. Interventions using reflective writing (Han et al., 2014) have been shown to be effective in helping students develop scientific reasoning and reflection skills.

Epistemic learning

Apart from learning outcomes in higher-order cognition, the studies in our review also provide evidence for epistemic learning—that is, learning how knowledge is established with respect to the material world, and how it is structured, produced and justified. Although closely related, this domain of learning is distinct from the cognitive domain in a way that it shifts the focus from *the learner*—along with their cognitive apparatus and associated processes—to *the learned*, that is, the nature, origin, limit and justification of the target knowledge. It also looks into the entire process that generates such knowledge.

In their study on the effect of cooperative problem-based chemistry laboratory instruction on graduate teaching assistants' epistemological and metacognitive development, Sandi-Urena et al. (2011), found that students were afforded opportunities to reflect on some important epistemological aspects of laboratory work and the knowledge it purports to generate. But most prominently, laboratory work has been found to facilitate an understanding of the nature of science (Marchlewicz & Wink, 2011; Pagano et al., 2018; Russell & Weaver, 2011). The terminology 'nature of science' typically refers to the epistemological commitments underlying the activities of science, that is, science as a way of knowing, or the values and beliefs inherent to the development of scientific knowledge (Bell et al., 2000). It also entails an understanding and appreciation of the work of scientists, processes of science and sociology of science (Yacoubian & BouJaoude, 2010). As a concept, it has been in a discourse of science education for well over a century. Eleven studies have substantiated these learning outcomes through various pedagogical approaches and theoretical frameworks, including research-based laboratory pedagogy (Russell & Weaver, 2011), process-oriented laboratory curriculum (Seung et al., 2016), constructivism (Cessna et al., 2009), activity model of inquiry (Marchlewicz & Wink, 2011), and meaningful learning (Saribas et al., 2013).

The empirical studies leading to substantiation of students' understanding of the nature of science in the context of the laboratory provide us with relevant insight into the role of the laboratory in fostering epistemic learning. Considering the current theories on the conceptualisation of this construct in science education (Allchin, 2013; Erduran & Dagher, 2014; Lederman, 2006), it is relevant to specify which theoretical frameworks the authors in our review have used. Four studies with explicit conceptualisation of the nature of science seem to refer to the consensus approach, which was initially proposed by Lederman's research group at the beginning of the twenty-first century (Akkuzu & Uyulgan, 2017; Marchlewicz & Wink, 2011; Russell & Weaver, 2011; Saribas et al., 2013), whereas the remaining seven in our review did not make an explicit reference to any theory on the nature of science. This is relevant to guide future research in laboratory education that wishes to focus on the epistemic domain, as the contemporary approach tends to highlight epistemic practice and family resemblance, as opposed to an attempt to find a consensus between various science disciplines.

Transversal competences

Apart from discipline-specific knowledge and skills, laboratory work has also been found to facilitate the acquisition of transversal competences. The construct 'transversal competences' has gradually gained recognition as one of the desirable outcomes of higher education, particularly in professional and vocational education, but has been somewhat neglected in competence research (Mulder, 2017). Authors in our review also refer to them as generic skills (George-Williams et al., 2018; Shultz & Zemke, 2019; Ynalvez, Ynalvez, & Ramírez, 2017). Although there is no consensus on what those constructs exactly mean, it is generally agreed that they are fundamental for a learner in applying knowledge, skills and attitude to meet an increasingly complex societal and professional demand. Some of the proxies of characteristics of transversal competences include transferability and cross-functionality, and thus, the constructs pertaining to higher-order cognition above are also transversal. In our review, it is sometimes signified with the term interdisciplinarity (Mulligan et al., 2011; Richter-Egger et al., 2010). Transversal competences are also typically related to social and interpersonal relations. The transversal competences have been substantiated to varying degrees in the studies. We are particularly interested in these competences as they can be observed, evidenced and developed. The following paragraphs illustrate some of this evidence.

Collaboration

The largest bulk in the learning outcomes pertaining to transversal competences in our review is concerned with collaboration (Bruck & Towns, 2013; Hass, 2000; Pezzementi & Johnson, 2002). In their study focusing on student interactions in the laboratory, Wei et al. (2018) found that there was an association between learning outcomes and the frequency of student interactions during laboratory work. Although most interactions observed in the laboratory were primarily concerned with procedures and results, as opposed to the chemistry behind the experiment, more interactions were observed to lead to a higher achievement level. In another study, collaborative learning was used as a pedagogical approach to examine its effect on student attitudes and performance in the laboratory (Shibley & Zimmaro, 2002). Using an experimental design methodology across three terms, they found that students in the collaborative treatment groups stayed in the laboratory longer to work on their results and seemed willing to question each other rather than relying on the professor for information. A similar effect was also reported by Pontrello (2016) and Turner, Jr. and Hoffman (2018).

Communication

Relevant to the acquisition of collaborative competence, the studies in our review also demonstrate that students learn various aspects of communication skills (Anwar, Senam, & Laksono, 2018b; Burt, 2017; Iler et al., 2012). Indeed, in studies by Díaz-Vázquez et al. (2012), Hill et al. (2019), and Li et al. (2019) collaboration and communication skills were evident in a single research setting. In these studies, students learned to articulate their ideas with clarity and communicate effectively through written and oral presentations. An interesting finding drawn from student reflections also provides an insight into student understanding of science communication and its importance in raising social awareness (Sewry & Paphitis, 2018).

A form of communication, writing is a useful transversal competence that can be developed through laboratory exercise. At face value, this competence is regarded as self-evident in laboratory education, considering most teaching laboratories use student laboratory reports as an artefact that can be directly assessed and marked. However, several studies in our review went an extra mile in substantiating learning outcomes related to writing skills that students acquired through laboratory work, as can be discerned from the works of Sampson and Walker (2012) using an argument-driven inquiry approach, van Bramer and Bastin (2013) using a progressive writing assignment, and Anwar et al. (2018a) using an orientation-decision-do-discuss-reflect method. In these studies, the researchers delved into some specifics of laboratory-related writing activities, inter alia, by attending to students' ability to justify the methods they used in the experiment and the alignment of such process with the epistemological commitments of science.

Affective domain

The affective domain in chemistry education has only relatively recently gained justified attention even though its importance has been described since the 1950s (Kahveci & Orgill, 2015). In general, this domain is concerned with such psychological constructs as values, attitudes, beliefs, perceptions, emotions, interests, motivation, and the like. One of the possible reasons why it has been studied to a lesser extent is the greater challenge in measuring the affective constructs. Conceptual and methodological knowledge of the affective domain is still developing—particularly regarding the adequacy of constructs, validation of instruments, and sensitivity of measurements. Empirical evidence for affective learning in the laboratory is, therefore, also developing. We have identified several constructs substantiated through a range of methodological approaches.

Expectations about laboratory learning

In a series of papers, a research group led by Bretz investigated students' cognitive and affective expectations and experiences of learning in the chemistry laboratory (Galloway et al., 2016; Galloway & Bretz, 2015b, 2015a, 2016). Their studies substantiate that students' expectations about laboratory learning direct their thinking and performance in the laboratory.

Their validated instrument 'Meaningful Learning in the Laboratory Inventory (MLLI)' is an attempt at an integrated perspective on student learning and assessment in the laboratory, whereby the psychomotor part of doing science should not be regarded in isolation, detached from the cognitive and affective parts. In their MLLI, the affective dimension of laboratory learning is reflected in statements such as that students expect 'to worry about finishing on time', 'to be nervous when handling chemicals', and 'to be excited to do chemistry' (Galloway & Bretz, 2015a). Mirroring their study, George-Williams et al. (2018) found that students started their university careers with very positive expectations of their teaching laboratory experiences, but these expectations became more negative each year they were enrolled in the programme.

Interest, enjoyment and engagement

In terms of frequency, affective constructs such as 'interest', 'enjoyment' and 'engagement' seem to be the most used by the authors in our review. Thirty-eight studies thematised how laboratory-related activities supported the development of student interest (Ablin, 2018; Costantino & Barlocco, 2019; Erasmus, Brewer, & Cinel, 2015), often operationalised using an attitudinal scale (Chatterjee et al., 2009; Erdem, 2015; Henderleiter & Pringle, 1999; Turkoguz, 2012). There was no singular focal point in these studies, except that they all reported on various levels of interest development—positive as well as neutral. In most cases, the term 'interest' was not used based on an explicit edifice of interest theory. Nevertheless, there were exceptions where more effort was spent on the theoretical clarification on the concept of interest. For example, Mulligan et al. (2011) situate their conceptualisation of interest in the broader scholarship of students' approach to learning (Marton & Säljö, 1976). However, they concede that their substantiation of student learning is primarily derived from students' qualitative feedback on their learning experiences, and not quantified as such. We argue that this may lend itself to a debate between methodological choice in substantiating student interest, whether there is a preference for quantitative over qualitative methods.

In most of the reviewed studies, interest was measured by asking students whether they found some intervention, activity or task interesting. And although the scope of the focus varied widely, most studies reported on (positive) interest development in the context of a course (Alneyadi et al., 2019; Kappler et al., 2017; Muryanto et al., 2017), a specific laboratory activity (Read & Kable, 2007; Zimmerman et al., 2019) or the use of a specific tool or device (Eid & Al-Zuhair, 2015; Erasmus et al., 2015; Fung, 2016). This colloquial use of the term 'interest' is a characteristic in studies that primarily focus on other factors and where interest is an *en passant* effect. However, in some of the studies found here the affective aspects like interest and enjoyment remain a focal point of the research (George-Williams, Soo, et al., 2018). In their study on inquiry laboratories, George-Williams et al. gauged students' level of interest in the experiments and found that an interesting and worthwhile experiment is key to students' enjoyment and engagement in the laboratory.

As it is the case with interest, there are several reports on positive findings regarding student enjoyment, appreciation and satisfaction (Chen, 2018; Goff et al., 2017; Tomasik et al., 2013). The same goes for findings of increased engagement in the subject or the laboratory activity (Burand & Ogba, 2013; Hartings et al., 2015; Mulligan et al., 2011; Stevens, 2017; Wilson & Wilson, 2017). In such studies, students were often surveyed in relation to an evaluation of a given course or a specific educational intervention.

In many of the studies mentioned above, student interest, enjoyment and the like were treated as one parameter that either increased or decreased due to a certain intervention. However, Ertmer, Newby and MacDougall (1996) revealed that students with contrasting goal orientations responded differently to cases they found difficult and challenging: students with a mastery orientation found such cases interesting whereas students with a performance orientation felt frustrated with these cases. This result suggests some alignment with outcomes pertaining to the mastery of a discipline presented earlier.

Self-efficacy

Self-efficacy is a specific affective construct that has been considered as particularly important in educational research. It refers to beliefs or perceptions about one's own capability to learn or perform tasks at a certain level (Zimmerman et al., 1996). In our review, seven studies explicitly mention the term self-efficacy as a learning outcome of laboratory instruction. Three of them investigate the effect of an inquiry-based or problem-based instruction on self-efficacy beliefs, and demonstrate positive results (Evans, Heyl, & Liggit, 2016; Mataka & Kowalske, 2015; Winkelmann et al., 2017). Some of these articles point to the importance of emulating some form of research experience for students to increase their self-efficacy beliefs of their ability to execute projects and solve problems. For instance, Winkelmann et al. (2017) revealed that research-inspired laboratory modules increased students' self-efficacy beliefs of their ability to complete inquiry activities. This result reflects the powerful impact of authentic research experience, which was also substantiated in the previous section on experimental competence.

Beside a full research experience, increasing self-efficacy belief was also associated with a pharmacy laboratory (Alsharif et al., 2016) and a laboratory module that included both a traditional “live” experimental component and a student-designed “virtual” computer simulation component (Goudsouzian et al., 2018). Two studies treated the relationship between self-efficacy beliefs and attitudes to chemistry (Erdem, 2015; Kurbanoglu & Akin, 2010). Both studies found a positive relationship between attitudes and self-efficacy beliefs. In their study, Kurbanoglu and Akin also looked at the relationship between self-efficacy beliefs, attitude and laboratory anxiety, which will be described in the following section.

Related to the findings on self-efficacy beliefs, many studies also report evidence of an increase in students' confidence. The increase in confidence is most often related to technical skills but occasionally also conceptual understanding. We see examples of studies demonstrating an effect from research-like educational settings on student confidence (Knutson et al., 2010) or a laboratory-intensive course that teaches students specific techniques (Witherow & Carson, 2011). We also see an example of increased confidence in a study of chemistry students in an organic practical class, where they were required to work individually, as opposed to working in groups (Lyall, 2010). The incorporation of virtual simulations and videos as a pre-laboratory activity also demonstrates that students felt substantially more confident and comfortable operating laboratory equipment (Dyrberg et al., 2017; Seery et al., 2017; Towns et al., 2015).

Laboratory anxiety

Affective constructs do not always connote a positive trait or state. Indeed, emotional states such as frustration, confusion, nervousness, boredom, anxiety and worry have been associated with laboratory work (Galloway et al., 2016). In our review, we have identified at least one of these more negatively associated affective constructs: anxiety. Focusing solely on this construct, Abendroth and Friedman (1983) implemented an actual psychological anxiety reduction programme into the chemistry laboratory sessions for first-year students and found a good effect on anxiety level. In comparison, Kurbanoglu and Akin (2010) investigated several affective constructs and examined the relationships between laboratory anxiety, chemistry attitudes and self-efficacy beliefs. Specifically, they found that laboratory anxiety correlated negatively to chemistry attitudes and self-efficacy. Mirroring this study, other studies also substantiate that different pedagogical interventions such as usage of laboratory techniques and guided inquiry reduced laboratory anxiety, while actual skills (Aydoğdu, 2017) and academic achievement (Ural, 2016) improved. The latter also observed a significant increase in students' attitudes towards the chemistry laboratory as an effect of the guided inquiry intervention.

There is an indication that the use of a virtual laboratory may reduce anxiety in comparison to a wet laboratory, although a clear effect is not established (Dalgarno et al., 2009). Similarly, the use of technology in a form of pre-laboratory video demonstration indicates that students experience less anxiety about the practical procedures in the laboratory (Teo et al., 2014). As virtual tools are getting more widely used to support learning in the laboratory, it is worthwhile to consider how they can be harnessed to not only reduce cognitive load but also laboratory anxiety.

Motivation

Motivation has often been conceptualised as belonging to the affective domain. However, its origin can be found in the research tradition of philosophy of mind, especially in its intersection with psychology. Motivation is considered to energise and direct action (Flaherty, 2020) and is seen as a precursor to the volition (Goldin, 2019). While motivation only impacts decisions to act, volition manifests as cognitive control strategies that keep a learner focused on intentions despite other opportunities and distractions.

A positive relation between increased motivation among students and an inquiry and problem-solving approach was substantiated by Knutson et al. (2010), investigating a year-long biochemistry experience. Similarly, Amante et al. (2011) found positive effects on motivation from incorporating a specific method for problem solving into laboratory activities of different engineering courses. In line with these findings, McDonnell, O'Connor and Seery (2007) find that problem-based mini-projects have increased class participation and engagement and improved class morale. Other interventions that are found to have a positive impact on student motivation are the implementation of a citizen science approach into current laboratory practices (Borrell et al., 2016), and the use of concept mapping among chemical engineering undergraduate students (Muryanto et al., 2017).

In the corpus of educational research on motivation, the learning environment is often referred to as an essential element that influences learners (van Lange et al., 2012). Deemer et al. (2017) and Park et al. (2017) treated the influence on motivation from the social environment or climate in the laboratory. Using interviews and observations of 10 students and a visiting scholar, the former revealed that the learning environment and culture in the laboratory influenced individuals' productivity and motivation to participate in research. In comparison, the latter showed that high affiliation in a laboratory session strengthened the positive association between research mastery goals and class-based mastery goals, based on surveys of 185 students using validated questionnaires.

Comparing a virtual and a traditional learning laboratory, Tarng et al. (2018) found that most students considered the virtual laboratory useful, also with regard to improving their learning interest and motivation. Likewise, de Vries and May (2019) evaluated a virtual laboratory simulation for educational use and tested if and how the virtual laboratory simulation could be applied to a practically oriented education aimed at motivating students. The overall conclusion of this study was that virtual laboratory simulation was an effective supplement to traditional teaching activities for the education of laboratory technicians. Furthermore, the study indicated that the use of virtual laboratory simulation cases increased study activity as well as motivation.

Dyrberg et al. (2017) tested a hypothesis that virtual laboratory work increased student motivation because they felt better prepared for the real laboratory exercises. They found that students did feel more confident and comfortable operating laboratory equipment, but they also found that the student did not feel more motivated to engage in virtual laboratories compared to real laboratories.

Self-regulation

Research development in self-regulation, also known as self-direction, is often aligned with reflective practice and metacognition (Sperling et al., 2004; Tillema, 2000). But more than three decades' worth of empirical and theoretical work in human motivation in a social context reveals that self-regulation is one of the most fundamental psychological needs, in which sense of autonomy and freedom to determine our own learning trajectories are crucial to our competence development (Black & Deci, 2000; Deci et al., 1996; Deci & Ryan, 2011; Ryan & Deci, 2006). In their extended work on academic achievement and self-efficacy, Zimmerman et al. define academic self-regulation as self-generated thoughts, feelings and actions intended to attain specific educational goals (Zimmerman et al., 1996). Properly designed and instructed, laboratory work provides an ample scope for developing self-regulation, provided that the experiments are not of 'cookbook' variety (Silverman, 1996). Our review substantiates this argument, as described below.

Goodey and Talgar (2016) and Seyhan (2016) found a positive effect from respectively a problem-based and inquiry intervention on students' self-regulation. Echoing this, Günter et al. (2017) found that the students took a more active role in this kind of laboratory. Positive influence on aspects of self-regulation is also found in studies conducted by Alsharif et al. (2016) in a pharmacy laboratory and Jordan et al. (2016) using student-generated video instruction.

In a thorough qualitative study using ethnographic methods Burt (2017) looked into the engineering graduate students' learning experiences to determine what students learned, and sought to identify the practices and activities related to the laboratory that facilitated their learning. It was found that research group members developed four dominant competences, one of them was receiving and responding to feedback. Another study by Hill et al. (2019) investigated the extent to which students recognised laboratory course-related skills development and understood the skills that employers are looking for. Around 10% of the students studied pointed to independent learning and study skills.

Professional identity

Three studies substantiate how laboratory work may influence students' professional identity (Nadelson, Warner, et al., 2015; Perez, Cromley, & Kaplan, 2014; Ynalvez et al., 2017). For instance, Nadelson et al. (2015) describes a study of how research experience influences the professional identity development of undergraduates. Students involved in the Research Experience for Undergraduates (REU) programme were provided with a basis for consideration of their career choices. In this programme the students were residents on campus during a 10-week summer experience where they were engaged in chemistry research. This experience allowed them to gain greater insight into the work of research scientists. Not only did REU provide students with a basis upon which they can make career plans, it also provided opportunities for students to develop their professional identity and competence. Engagement in an authentic research community influenced students' development of deeper knowledge and enhanced perceptions of themselves as science professionals.

Sjöblom et al. (2016) also found an influence on the professional identity development among students from the physical environment where they conducted their experiments, as they maintained that the usability and functionality of spaces and tools contributed to not just the fluency of the intellectual activity but also to the related emotional experience of oneself acting in a particular environment. The everyday successes or struggles in the laboratory built on the students' developing professional identity as well as their sense of belonging to the professional community.

The concept of professional identity described above is also closely related to studies seeking to understand students' choices of career paths and retention in STEM subjects. For instance, Perez et al. (2014) argue that identity development is important in college STEM student perceptions of values and cost of continuing as STEM majors. Using a short-term longitudinal survey study over one semester, they found empirical evidence showing that students' perceived cost (drawbacks associated with effort, lost opportunities, and stress and anxiety) played an important role in academic choices in STEM. Mirroring these studies, career paths and retention in STEM were also associated with work experience as laboratory assistants (Hughes et al., 2008), a laboratory course on research methods (Chen, 2018), and an undergraduate research experience (CURE) programme (Kowalski et al., 2016).

DISCUSSION

In this section, we will discuss the results of our synthesis in order to: (1) characterise learning in the laboratory; (2) provide a landscape overview of research on learning outcomes associated with laboratory instruction at university level, by identifying representations and gaps of knowledge; and (3) present implications for research, practice and theory development. The section will in general follow the structure of the results section with elaborations based on the theoretical discourse in the learning sciences and laboratory education research.

The many dimensions of learning in the laboratory

Our synthesis of 355 empirical studies on university chemistry laboratory education demonstrates that learning in the laboratory is distinctively multidimensional. The different types of learning outcomes substantiated through laboratory teaching spans several domains of learning and a range of constructs. We can discern domains of learning that involve cognition, affect, conation, psychomotor and the epistemic dimension of science. Within some of these domains, stratifications of learning are employed, such as from lower- to higher-order, basic to advanced, concrete to abstract, general to specific, naïve to sophisticated understanding, and isolated to integrated.

The notion of multidimensionality of learning is rooted in educational psychology, particularly in the critique of cognitivism, as a dominant approach to understanding human learning in the twentieth century. Dai and Sternberg (2004) assert that a cognitivist-reductionistic view on reasoning, whereby motivation and emotion are seen as peripheral to cognition, disregards essential components of intellectual functioning and development. In a real-life context, learning is a dynamic, multifaceted phenomenon that may only be understood properly when all related elements are considered. Accordingly, as a complex phenomenon, it is affected by a host of motivational, emotional, self-regulatory and phenomenological aspects (Illeris, 2018). In chemistry education, this notion has also been explored in large-scale studies and curriculum reforms, highlighting the importance of redirecting science instruction towards integration of content knowledge and scientific practices (Cooper & Stowe, 2018; Pazicni et al., 2021; Stephenson et al., 2020) and theorised further to frame a comprehensive assessment of learning in the laboratory (Agustian, 2022). Our synthesis provides insight into the dimensions and underlying constructs employed in current research.

The manner in which those learning domains have been substantiated still necessitates integration. One of the most perpetuated learning goals in the laboratory is the theory-practice connection, whereby students are expected to obtain an understanding of the underlying theoretical, conceptual and epistemic assumptions during laboratory work. Getting students to have 'minds-on while hands-on' is still a challenge to laboratory education practitioners, and it is reflected in our review. When this lack of integration is extrapolated to a broader landscape of learning domains, considering students' conation, affect and social construction of meaning, it seems clear that the potentials of meaningful laboratory learning have not been reached. This problem may be caused by a fragmented approach to curriculum design, instruction and assessment. In seeking to improve the quality of laboratory education, both researchers and practitioners involved in teaching laboratories should aim at a high level of integration of these learning domains. From the perspective of curriculum development, this will ensure coherence between the three levels of curriculum, namely intended, implemented and attained levels (Thijs & van den Akker, 2009), as argued at the beginning of this review. From the pedagogical perspective, stronger integration could lead to more meaningful learning and holistic experience of doing science (or learning to do science) in the laboratory (Dai & Sternberg, 2004).

Experimental competences and laboratory skill performance assessment

Over the course of more than a century, teaching laboratories have been established as a place to learn to do science (Bretz, 2019; Hofstein & Lunetta, 2003; Kirschner & Meester, 1988; Seery, 2020). The activities of preparing for an experiment, planning an inquiry, executing it, analysing the collected data and reporting the results, require a lot of knowledge and skills, which renders laboratory learning distinctive. Nevertheless, critics often lament the lack of assessment of, for example, laboratory techniques and practical skills (Agustian, 2020a, 2022). The psychomotor domain is often hailed as the *raison d'être* of laboratory education, but although laboratory work in university chemistry courses often involves skills such as manipulating glassware and performing instrumental techniques, assessments are not always designed to measure students' performance of these skills and techniques. This is mirrored in our review. To illustrate, about a third of the studies mention learning outcomes related to experimental competences. Of this, the actual practical skills performance has been assessed to an even lesser extent (51 out of 355 studies, or around 14%). If the psychomotor domain lies at the heart of laboratory pedagogy, why is it not assessed adequately?

A part of the answer may be that many basic practical skills such as titration and distillation are becoming obsolete and are being replaced with automated systems. Therefore, the importance of these basic skills in scientific practice is diminishing. However, if they are part of the laboratory curriculum and the longer progression of student learning trajectories, we argue that they should be assessed. If students are taught and make efforts to develop those skills, they should receive feedback on how their learning is progressing. Of course, this is primarily relevant for laboratory courses offered to science majors and presumably less so for those aiming at non-science students.

The assessment of practical skills and laboratory techniques is evident in our review, but it is mostly an indirect assessment, in which students' self-reports are used to gauge their perception of skill level, as described in the results (Carson & Miller, 2012; Warner et al., 2016). In cases where direct assessment is administered, it is mainly an assessment of content knowledge, with a few exceptions of observations of behaviour in the laboratory, including using video registration (Galloway & Bretz, 2016; Harsh, 2016). The self-reports are usually generated from interviews or surveys, where students are asked to what degree or if they think they became better at performing at certain laboratory-related task. Such reports are important mainly for establishing and attending to students' self-beliefs and self-efficacy in the laboratory, two constructs primarily associated with the conative domain of learning. However, a proper practical assessment that works well on many levels is not easy to design and implement. Several authors have tried and succeeded (Kirton, Al-Ahmad, & Fergus, 2014; Towns et al., 2015), but today's reality of science courses admitting large numbers of students each year often forces laboratory course designers to employ conventional written tests rather than actual performance assessment of practical competences. Thus, there is a need to reconsider the types of summative assessment employed by institutions and for students and institutions to shift the focus towards the continuous formative assessment, rather than summative assessment.

Laboratory instruction and corresponding assessment should be directed towards higher-order experimental competence, defined here as competence related to designing an experiment. This will address the problem of students just following predesigned protocols that is often associated with a ‘cookbook’ approach to laboratory curricula.

In our conceptualisation of experimental competences, we refer to inquiry as a pedagogical and methodological approach to *learning to conduct* scientific investigations. Due to the nature of progression of most undergraduate degrees in science, inquiry-related competences such as experiment design, critical evaluation of data and argumentation will be indispensable, because towards the end of their degree, students are typically expected to conduct a full inquiry on a scientific theme of interest (Seery et al., 2019). Surely students cannot be expected to acquire this competence without experience of planning, executing, evaluating and reporting a scientific investigation. In the case of laboratory education, the execution part entails practical skills and laboratory techniques, and we assert that these need to be assessed adequately as well.

Pre-laboratory work plays an important role in facilitating the experimental competence acquisition and cognitive learning. We have identified recurring foci on pre-laboratory activities and their role in providing scaffolding on both theoretical and practical accounts (Chaytor et al., 2017; Darby-White et al., 2019). Students are usually urged to prepare their laboratory session by reading the laboratory manual, reviewing related concepts from lectures, and becoming familiar with the techniques and manipulations of the experiment, but typically far from all students actually do so (Agustian, 2020a). Lack of preparation is one of the factors that causes anxiety during the laboratory work (Kolodny & Bayly, 1983). Johnstone et al. (1998) posit that the aim of the pre-laboratory activities is to prepare students to take an intelligent interest in the experiment by knowing where they were going, why they were going there and how they were going to get there. In a previously published review, Agustian and Seery (2017) argue that pre-laboratory activities have been used on the grounds of at least three rationales, namely to introduce chemical concepts, to introduce laboratory techniques and to address affective dimensions. This systematic review confirms the findings. Pre-laboratory work should be designed within an appropriate pedagogical framework to ensure progression from pre- to in- to post-laboratory by means of scaffolding.

Disciplinary learning outcomes: need for more focus on higher-order cognition

Unsurprisingly, our synthesis shows that chemistry-specific outcomes are strongly represented, with more than half of these studies associated with some form of disciplinary learning. A tendency is that much of what is measured pertains mainly to lower-order cognition and many studies are focused mainly on content knowledge. In the critical analysis of the quality of the studies, we identified several published articles that had quality issues. Some were based only on course evaluations, some lacked clear formulation of research questions or hypothesis, some failed to employ appropriate use of relevant educational theories, some lacked methodological rigour. There is scope for more investigation into higher-order cognition in laboratory settings. In our review, this is exemplified in several well-designed studies that focus on problem solving and argumentation in the laboratory, in which students use core concepts to construct arguments, explain a phenomenon and solve a problem.

We have found a large number of studies where students' conceptual understanding was measured, as specified in the results section. Likewise, some of the studies focused on higher-order thinking skills and related constructs, namely problem solving, critical thinking and metacognition. The importance of attending to complex cognitive tasks and higher-order skills is that these skills are required in the acquisition and development of competence, whereby highly integrated knowledge structures, interpersonal skills, attitudes and values work in synergy (van Merriënboer & Kirschner, 2017). The integration of these skills into laboratory exercises is possible precisely because of the complex nature of the learning environment (Seery et al., 2019). Thus, while the complexity of the environment is often considered detrimental to learning, it also holds potential for the development of higher order thinking.

In developing effective instruction to address higher-order cognition, it is important to consider relevant theories as a framework of reference. For example, regarding argumentation, science educators may focus on argumentation as a critical element in the design of learning environments in order to make scientific thinking and reasoning visible (Duschl & Osborne, 2002). As such, students should be encouraged to explore critically the coordination of evidence and theory that support or refute an explanatory conclusion, model or prediction, much of which is pertinent to laboratory work.

Transversal competences: need for more focus on social and epistemic domains

In the literature of laboratory education, generic skills, transferable skills or transversal competences are often lauded as one of the valued potentials of laboratory work (Hodson, 1993; Johnstone & Al-Shuaili, 2001; Reid & Shah, 2007; Seery, 2020), albeit with some reservation (Wellington, 2005). In our review, these competences are represented by collaboration and communication, but the constructs related to higher-order thinking skills could be also interpreted as transversal.

The reference to constructs such as argumentation, collaboration and communication shows that the social domain of learning is clearly a characteristic of laboratory education. However, this is more often assumed than actually studied (Nakhleh et al., 2002). We identified a gap in our understanding of how social interactions facilitate students' chemical learning, that is, relating the three levels of chemical representations (macroscopic, submicroscopic and symbolic), which is a typical problem in chemistry education (Johnstone & Al-Shuaili, 2001).

There is still much scope for investigation into various aspects of social interactions in the laboratory. Of great interest is the kind of interactions that involve artefacts such as laboratory instruments. We still have limited understanding of how learning unfolds and extends from the personal to the social in a learning environment where instruments and equipment are used to perform learning tasks (Agustian, 2022). With more research-based knowledge in this area, for example in distributed cognition (Hutchins, 2001), curricular and pedagogical interventions could be directed towards increasing the use and usefulness of the social and material interactions to enhance learning experiences in the laboratory. Also in relation to the social domain, our current understandings in the learning sciences and science studies highlight the importance of finding a balance between teaching for conceptual, epistemological and social learning goals (Duschl, 2008; Duschl & Grandy, 2013).

We described how the epistemic domain has been addressed primarily in terms of students' understanding of the nature of science. In the university setting, there is certainly a need to understand the role of the laboratory for student learning about how knowledge is established in the sciences (Agustian, 2020b). The 'material turn' in the philosophy of science—stressing the complex interplay between material, technologies and theory development—has shed new light on the crucial role of the experiment and the experimental process in the overall scientific development (Hacking, 1983; Latour, 1986; Pickering, 1995). However, the implications of this renewed focus on the role of the material aspects of scientific knowledge production has not yet impacted laboratory education research.

Engaging students in epistemic practices of science is pivotal to the deep understanding about the nature of their disciplines through participation (Matthews, 2018). However, 'cookbook' laboratory procedures do not necessarily help students develop knowledge and understanding of the scientific knowledge creation process. We argue that research can play a role of organising the efforts so that students have an opportunity to reflect on some of the epistemic dimension and problems related to their laboratory work (for instance, concerning research conduct, inter-subjectivity and so forth).

The affective domain: need for more theoretical grounding

Our analysis shows that a relatively large number of studies report on aspects of affective learning. Thus, there is a substantial emphasis on the affective domain in the description of laboratory-related competences. However, although we have coded seven distinctive constructs, some of them were presented as a lay-term or in a not very theoretically informed manner. For instance, statements in the results section along the line of 'Students *enjoyed* the laboratory work' or 'They were *interested* in the new laboratory structure'. This is particularly true for studies involving self-reports in data collection. Sometimes the indication of affective response is perhaps simply expressing the subjectivity that student self-reporting entails, rather than an actual investigation of the role of a specific affective construct for learning.

STEM education scholars have highlighted the importance of attending to the affective domain of learning and instruction, including in a laboratory context (Alsop, 2005; Chamberlin & Sriraman, 2019; Kahveci & Orgill, 2015; Wellington, 2005). In the context of constructivist pedagogy, this domain is often associated with the question of *how* students experience learning, as opposed to *what* they learn. It is difficult to think of the affective domain in isolation from the cognitive. In the context of our argument for more integration of learning domains, researchers and practitioners should consider affective factors in laboratory instruction. An attempt at integrating the cognitive and affective domains of learning can be discerned from the work of Oatley (2000) which is highly relevant for laboratory education due to its close association with distributed cognition. This is illustrated in the way long-term emotional states such as enjoyment, enthusiasm and affectionate warmth can influence learning through mobilisation of resources and maintenance of commitment to the learning goals, particularly in the context of social interactions involving artefacts in laboratory learning environments.

IMPLICATIONS

Implications for research

Findings from this systematic review provide a roadmap for future studies in laboratory education. Learning in the laboratory is multidimensional, and future research should be directed towards a more comprehensive substantiation of student learning that considers different learning domains, the interplay between them, and ways in which they could be enhanced. This includes (1) considerations of all learning domains associated with laboratory work, namely cognitive, affective, psychomotor, social and epistemic; (2) use of both direct measures, such as rubrics and observation protocols, and indirect measures, such as validated questionnaires (Demeter et al., 2019); and (3) focus on not only learning outcomes but also learning processes, including constructs regarded as prerequisites for learning. As discussed, a higher level of integration between the different learning domains in substantiating student learning could also improve our understanding of the interplay between aspects of learning and how they could support each other. For example, when designing a research instrument to measure a specific cognitive construct, it is important to bear in mind that cognitive processes in the laboratory are not isolated and devoid of a broader context of learning. Thus, larger-in-scope constructs such as epistemic practice (Kelly & Licona, 2018) and scientific inquiry (Hodson, 1996) are relevant.

Research endeavour to improve rigour and relevance is argued to strengthen the evidence for student learning in the laboratory and the quality of laboratory education research in general (Lodge & Bonsanquet, 2014; Van Merriënboer & Sweller, 2005). There is strong evidence for the added value of laboratory work in higher science education compared to a less expensive format such as lectures, as described in the results. However, some of the evidence discerned from the included studies could benefit from greater methodological rigour. Triangulation is particularly relevant and important for a more comprehensive understanding of student learning in the laboratory. Data obtained by different means would have strengthened the findings.

There is a need for further studies in higher-order cognition and epistemic learning in the laboratory, particularly metacognition and social epistemology. The laboratory is a fertile field of research, primarily due to its complex nature, and we still have a limited understanding of social-epistemological aspects of teaching and learning in this setting. We need to better understand how the social interactions in the laboratory, either among students, between them and the instructors, and between both and the instruments, influence personal beliefs, knowledge and competences. There is little knowledge as to whether and how the widely practised grouping in laboratory work elevates the personal to the social and how it contributes to learning. In terms of conceptual clarity, the construct 'critical thinking' may need to be defined more clearly, especially when it is part of the investigation or reported as a learning outcome.

Correspondingly, a better understanding of how students develop their higher-order experimental competences is needed. Scholarships in science studies and the learning sciences may prove to be a useful body of knowledge to consult. A few studies have been published (Anagnos et al., 2007; Goodey & Talgar, 2016; Lefkos et al., 2011), but there is a large scope for more rigorous intervention studies in which students are adequately supported in their development of experiment design competences. This is crucial also from a practice perspective, as we elaborate next.

Implications for practice

For laboratory curriculum designers, it is important to develop a curriculum that accommodates and fosters students' progression of learning, as mapped in our review. Consider, for example, students' development of experimental competences, from acquisition of basic practical and data-related skills to a more advanced ability to design an investigation. To be able to design an experiment, students must be proficient and confident with basic skills and procedures needed for the design. Therefore, both have a place in the curriculum. A pitfall in much laboratory instruction is that this progression is not scaffolded, or worse, entirely disconnected in the curriculum. If the preceding laboratory courses are entirely prescribed for students, students dislike being required to design their own scientific inquiry towards the end of their science degree (Agustian, 2020a). They need to be exposed to an increasingly higher level of inquiry as they progress in their higher education (Etkina et al., 2010).

For laboratory instructors, it is important to revisit assessment and feedback practices in the laboratory. As argued in this review, the learning continuum related to laboratory instruction starts before students enter the laboratory and continues after the exercise has been completed. While the practice of pre-laboratory activities has been prevalent at least since the 1970s (Agustian & Seery, 2017), they are not always assessed, and students do not always get feedback on their pre-laboratory work (Chittleborough et al., 2007). *Formative* feedback and assessment practice to support students' competence development should be a central focus and permeate the learning continuum mentioned above. For instance, although laboratory reports are widely adopted to document students' laboratory work, there is still a need for empirical investigations of how feedback on these reports impacts on students' understanding of the experimental work they have carried out.

Implications for theory

As a part of science education research, laboratory education research has a large potential for theory development. We have identified at least three areas in which relevant theories could be developed, departing from this review. Firstly, epistemology in higher education. Experimental work has been a central and largely influential element of scientific knowledge development. To date, parallels between the inner workings of science and educational practices that reflect these workings have been studied (Berland et al., 2016; Jiménez-Aleixandre & Crujeiras, 2017; Knorr-Cetina, 1999), but there is arguably a large scope for research and development in the context of laboratory education. A useful work is, for example, Jiménez-Aleixandre and Reigosa (2006). Future work on epistemic orientation in this context can advance theoretical development in philosophy of science, particularly the intersection between philosophy and education.

Secondly, the learning sciences. The complex nature of learning environments in the laboratory lends itself to various foci, depths and levels of interdisciplinarity. The cognitive-psychological focus that permeates the scholarships in science teaching and learning could be enriched with the social- and cultural-psychological foci. The manifestation of embodied learning in the laboratory may also further our understanding of bodily and perceptual experiences involved in science learning. Accordingly, the affective and conative domains of learning in the laboratory represented in our review with constructs such as self-efficacy beliefs and motivation may contribute to a more nuanced understanding of how related theory such as self-determination theory (Deci & Ryan, 2011) can be contextualised in scientific practices.

Thirdly, curriculum theory in higher science education. We purposefully make references to curriculum design and development as an important framework in which researchers and practitioners could work (collaboratively) on student learning outcomes and processes. The notions of inquiry, scaffolding and competence development are chief to the theoretical and methodological choices made in the primary studies. Synthetic work such as this systematic review has an implication for a more thorough overview of the central role of curriculum development in university science education.

CONCLUSIONS

We have systematically reviewed empirical studies focusing on student learning outcomes in the chemistry laboratory at university level. Based on established criteria, we have identified five large clusters of learning outcomes: experimental competences, disciplinary learning, higher-order thinking skills and epistemic learning, transversal competences and the affective domain. Each of these clusters have been specified and described. Firstly, disciplinary learning in the laboratory is related to conceptual understanding, theory-practice connection, academic achievement and mastery of chemistry. Secondly, experimental competence pertains to experiment design, conducting an experiment, laboratory skills and techniques, as well as data analysis and interpretation. Thirdly, higher-order thinking skills are concerned with problem solving, critical thinking, argumentation, metacognition, reasoning and reflection, as well as epistemic learning. Fourthly, transversal competences identified in our review are collaboration and communication skills. Finally, the affective domain associated with laboratory instruction manifests as learning expectation, interest, enjoyment and engagement, self-efficacy beliefs, laboratory anxiety, motivation, self-regulation and professional identity.

Our analysis of published studies led to a substantiated view of multidimensional learning in the laboratory, in which the conceptualisation of student learning goes beyond the cognitive view. With considerations of the affective, conative, psychomotor, social and epistemic dimensions of learning, our synthesis reveals a broad landscape of research on student learning, with areas deserving appraisals and gaps of knowledge yet to be resolved. Several issues related to each of the identified constructs have been discussed in light of contemporary scholarship in learning sciences and STEM education research. We have presented recommendations for future research to focus more on higher-order cognition. Likewise, we have identified a sizeable scope for developing and assessing higher-order experimental competence that goes beyond indirect assessment of skill level perceptions. We have also identified various constructs belonging to the affective domain but there is a need for more theoretical grounding in current scholarship in the affective dimension of chemistry education, a field of research that has only recently gained the relevant attention. Transversal competences are well substantiated in our review but there is room for more focus on the role of the social and epistemic domains of learning in the laboratory.

Our review sheds some light on how virtual laboratory has been used, and it is pertinent across the clusters of learning outcomes we have identified. There is a modicum of evidence for its benefit in terms of conceptual learning, self-efficacy beliefs and motivation. However, most of the studies used it in combination with the physical laboratory, either in the form of pre-laboratory activity or a supplementary simulation resource, as opposed to a substitute for the real experience. As the world witnessed the Covid-19 pandemic, faculty worldwide were forced to immediately shift laboratory teaching online. We completed our search process prior to this unprecedented situation, and as we worked on the analysis and synthesis during the lockdowns, a multitude of studies on laboratory education which were presumably entirely virtual are not included in this review. Therefore, there is a scope for an extension of this systematic review to also explore laboratory education where laboratory work is not present. See, for example, Kelley (2021), Finne et al. (2021), and other special publications in *Journal of Chemical Education*.

In general, research development in laboratory education necessitates more rigour in terms of theoretical and methodological frameworks. We have identified specific areas where this could be enhanced, such as formulation of research questions, clear theoretical framing, relevant triangulation, and clarification of the construct definitions. Implications for practice have been suggested, particularly concerning curriculum design and assessment. Likewise, we have proposed implications for theory development in philosophy of science, the learning sciences and curriculum theory in higher education.

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CONFLICT OF INTEREST

There are no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

Data available on request from the authors.

ETHICAL APPROVAL

As this research is based on a systematic review of published studies, ethical approval is not applicable to our research.

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ENDNOTE

[1] The American Educational Research Association, https://www.aera.net/Education-Research/Beyond-AERA/Education-Resources-Information-Center

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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Paper 2

Jørgensen, J. T., Gammelgaard, B., Christiansen, F. V.

Teacher Intentions vs Student Perception of Feedback on Laboratory Reports

Submitted to Journal of Chemical Education

Teacher Intentions vs Student Perception of Feedback on Laboratory Reports

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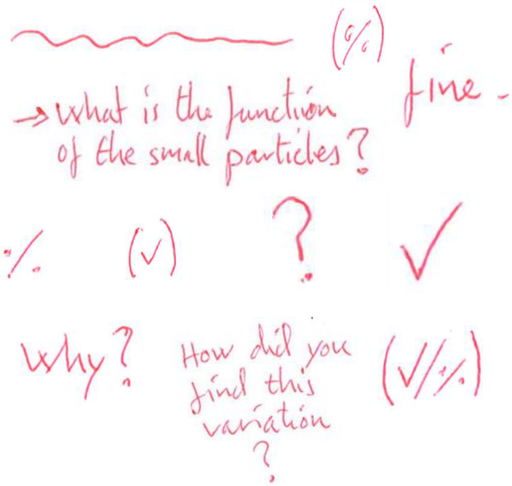
ABSTRACT

In pharmaceutical laboratory teaching and learning, students' written reports allow them to express their understanding. Therefore, feedback on these reports is crucial for the students' continued learning. This study investigates written feedback on laboratory reports and compares the students' perceptions with the teachers' intentions. The study is based on interviews and student reports containing written feedback notes. Four teachers and five students were interviewed. Results show that written comments are typically brief and intend to quickly guide the students towards further action. However, students often fail to use the comments as intended. Reports are assessed as passed or not passed. Results indicate that students may disregard feedback when their report is passed, showing how a summative element in the feedback may overshadow the intended formative feedback. Teachers and students value oral dialogue in the laboratory. Based on the theory of congruence of learning environments, implications for feedback practices are discussed.

GRAPHICAL ABSTRACT



KEYWORDS

Second-Year Undergraduate, Upper-Division Undergraduate, Chemical Education Research, Laboratory Instruction, Hands-On Learning / Manipulatives, Testing / Assessment

INTRODUCTION

Undergraduate laboratory teaching is often organised as experimental exercises from which the students prepare experimental reports. Such reports are essential objects of educational research as students unfold their reasoning about the underlying principles and outcomes of the experiments in the reports.[1] In this study, we explore the feedback given and received on the written reports from a pharmaceutical laboratory course, considering the perspectives of students and teachers.

Higher Education teachers appear to have various ideas about what constitutes feedback practice.[2] A few research studies explore both teacher and student perspectives on feedback, and in a review, qualitative research that compared the perspectives of students and teachers concerning laboratory teaching was requested.[3] A qualitative study on teachers' intentions and students' use of feedback on assignments showed a misalignment between tutor intentions and students' use of feedback.[4] A quantitative study found that teachers and students believe that individual face-to-face feedback is most effective but that teachers prefer to utilise written feedback.[5]

Much research shows that formative feedback supports quality learning processes and outcomes[6,7], and various influential recommendations about formative feedback exist.[8–10] Formative feedback should clarify rather than confuse, facilitate continued learning rather than assess at the end of learning, and be an interaction rather than one-way communication. Notably, formative feedback's effectiveness depends on how the students use the feedback provided.

A particular type of feedback is written feedback from teachers on written work by students. Research in non-science subject areas shows that students value written feedback on their assignments.[11] It has been shown that physics students are likely to use the written comments they receive on their laboratory notebooks.[12] Research that compares teachers' and students' perceptions of feedback has recently been called for.[2] The research question of this study is:

- How do students' perceptions of feedback for laboratory reports correspond to teachers' intentions?

We explore this general question in the context of a 3rd year BSc course in a Danish pharmacy education programme.

METHODS

We use the congruence framework[13] to compare teachers' intentions with the perception of students about feedback on laboratory reports. The congruence framework generalises the concept of constructive alignment,[14] which describes the students' conception of the relationship between the curriculum objectives, the teaching and learning activities, and the formative and summative assessment types. The congruence model adds three other elements of the perceived learning environment that also shape the students' learning experience: Students' background and aspirations, Course organisation and management, and Learning support. The congruence framework helps understand students' complex and interrelated teaching and learning environments in higher education. According to this model, congruence between the different aspects of the learning environment will affect the students' ways of thinking and practicing in the discipline. Thus, perceived congruence is a prerequisite for high-quality learning processes and outcomes. The congruence model focuses mainly on the students' conceptions of congruence in the learning environment. However, in planning a course, teachers must also consider the strong relations between the different elements of the congruence model.

This study is part of a larger research project on higher education laboratory learning over time. As part of the overall project, we conducted interviews with students and teachers in several courses in the pharmacy bachelor program. In this study, we focus specifically on conceptions of feedback in a single course and refer only to the parts of the interviews concerning the teachers' and students' perceptions of feedback in the interviews about this specific course.

Course/ Context

The course is a compulsory third-year course dealing with the formulation and production of drugs in solid dosage forms. The course workload is estimated as 7.5 credits in the European Credit Transfer and Accumulation System (ECTS), of which laboratory work constitutes 2.5 credits. One full-time academic year awards 60 credits.[15] The course consists of 40 lectures, 21 hours of laboratory work, eight seminars (where the teachers and students work on a specific course topic), and two whole-class feedback sessions to discuss laboratory reports. Sixteen teachers and approximately 200 students attend the course. They are divided into eight classes for the seminars, laboratory work and whole-class feedback sessions.

In the laboratory, students in groups of 3-5 perform various pharmaceutical unit operations used to produce solid dosage pharmaceuticals, such as tablets. The students produce two group-based reports, each based on three laboratory sessions. The first report covers the unit operations from powder to solid dosage forms. The second is more focused on quality assurance. Both reports must be accepted for the student to pass the laboratory part of the course. A 3-hour written exam concludes the theoretical part of the course.

Students complete a pre-lab quiz via their learning management system before the exercises. The quiz consists of ten multiple-choice questions concerning laboratory safety, good laboratory practice, the function of apparatus and conceptual knowledge.

Students must demonstrate an overview of the concepts and principles of drug formulation and production, describe factors influencing the quality of drugs, assess the role of drug formulation for the bioavailability of drugs, and employ methods from the Pharmacopoeia and Good Manufacturing Practice rules in drug production and documentation. The report writing is based on the students' activities in the laboratory, and the report is written with reference to questions given in the assignments. Each report includes results, analysis and discussion of findings and appendices with batch documentation. They are approximately 20 pages long, excluding appendices. The reports are delivered on paper with relevant laboratory material as appendices (e.g. batch documentation). Teachers provide feedback as handwritten notes. After the students have received the written feedback, they attend a whole-class feedback session where the reports are discussed, and the teacher provides general feedback.

Students do not necessarily meet the same teacher in the laboratory and the whole-class feedback session. Altogether, sixteen teachers with different roles and responsibilities participate in the course. Nine teachers conduct the laboratory sessions. Three of these teachers give written report feedback and conduct the whole-class feedback sessions in classes of around 25-30 students. The basic structure of the laboratory exercises and feedback on reports is as follows:

1. Students read the protocol for the exercise
2. Students do a pre-lab quiz online
3. Students do the laboratory exercise in groups with teacher help and supervision
4. After three exercises, students write and hand in a group report
5. Teacher provides brief written comments as feedback on the group report
6. Teacher assesses whether the report is accepted
7. Students attend the whole-class feedback session prepared by the teacher. Students bring the report with written feedback from the teacher.
8. Students follow up on the feedback in their own time or resubmit (once) if the report was not accepted at step 6.

Study participants

Four teacher respondents with different levels of responsibility (two senior and two junior staff) and five students in the course were recruited for interviews. Student participants were recruited through their learning management system while enrolled in the courses. Teachers were recruited via the course director, who was interviewed and suggested further interviewees. The interviewed students were from different groups. All participants signed written consent forms to participate in the study.

Interviews and analytical approach

The interviews were semi-structured and of one-hour duration. The interviewer sought to be receptive, respecting what interviewees had to say while seeking to understand their point of view.[16] The teacher interviews explored the teacher's perspectives and intentions and focused on the structure of the laboratory exercises, the feedback practices, perspectives on the students' approaches to studying in the course and the challenges involved. The student interviews likewise explored the individual student's perceptions of the structure of the laboratory exercises, the feedback practices, their approach to studying/learning and their conception and use of the provided feedback.

Course materials were used in designing the interview guide, including the program description, course description, laboratory protocols, and laboratory reports from students with written feedback from teachers. The reports with feedback were discussed during three of the student interviews. The two remaining students had not yet received their feedback. The teacher interviews were conducted a few weeks before the student interviews and were transcribed verbatim. The interview questions are provided in the supporting information.

Thematic analysis was conducted using a realist, semantic and theoretical approach.[17] Thus, the interviewee's statements were assumed to reflect experiences and intentions, which could be interpreted at the available surface level. The analysis was rooted in the research question.

The first author conducted all interviews. Next, relevant data extracts from students' and teachers' interviews were located, read and re-read by all authors to familiarise us with the data. Next, the authors developed initial codes and discussed possible themes with other researchers. Finally, all interviews were recoded with the research question and initial codes and themes in mind and the final themes were produced using Nvivo.[18]

After writing the manuscript, trustworthiness was improved by conducting a member check;[19] the interviewed senior teachers were invited to read the manuscript and give comments or correct misunderstandings.

RESULTS

The thematic analysis resulted in four themes related to different aspects teachers' and students' conceptions of feedback:

- Written feedback on reports
- Formative feedback on reports and whole-class feedback
- Summative feedback on reports
- Opportunities for interaction

Each theme is presented below with a description supported by empirical material highlighting teacher intentions and student perceptions. There is overlap in the themes, e.g., the written feedback has both formative and summative components and the whole-class feedback is a potential opportunity for interaction. However, students' and teachers' expressed conceptions with meaningful delimitations in the presented themes. Furthermore, It should be noted that the university was partly closed when the course took place, resulting in restricted access to the university. As a result, laboratory courses were prioritised and completed with students present, while lectures and classroom teaching were given online through the Zoom platform.

Conceptions of the written feedback on reports

From the interviews, it appeared that teachers' intention with the written feedback on reports is to direct students towards further learning, but the students fail to interpret the written comments as intended. The teachers' written feedback on students' reports are mainly brief handwritten markings and short comments, exemplified by the six examples in Figure 1.

Example 1

1.1.1 Describe how microscopic observations of particulate diameter correlate with the results from the measurement of diameter with [apparatus].

Results from [apparatus] show that most particles have a size between 10 and 100 µm.
With microscopy, most particles were measured in the interval 16.202 µm – 144.884 µm. These results correlate well.

1.1.2 Describe how diameter is estimated with microscopy

In microscopy, we can observe particles and estimate their size using software installed with the microscope.

Example 2

1.1.1 Describe how microscopic observations of particulate diameter correlate with the results from the measurement of diameter with [apparatus].

Via the microscopic observations of particulate diameter, we found an average diameter of 55.4654 µm. This diameter was compared with data measured at 1, 2 and 3 bar on [apparatus]. Data acquired at 2 bar is unusable because the curve is binominal and since the particles have a diameter of 1 mm. From qualitative observation of the sample, we see that no particles have such a large diameter. Therefore, we use data acquired at 1 and 3 bar.

At high pressure, there is a risk that particles a blown apart and that small particles stick to large particles. At low pressure, there is on the other hand a risk that particles are not distributed well enough, resulting in the measurement of larger particles than are actually present. Based on this, **there is no "correct" pressure to measure** by, but it must be estimated based on measured data

Uniformity is 0.572 at 1 bar and 0.616 at 3 bar. Since data from 3 acquired at 3 bar has a uniformity **closer to 1, this measurement is used for comparison of particulate size. At 3 bar, it is seen that** volume-surface diameter (dvo) and volume diameter (dv) are at 33.544 µm and 64.560 µm respectively, which correlates well with microscopy observations.

Example 3

1.1.1 Describe how microscopic observations of particulate diameter correlate with the results from the measurement of diameter with [apparatus].

The microscopic observations are inserted below. It is seen that the smallest particle size we measured is 28.073 µm and the highest is all the way up at 209.808 µm. The median of these particle sizes is determined to be compared with [apparatus] later:

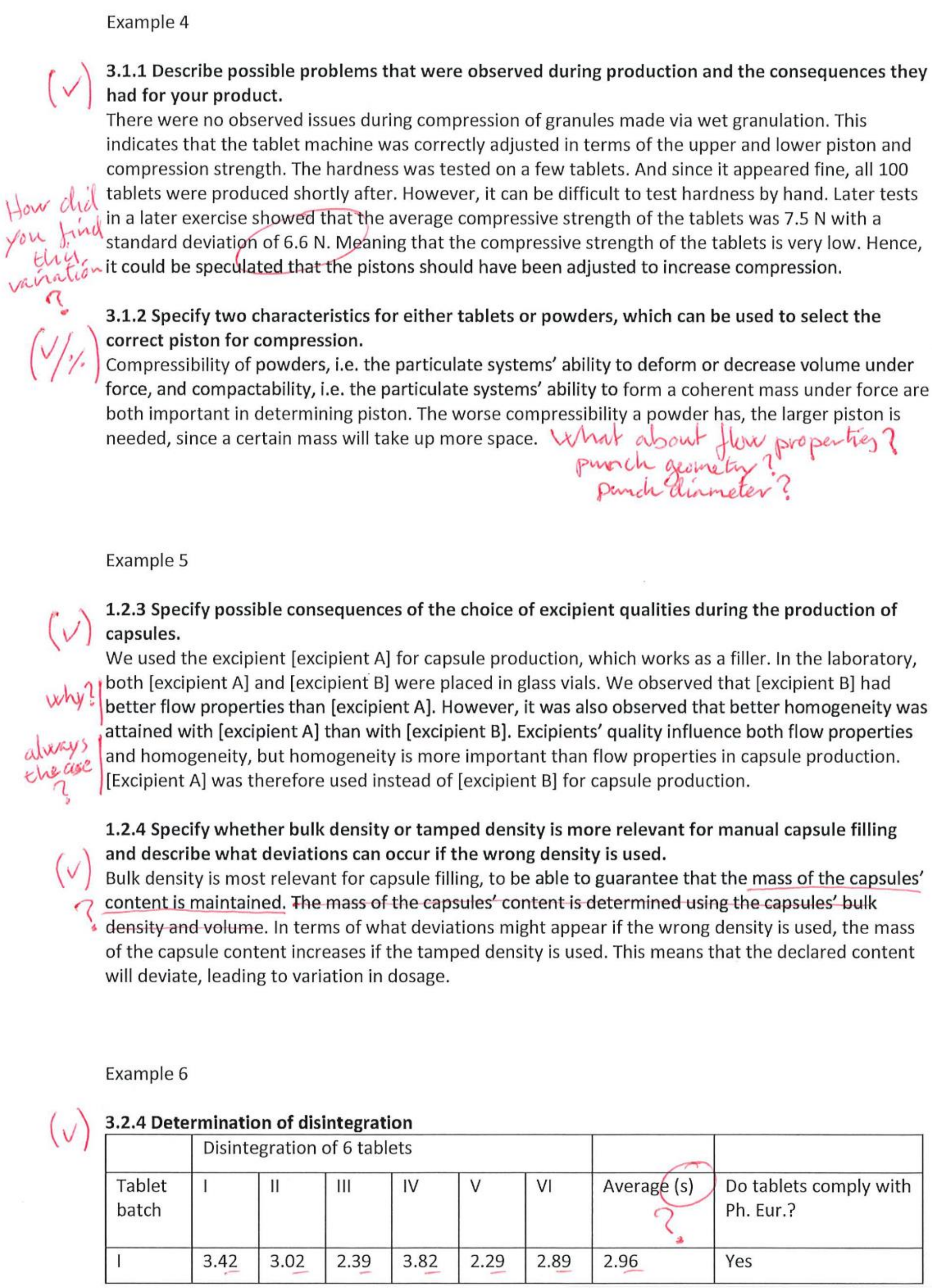
Median: 28.073 µm; 63.673 µm; 122.944 µm; 146.125 µm and 209.808 µm,

3 analyses were done with [apparatus] that were handed out because we could not conduct the exercise this year. The analysis from the [apparatus] is conducted at 1 bar, 2 bar and 3 bar. The median values of the three measurements are 70.960 µm, 223.955 µm and 64.560 µm respectively.

These values can be compared with the microscopy median of 122.944 µm. That is a deviation of 42.3 %.

1.1.2 Describe how diameter is estimated with microscopy

The particles were studied using a microscope. It could be adjusted for the particles to be viewed in an enlarged and clear version. Particles with various shapes and diameters were measured in the computer program by using a digital ruler.



Example 4

3.1.1 Describe possible problems that were observed during production and the consequences they had for your product.

There were no observed issues during compression of granules made via wet granulation. This indicates that the tablet machine was correctly adjusted in terms of the upper and lower piston and compression strength. The hardness was tested on a few tablets. And since it appeared fine, all 100 tablets were produced shortly after. However, it can be difficult to test hardness by hand. Later tests in a later exercise showed that the average compressive strength of the tablets was 7.5 N with a standard deviation of 6.6 N. Meaning that the compressive strength of the tablets is very low. Hence, it could be speculated that the pistons should have been adjusted to increase compression.

3.1.2 Specify two characteristics for either tablets or powders, which can be used to select the correct piston for compression.

Compressibility of powders, i.e. the particulate systems' ability to deform or decrease volume under force, and compactability, i.e. the particulate systems' ability to form a coherent mass under force are both important in determining piston. The worse compressibility a powder has, the larger piston is needed, since a certain mass will take up more space.

Example 5

1.2.3 Specify possible consequences of the choice of excipient qualities during the production of capsules.

We used the excipient [excipient A] for capsule production, which works as a filler. In the laboratory, both [excipient A] and [excipient B] were placed in glass vials. We observed that [excipient B] had better flow properties than [excipient A]. However, it was also observed that better homogeneity was attained with [excipient A] than with [excipient B]. Excipients' quality influence both flow properties and homogeneity, but homogeneity is more important than flow properties in capsule production. [Excipient A] was therefore used instead of [excipient B] for capsule production.

1.2.4 Specify whether bulk density or tamped density is more relevant for manual capsule filling and describe what deviations can occur if the wrong density is used.

Bulk density is most relevant for capsule filling, to be able to guarantee that the mass of the capsules' content is maintained. ~~The mass of the capsules' content is determined using the capsules' bulk density and volume.~~ In terms of what deviations might appear if the wrong density is used, the mass of the capsule content increases if the tamped density is used. This means that the declared content will deviate, leading to variation in dosage.

Example 6

3.2.4 Determination of disintegration

	Disintegration of 6 tablets							
Tablet batch	I	II	III	IV	V	VI	Average (s)	Do tablets comply with Ph. Eur.?
I	3.42	3.02	2.39	3.82	2.29	2.89	2.96	Yes

Figure 1. Six examples of types of handwritten feedback in a laboratory report. Each example consists of one or two questions (bold) and answers from students (plain text). Examples 1-3 are from three different groups answering the same questions. The material is translated, rewritten and redrawn from student reports by the researchers.

The handwritten markings and short comments are intended to guide the students to sections in the textbooks for further learning. One teacher (T1) describes how the most superficial feedback – as a minus or tick mark – provides students with immediate feedback on an error they can correct. Thus, the teachers' intentions with the simple corrections are to provide students with an overall sense of the quality of their report and make them aware of what they did correctly or point to specific parts where they made errors:

> T2: So what [i.e. the feedback] they get on the written report, that is relatively crude: It's like, "that's right", "that's wrong", "something is missing here", and some cues.

This teacher expresses that students are responsible for their own learning and if the students want to develop their understanding, they should work on this themselves:

> T2: But then it is ... It's in that way that we try to get them to take responsibility themselves, because like [...] I cannot learn for them. I can only help them.

However, students do not describe using the short comments as an easy help to continue their learning. For example, when a student (S1) is asked about a specific minus in a report, the student does not know what the actual error is or what a correct answer would be, and since other groups also had an error at that specific point, the student's group could not get help. This same student also describes being unable to act on a specific marking made by the teacher in the assignment – a tick in parentheses:

> S1: you don't necessarily know what the error is or what is missing.

This student describes that in other courses, the student would go through a report and make sure to know all correct answers to be able to use the reports in preparation for the exams, but the brevity of the comments or the lack of useful information resulted in the student not doing that in this course.

A second student describes how the group was unable to interpret the written feedback:

> S2: For assignments as such as these, we go through it all. [...] And then we must figure out for ourselves what it was, because [...] [the teacher] has not made any underlining, or any circle, or anything. [...] I laughed when someone from my group wrote how [they] cracked up that so much was in parentheses. [They] did not think all those parentheses [laughing] made sense [laughing]... So, the first thing we noticed was actually all the parentheses.

A third student describes difficulties in interpreting the written feedback:

> S3: So, I do not quite know what [the teacher] means by just making a circle and a question mark.

At another instance where the interviewer asks how to interpret a specific minus in parentheses next to a tick mark in the student's report, the student replies that they have no idea. Finally, a fourth student also has difficulty with the markings on their report and expresses some disappointment about this:

> S4: then we had to hand in the report physically [i.e. on paper], and then we get it back physically, and then there are [...] written comments throughout. But we experienced that actually there was just a minus when things were wrong, and it did not say what was wrong, or maybe was elaborated in some places if something was correct. So, it was mostly like tick or minus. But it was not really [...] I do not think that is such good feedback to receive on a report.

The teachers' intention with the written feedback is apparently not met as students often find themselves unable to use the comments. Furthermore, even if groups go through the comments together or even reach out to other groups, they may have difficulty resolving what is referred to in the brief written feedback.

Conceptions of formative feedback in whole-class

Some misalignment between teachers' and students' conceptions of the formative feedback provided on the laboratory reports and the subsequent whole-class feedback session emerge from this theme.

In the whole-class feedback session, a teacher presents and clarifies the most common misunderstandings and errors in the reports. This is intended to be an opportunity to elaborate on the written feedback. Thus, students are encouraged to ask questions about the exercises and the reports. This feedback does not necessarily relate to the *individual group's* work. A teacher explains how the whole-class feedback sessions are organised:

> T1: I usually have a PowerPoint, and they are usually fond of that [...] where I have, like, general errors, I then cover in the plenary with them. [...] My rule of thumb is if more than one group has made a mistake on this problem, well, then we'll include them in the slides

One teacher describes the process and their expectations of the students as follows:

> T2: You [students] do it as best you can, then, we look at it once, and then we talk about it. [...] We say it's up to you [...] if you feel you're on top of it, fine. [...] If you feel that you don't understand, then you must continue working on that on your own. So, they must have responsibility for their own learning."

Although students receive their reports with written feedback and take part in the whole-class feedback sessions, they often find themselves unable to act on the feedback provided and are then unable to continue their learning:

> S1: We have not been able to correct anything. […] We missed a little more like: ”You have misunderstood…”… for instance, a more in-depth, or like, constructive feedback. For example, something about how we can do better next time.

Even though this student asks for suggestions on improving, the group has not used a piece of written feedback where the teacher explicitly suggests what to look up and where. When asked about it, the student says:

> S1: But uh ... Yes. There we should have looked at the book [the teacher] refers to, but… well, we did not get around to it.

In that example, the student missed an opportunity to use the feedback, not because the instruction was unclear or too brief. However, as it is clear to the student what should be done, the student can return to this later – for instance, before the final exam in the course.

In the whole-class feedback session, students do learn something, but they still feel that they have unanswered questions. An example is:

> S2: We’re not so happy with the feedback. […] We have had a [whole-class feedback session] where we could ask about it, but we have not had the opportunity to, like ... go very in-depth with the teacher. […] [In the whole-class feedback session], [we] went through some …, something in the plenary as a whole-class […] And then you have not in the same way …, the same way had your errors explained to you.

Thus, it appears that students feel that the whole-class feedback is unrelated to specific problems in their reports and that opportunities for close dialogue with the teacher are limited because of class size and the online format (due to the COVID-19 lockdown).

Conceptions of summative feedback

Teachers are aware that the assessment of the reports has both formative and summative functions; this is the main finding within this theme, and some teachers suspect that this may lead some students to focus on passing the report delivery rather than promoting their learning. This suspicion is partly confirmed in the student interviews.

The assignments for the reports include questions relating to each laboratory experiment, the different units of operation or the conducted procedures. Reports should demonstrate that students have done the laboratory work correctly and answered the relevant questions. In cases where students have made critical errors, the report will be graded “not passed”, and the students will have to resubmit. A senior teacher described this as a problem because it makes some students focus on passing the report rather than learning:

> T1: You see [students] who think that - and again, that may also reflect their interest - if they can give an answer, and a report can be approved, or at least should not be resubmitted, then that’s what they’re aiming at.

Another teacher also suspected that the feedback teachers provide is not always used in the way it was intended:

> T2: Again, the feeling you have that those who do not need it keep working on it. […] [Whereas] those who have not understood anything, they think: “Yes! We do not have to resubmit. We are done with this course.” […] And then the theoretical exam comes, and then they flunk because they have not looked at it again or thought any further.

None of the five students who were interviewed explicitly said that they only produced the report to get it accepted. However, two students mentioned that they move on to other work once it is accepted:

> S1: You just get it out of your head quickly because you think more about the other courses. Is there something else I can work on?

Thus, although no student interviews reveal any students bluntly focusing on “passing rather than learning”, we find indications that some students may disregard the formative feedback provided by the teachers if the report has been passed. Some students tended to focus more on the summative aspect of the assessment than the formative.

Opportunities for interaction

Opportunities for interaction on written feedback

The written part of the feedback is asynchronous; it is given by the teacher at one time and can be considered by the students at another. It does not entail a dialogue between students and teacher(s). A teacher (T2) explains that this is time efficient for the teachers and that students are responsible for revisiting their reports and diving into the assignments if they want to learn.

Opportunities for interaction in the whole-class feedback session

The whole-class feedback session is intended as an opportunity for students and teachers to interact as students can ask questions regarding their reports. One teacher will conduct this feedback session and will use it to cover mistakes, problems and misconceptions that were widespread in the students' laboratory reports:

> T2: And then we use these [whole-class feedback sessions] to talk about the general issues that we have observed during the report correction. So, if there are some mistakes that they have all made in their report, then that is what we focus on.

Students describe that some issues were clarified in the whole-class feedback sessions, but they also express that they would like other opportunities to talk to the teacher who corrected the report because the content of the whole-class feedback was difficult to connect with the problems in the group's report:

> S2: but we have not had the opportunity to, like... go very in-depth with the teacher.

> S4: But of course, we can... we have been able to use it as a supplement to the assignments that have been presented. But that does not necessarily mean that these are the tasks that have been problematic for our group [...] So really, I think I was left somewhat disappointed because it was not really that instructive [...] It might have helped with a few things, but there were many other questions [...] which I do not think I got answered.

> S1: it is not possible for us to talk to our teacher who reviewed the report, which is a little bit ... It's a bit frustrating [...] You really miss a lot of understanding when you do not have someone to talk to like that. But of course, under certain conditions, you just absorb it as best you can.

The "certain conditions" mentioned in the final quote refer to the situation that the session had to be conducted with half the students online due to restrictions related to the pandemic. Hence, it is acknowledged that engaging with the teachers would have been easier in an onsite learning situation.

Teachers intend to follow up on widespread errors and scaffold the continued learning of many students, but students find it difficult to make relevant connections to their reports and yearn for more direct interaction with the teacher. Instead, all five students mention that they are using other students when trying to make sense of the report, for example:

> S4: Then we can ask our friends, classmates, if they have a report so you can have a look at how they have done it.

Opportunities for interaction in the laboratory setting

A recurring theme in the interviews with both teachers and students is the feedback provided in the laboratory setting. Teachers describe the usefulness and problems related to students' collaboration in the laboratory. Some teachers describe the laboratory as a good place to talk to students about their learning and the reports. Similarly, the students mention that the laboratory is a good place to talk to teachers and fellow students.

Teachers mention the opportunity for students to collaborate in the laboratory, but there is some disagreement about the outcome. One teacher explains how students learn to help each other:

> T3: They do group work all the time. They have to divide work. … [T]hen they learn to … split the group, but still work together: Help each other, and move around in their group so they can see what the other part of the group has worked on.

While the division of labour can be perceived as positive through the collaboration it affords, the sizable groups can also imply that some students miss out on valuable learning:

> T2: And we have groups of 4-5 students. It's fairly easy to be a free rider to an extent. […] That is kind of the impression you get. Like, you could get a lot more out of it if you wanted to. And I think those who want to, do get something out of it. But some get nothing out of it, because you can sneak through too easily.

The laboratory provides an opportunity for interaction between students and teachers about reports before delivery of the reports. For example, one teacher explains how fundamental mathematical miscalculations are quickly cleared up:

> T4: suddenly, they are there saying: "But we have to get the right weight for the tablet, within something, half a mg…and that cannot be done". And then I'm like: "But that … that cannot be done at all […]" And then I ask if I can see it, and then I find the exact place where it went wrong.

Another teacher (T3) explains that teachers do not necessarily meet the same students throughout the course, so continually talking to them about their learning and judging their progression is difficult. This teacher expects that the large number of students is the reason, but tries to talk to all groups in the laboratory:

> T3: Usually, when I go around, I always ask if they have any questions first, and if they don't, then I come up with some.

The student interviews also reflect that the students see the laboratory as an excellent place to talk to teachers and get valuable input for the reports:

> S2: [The report] is like a completion of the laboratory teaching. To one hundred percent understand what you did in the lab. [And] you have an opportunity to ask questions in the laboratory, to the teachers.

S3: We are going in the laboratory again here on Thursday, and then you will talk to them there. [...] Because we had the opportunity to do that with the other assignments, here in the report, exercise 1, where we got to talk a lot with the teachers during the laboratory, and it was ... Yes, you get many pearls of wisdom, ha ha.

The benefits of interaction in the laboratory are highlighted both by teachers and students. For students to collaborate, as a venue for students and teachers to talk to each other where students feel they can get the feedback they find relevant for their learning.

DISCUSSION

The interviews show that teachers have specific and thought-through intentions for providing formative feedback to the students on their report work. First, in the form of a pre-lab quiz, then through dialogue in the laboratory prior to the report delivery, then in the form of simple written corrections on reports, and then by providing whole-class feedback focusing on the most general problems encountered in the students' reports. In addition to this structure, the course is organised with students working in groups helping each other out and in smaller classes where they can also share perspectives. On the positive side, the interviews with students demonstrate that students depend on the group structure and the class structure to seek guidance and help.

In both teacher and student interviews, they express that they value the close teacher-student dialogue in the laboratory setting. They find the laboratory functions as a vital context for dialogue between students and teachers, as described in research.[20]

However, the interviews also show that students do not necessarily experience congruence between the planned teaching and learning activities and the assessment in the staged feedback process related to the reports. Written feedback in the form of simple corrections is often considered less ideal compared to more detailed feedback,[2] and students prefer personalised or individualised feedback to generic whole-class feedback,[21] which may be difficult for individual students to employ. In this course, we see these two forms of feedback linked so that students ideally should know what to act upon and which of the feedback given in the whole-class feedback pertains to them and their report. However, while teachers intend for this staged feedback approach to increase students' ownership and ability to act on the feedback, we see that students may still fail to use the feedback for learning and end up being somewhat dissatisfied with the received feedback in the process.

Teachers emphasise that the whole-class feedback session is the place to discuss reports. Students agree that there is something to gain from these sessions but often find that the feedback becomes too general and does not provide (enough) opportunity to talk to the teacher. Feedback might be better received and acted upon if time were allocated to meet face-to-face and give oral feedback.

A contributing factor may be related to course organisation and management because this is a comprehensive course with many teachers involved. Thus, the teacher who corrects reports may be unable to talk to those students about that report in the laboratory. Whole-class feedback sessions attempt to provide this opportunity but do not provide adequate room for engaging teachers and students in fruitful dialogue about the reports. In this way, some students experience a lack of congruence between assessment and feedback and the course organisation and management.[13]

In recent years feedback has increasingly been described as a process involving students actively;[21] for feedback to be effective, students should engage with it. Thus, a general and straightforward criterion of good feedback is that it ends not in providing information but in students acting.[22]

Students improve when they access and spend time on formative feedback.[23] Students look at their reports and try to use the markings, but the written feedback is too brief, and the teachers do not communicate their interpretations of the students' work, details about the quality of the student report and what students can do to improve. Written feedback should perhaps instead consist of fewer comments with richer information.[24,25] Ideally, teachers should balance assignment specific with transferable feedback while including comments on why something was right or wrong.[26,27]

If the brief corrections only lead students to quickly go through their report, ignoring everything correct and not having enough information to work on the wrong things, then the feedback does not meet its potential. Some of the teachers in our interviews express that they suspect that a portion of the students will not use the feedback in the way it was intended, and the students also recognise such missed opportunities because they did not take action on the feedback themselves or did not understand how to do it. This may be seen as a lack of congruence between curriculum aims and the feedback provided.

We also see a lack of congruence between the formative feedback and the summative assessment. The lack of congruence is seen when summative and formative feedback for laboratory reports is given simultaneously. The summative intention is achieved in the way that students quickly check if their report is approved, but the formative intention is not always achieved. This may be because the focus on summative approval overshadows other possible learning outcomes. Students may ignore otherwise well-intended formative information, as is suspected by some teachers and partly confirmed in the student interviews. This matches earlier findings that summative feedback may remove attention and action from formative feedback.[8,28] If the report has been approved, then why put in the effort to understand?

In the present course, we have seen that students were relying on both their group members and members of other groups in trying to understand the feedback given. Perhaps this strength in the course and student culture can be utilised to engage students in peer-feedback activities. For example, it has been shown that students may undertake the correction of reports as a peer-assessment activity.[12] One advantage of this would be that there would be potential to increase students understanding of the assessment criteria, and it might solve some of the issues related to the many different teachers in the laboratory, in the whole-class feedback sessions and in other course units.

In the interviews, teachers emphasise time efficiency in the course structure and feedback practice. However, time-saving measures can make the feedback unclear and unusable.[27] Feedback mostly provided as right/wrong can discourage students and make them feel that report writing is pointless.[29,30] If students actively engage in the feedback process,[31] student engagement and learning could be achieved through peer-feedback.[32] For example, students could support each other's learning process by being asked to provide high quality peer-feedback on each other's writing while in the laboratory.[33,34]

Limitations

Five volunteering students were interviewed; thus, the study does not represent the general perceptions of the 200 students participating in the course. However, the recruitment of participants did not pertain specifically to the congruence of feedback practice, which limits the risk that the selected students had strong agendas regarding this topic. Nevertheless, results should be generalised with caution

Teacher intentions were compared with actual feedback and course materials. However, regarding the student perspective, results stemmed from what students said and not what they did. Thus, the study can easily highlight teaching practices while overlooking student practices.

There is little doubt that the COVID-19 restrictions have affected the students learning experience.[35] The interviews were performed after an unusual course set-up as whole-class sessions were conducted in an online format, and restrictions on presence at the university made it difficult to hand in and re-collect written reports promptly. In addition, it has likely meant that the whole-class feedback sessions have been less student-centred than is usually the case. Thus, the students' perceptions of the quality of feedback in whole-class feedback sessions probably have been influenced negatively.

CONCLUSION AND IMPLICATIONS

Teacher intentions and student perceptions of feedback on laboratory reports have been explored within the congruence framework. The importance of congruence in facilitating high-quality learning for students and interconnectivity of the areas of congruence has been confirmed. Thus the students' perception of congruence concerning the feedback on laboratory reports has been shown to relate to:

- How the teaching activities in the laboratory provide the students with relevant feedback that they use in their reporting
- The course organisation and management (e.g. the number of teachers and tasks of the teachers, the organisation of the course in groups and classes)
- The relationship between formative and summative assessment in the course and how the summative assessment may distract from the formative functions of assessment.
- The learning support: Brief markings in feedback on reports do not appear to serve the functions intended by the teachers, as students are often unable to act on the provided feedback.

The implication is that high-quality learning might be supported by focusing on relevant and clear feedback that facilitates continued learning and affords student engagement and interaction. For example, a small change would be to develop a key for students' to interpret brief markings, and a big change would be to change the feedback process so students' are incentivised to act on written feedback. The laboratory is an essential venue for achieving this, and incorporating additional time for peer-feedback and teacher-student feedback might increase the use of the feedback. A large number of students can hinder the easy implementation of course changes. However, feedback must add value to students' learning and use teacher time well. Therefore, it is worthwhile to allocate resources to achieve effective formative feedback.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.XXXXXXX. [ACS will fill this in.]

Interview questions (PDF)

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Paper 3

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Progression of laboratory learning outcomes in the third year of pharmaceutical education

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Progression of laboratory learning outcomes in the third year of pharmaceutical education

Abstract

In higher education, laboratory work provides students with distinct learning experiences and offers an entry into the nature and cultural practice of science. In this article, we take a longitudinal and simultaneous view of teachers and students perception of learning and progression in laboratory education. To gauge progression, we conducted a longitudinal study based on teacher and student interviews, as well as analyzing program and course descriptions for the third year in a pharmaceutical bachelor's program. The empirical material was analyzed with respect to perceptions of learning and the structure of the observed learning outcome (SOLO) taxonomy to synthesize intended learning outcomes that represent progression. With this, we present empirically based learning outcomes that show progression of laboratory learning outcomes, where especially independence is viewed as a prerequisite for progression. The results presented thereby expand our understanding of laboratory learning outcomes in higher education.

Introduction

Higher education train students to become independent learners, support students in learning competences they need for a future career and science programs often plans for ongoing laboratory experiences as part of the curriculum. Laboratory work is an activity that affords unique experiences and learning outcomes in higher education science (Reid & Shah, 2007; Agustian et al., 2022). As a central practice and integrated part of the curriculum, laboratory work offers an entry into the cultural practice of science. In addition, the close connection to, dialogue with, and feedback from teachers further strengthen students' learning processes in the laboratory (Finne et al., 2022). In the laboratory, students can learn to handle instruments, test theory and concepts, and over time build identities on the trajectory to become scientists. In this longitudinal study, we investigate the progression of learning outcomes of laboratory work in the third year of the bachelor's program in pharmacy at the University of Copenhagen.

Progression of laboratory teaching traditionally have first-year courses being highly structured and organized through a progressive development towards the final year courses that are more driven by independent student critical reflection on practice (Prades & Espinar, 2010). Recently, it has been shown that an entire pharmaceutical program can be built on the idea of inquiry-based teaching, with a focus on student autonomy, already from the first year (Meijerman et al., 2016). Still, increasing student autonomy throughout the program is emphasized.

In this paper, we employ the concept of constructive alignment to focus the study. When aiming for alignment in a higher education program, it is central to align expectations in planning, execution, and experience at the program and course level to support student learning (Biggs & Tang, 2011). To secure constructive alignment, teachers and course planners must settle on a few intended learning outcomes that provide an overview of the course and communicate their integration with teaching and learning activities and assessment tasks (Biggs & Tang, 2011). To sharpen the focus on learning outcomes, we apply the established framework: Structure of the observed learning outcome (SOLO). SOLO is an empirically developed taxonomy of learning outcomes that describe a specific performance at a particular time. The taxonomy is arranged in five steps: Prestructural, unistructural, multistructural, relational, and extended abstract (Biggs & Collis, 1982). Within these steps, appropriate corresponding action verbs have been formulated to develop learning outcomes (Biggs & Tang, 2011). The SOLO taxonomy has previously proven useful in research on pharmaceutical and laboratory education, e.g., in evaluating learning outcomes of e-learning tools (Baumann-Birkbeck et al., 2015; Karaksha et al., 2014) and within higher education to develop a rubric for capturing students' knowledge progression (Ramberg et al., 2021). SOLO was also chosen as the framework in the context of broader development for laboratory experts in the global health sector (Albetkova et al., 2019).

A review of empirical research on learning outcomes of laboratory work in higher education recently found that laboratory learning outcomes can be grouped into five clusters: Experimental competences, disciplinary learning, higher-order thinking skills and epistemic learning, transversal competences, and the affective domain (Agustian et al., 2022). These clusters are derived from a wide range of laboratory learning outcomes in higher education chemistry teaching, and in this study, we focus on a specific context and explore how progression can be shown in the five clusters.

The present research investigates how learning outcomes develop longitudinally, using a dual perspective of teachers and students. The study aims to contextualize the perception of progression in a specific program and add new insights into how laboratory learning outcomes change with the changing context through laboratory courses to bachelor's projects in pharmaceutical education.

Research Question

This paper explores the perception of progression in the third year of pharmaceutical education through analysis of official university documents, i.e., program and course descriptions, and interviews with students and teachers, guided by the research question:

- How do teachers' and students' views on laboratory learning outcomes show the progression from the context of two laboratory courses to the context of a bachelor's project?

Methods

Educational context

This research was conducted in the third and final year of the Bachelor of Science (BSc) in Pharmacy at the University of Copenhagen (UCPH). Approximately 200 students distributed in eight classes are enrolled. The empirical material was collected in two courses with substantial laboratory work and while students conducted their bachelor's projects (Table 1). Most students continue into a two-year master's education, as is common practice in Danish higher education (Danmarks Statistik, 2017; Hovdhaugen & Ulriksen, 2021).

Table 1. Context information. Data collection was conducted during three courses at the pharmaceutical bachelor's degree program at [anonymized]. The third year also includes the courses Systems Pharmacology, Pharmacotherapy and two electives in which no data was collected.

Course	Drugs from Nature	Pharmaceutics 2	Bachelor's project
ECTS	7,5	7,5	15
Time period	Aug-Nov 2020	Aug 2020 - Jan 2021	Feb-Jun 2021
Lecture hours	25	40	4
Classwork hours	25	8	40
Laboratory hours	24	21	96
Estimated preparation	130	134	180*
Exam	2 hours written. Participation in laboratory exercises and report submission.	3 hours written. Participation in laboratory exercises and report submission.	Written project report. Oral examination

*In addition, 82 hours of project work and 10 hours of supervision is estimated

Official documents

In coherence with the Bologna process and the European qualifications framework (European Commission, n.d.) Denmark and thus UCPH have implemented the Danish qualifications framework (Ministry of Higher Education and Science, n.d.). Descriptions of the program of study (Faculty of health and medical sciences, 2018) and the specific course descriptions (University of Copenhagen, 2020b, 2020a) officially regulate the content of educations and contain intended learning outcomes presented as objectives within competence, skills, and knowledge (Cristiansen et al., 2015). The documents constitute the study program's frame and intention as well as detailed information on learning outcomes on both bachelor's and master's levels.

Interviews

One-hour semi-structured interviews were conducted with teachers and students during two courses and while the students did their bachelor's projects (Table 2). Interviews were held over 10 months. Student participants were recruited through their learning management system while enrolled in the courses. Teachers were recruited by snowball sampling (Rosenthal, 2016) where the course responsible teacher was interviewed and then suggested additional interviewees. All interviewees signed a declaration of consent per current data protection legislation. The interviews contained multiple topics related to laboratory teaching and learning. Questions from the interview guide are available in Appendix A. The interviews started with open questions on the program, the course, and the exercises. Towards the end of the interviews, the five clusters of laboratory learning outcomes (Agustian et al., 2022) were presented and described by the interviewer using a list that showed the clusters and related constructs (Appendix B). Then participants were asked to elaborate and discuss how the five clusters of laboratory learning were expressed in their course (teachers) or for themselves (students). Thus, the interviewees were introduced to terms defining the clusters and used some words in their continued reflections and explanations. An uninvolved outsider transcribed interviews. Interviews, transcription, and analysis were conducted in Danish, and the final quotes for publication were translated into English.

Table 2. Interviewed teachers and students and the context of the interview. 23 interviews in total.

Interviewees T=Teacher, S=Student	Drugs from Nature	Pharmaceutics 2	Bachelor's project
T1	X		X
T2	X		
T3	X		
T4	X		
T5		X	
T6		X	
T7		X	
T8		X	
T9			X
T10			X
S1	X	X	X
S2	X	X	X
S3	X	X	X
S4	X	X	
S5		X	

Analysis

The analysis of the empirical material was conducted in several steps. First, the transcribed interviews were coded pertaining to the five clusters of laboratory learning outcomes using NVivo (QSR International Pty Ltd., 2018) see illustrative quotes in Table 3. This analysis was conducted with a semantic and theoretical approach (Braun & Clarke, 2006) with the five clusters of laboratory learning outcomes (Agustian et al., 2022) used as the applied second step, and results were compiled in the five clusters sorted within each course and as teachers and students, making it possible to analyze across each of the five clusters. In the third step, the sorted material was analyzed concerning objectives, aims, goals, and outcomes. Then, the levels and verbs related to the SOLO taxonomy (Biggs & Collis, 1982; Biggs & Tang, 2011) were applied to synthesize a set of learning outcomes for each of the five clusters. In a fourth step, progression within each cluster was analyzed with respect to experiences when teaching moved from laboratory courses to bachelor's projects. This was compared to the official documents.

Results

In this longitudinal study, progression is analyzed in the transition from the context of laboratory courses to the context of making a bachelor's project. The development students are expected to undergo in this transition is substantial and present in multiple places in our empirical material. The development is linked to an expectation of students becoming more independent in everything from conducting experiments to managing a project process. The analysis identifies different discourses around independence linked to open and closed activities, the overarching aim of the program, and the way students and teachers talk about learning in the laboratory.

Progression framed as independence

When analyzing the empirical material with a progression lens, we find that both teachers and students identify a clear connection between progression and independence. The expression of independence is the lack of it in courses to an explicit expectation of independence in the bachelor's project, where students plan and conduct an independent laboratory-based project.

In design and planning experiments

The analysis shows that the main difference between courses and the bachelor's project lies in the design of the laboratory work and the expectations of how the students work. Teachers describe how they design laboratory work as assignments with a clear workflow and instructions in courses. The laboratory work is constrained with the purpose of teaching students to follow a protocol or be able to repeat experiments.

> They do not learn that so much here [in this course] . . . We're still in some cookbook . . . Or it's a description of exactly what they're doing. Take this, mix it up. There is a SOP by the apparatus. . . . It's more in the bachelor's part that they learn to design experiments (T6 P2).

> [T]hey simply become better at being in the laboratory, and they become better at handling, doing experiments. . . I allow myself to call it a craft. Sometimes chemistry and analytical chemistry are crafts (T1 DfN).

The contrast becomes apparent when the bachelor's project is described as an open exploration. Here, students are expected to apply their knowledge from previous courses and work independently throughout the research process, from idea to design and data analysis.

> [T]hey [the students] must constantly design and plan experiments, they must perform them themselves, they must analyze data themselves. They really use some of what they have learned in the laboratory and must work independently and apply these practical skills (T9 B).

Students experience this additional expectation of independence in the bachelor's project as an increased responsibility for making decisions and managing the research and learning process. This is both challenging and empowering, and for some, it adds a new dimension to the laboratory work being fun.

> We have designed an experiment, conducted it and analyzed it ourselves. And again, like I said, it is also something independent. Work that we design ourselves and have done everything from scratch … Well, we do everything ourselves and that is very independent. (S1 B)

> [I]n the bachelor's lab ... we have had to be much more independent. At the same time, it has also been a lot of fun, because we had to go and do what we have planned**,** and like you have managed and structured it yourself, well, tomorrow we have to do this and that, and it just makes it a bit more fun to do the work because you can see the point of it and you can just put it into such a long-term plan (S2 B).

This student further describes an increase in independence in the explicit expectations of the written assignment based on their work in the laboratory.

> [A]ll our laboratory work usually just results in us answering some questions. This is the first time we just must . . . or not quite the first time . . . that we prepare a longer written assignment about the laboratory, where we have both theory and method and these different things. . . but it is also very much the written and the way you communicate things that is important (S2 B).

The student explains how there is a new type of expectation in the bachelor's project. The more open-ended process of the project is also seen in the written assignment, where students are expected to include theoretical and methodological considerations. This underlines the progression from tightly structured laboratory activities in courses to the independent learning process in the bachelor's project.

In solving problems

The progression between courses and the bachelor's project is further evident in the way teachers expect students to be able to solve problems. In courses, students are not expected to do problem-solving but rather show that they can follow instructions.

> They definitely have to relate to what they get. Their results and stuff like that. But it is not problem-solving, as such. They do not have to solve a problem. They just must show what they have done is right (T3 DfN).

Teachers express this notion in both courses leading up to the bachelor's project, and advanced problem-solving is therefore postponed and introduced in the bachelor's project.

> [T]hese are more things they learn in the bachelor's, where they must really get started with problem-solving. It's not the focus [in] Pharmaceutics 2, I would say. It is more the bachelor's project, which focuses on . . . higher-order thinking (T8 P2).

Students experience this progression in problem-solving as being challenged for the first time. The new type of expectations, i.e., being critical and making choices in their independent project, is not recognizable from teaching in the courses.

> [H]igher-order thinking, something like thinking critically and being able to solve problems, yes, and again I think it is even more expressed here in our bachelor's project, because it is ourselves who are responsible for it. It is up to us to make choices and be critical of our own choices . . . that is usually not something we are challenged so much with in the courses, because as I said, it is a given what it is we must do (S2 B).

This student sums up the new challenges as linked to all elements of conducting an independent project; design, planning, problem-solving, and communication of results. The progression from coursework to working on the bachelor's project is understood as increased responsibility in decision-making, managing, and carrying out the project.

Coherence across material

The longitudinal analysis above shows a similar perception among teachers and students about progression expressed as an increase in independence when transitioning from more expository laboratory teaching in the courses to the bachelor's project. That transition is also evident from analysis of the official documents, i.e., program description and course descriptions. Importantly, this tells us that the transition is intended and planned in the program.

The program description highlights how graduates can independently analyze, evaluate, and solve pharmaceutical scientific problems. The description also states that students learn to work according to good laboratory and manufacturing practice (Faculty of health and medical sciences, 2018).

The course description of Pharmaceutics 2 focuses on following procedures and learning to use apparatus correctly. It states that students can produce drugs by following standard operating procedures (SOP) of equipment while following and documenting good manufacturing practice (GMP) (University of Copenhagen, 2020b). The course description of Drugs from Nature focuses on a list of procedures and corresponding apparatus that students learn to use, also in concordance with the European Pharmacopoeia (Ph.Eur.) However, it states that students learn to act as independent persons in cross-disciplinary research projects and that students can act independently according to good laboratory practice and take responsibility for planning experiments (University of Copenhagen, 2020a). Hence, some level of independence is officially expected here, but not to the same degree as in the bachelor's project.

The course description of the bachelor's project is clear that groups of students should independently plan, design, and conduct the formulation, production, and evaluation of a drug. Here, the focus is clearly on ensuring that students take responsibility for all steps in the project. Some of these steps are still in terms of maintaining GMP, such as relevant batch documentation (University of Copenhagen, 2020c).

The analysis of the course descriptions shows that students are expected to work independently to a high degree in the bachelor's project and less so in the preceding courses. Across the material, official documents, and interviews with teachers and students, a progression is expressed as an increased level of independence. The official intended learning outcomes, the expectations from teachers, and students' experiences are coherent and we argue that this is an expression of constructive alignment.

Laboratory learning outcomes in the pharmaceutical program

Now we focus on learning outcomes related to pharmaceutical laboratory work and their progression. The interviews were conducted using the five clusters of laboratory learning outcomes. The five clusters are derived from previous research to categorize learning outcomes in laboratory work (Agustian et al., 2022). Examples of relevant interview data are presented in Table 3.

Table 3. Additional illustrative quotes from teachers and students pertaining to all five clusters of laboratory learning outcomes.

Cluster	Illustrative quotes	
Experimental competences	Well, some of them definitely learn this, and some might learn parts of it. . . . Designing experiments. They do not learn that so much here. We're still in some cookbook . . . Or it's a description of exactly what they're doing. Take this, mix it up. There is a SOP [standard operating procedure] by the apparatus. Pres this button, click, click, click, click. When you clean, do it like this. It's more in the bachelor's part that they learn to design experiments (T6 P2).	[we must] [F]ollow our protocol in every exact way (S2 DfN).
Disciplinary learning	[T]his connection between theory and practice. I hope they [the students] all get that, especially when we walk around and ask them. . . . I think it's one of the most important things (T8 P2). [T]o define the project, to design the experiments, they [the students] must have adequate theoretical learning. If they do not understand the connection between theory and practice, well then it becomes a mess, then they don't get very far (T9 B).	[G]et better at theory because I've had it in my hands. . . . That's probably exactly what I associate with laboratory work. Because I learn the academic content when I'm in the lab. Remember it and remember it even better than if I had read it in a book, or if I had heard it at a lecture (S3 DfN). You have it in your hands and are allowed to actually see a finished product that I have . . . Something I have read in a book, now I have it in my hands. Now I have something we give to a patient. So that's like then you can finally fuse things together. It's not that separate anymore (S5 P2).
Higher order thinking skills and epistemic learning	[T]he pharmacopoeia monograph is not necessarily the best method . . . you are actually working on a method that is not necessarily state of the art, but which is something that as many people as possible should be able to do (T1 DfN). You can quickly . . . get an idea of whether they generally just want an answer they can write down, or if it is something, we can discuss (T6 P2).	I think it might be more if you are [in] bachelor's lab or something where you are a little more independent (S2 DfN).
Affective domain	[Prepared students act] calmer (T1 DfN).	[The lab can be] fun (S2 DfN). [The lab can be] very exciting (S3 DfN). [The lab can be] boring (S2 DfN).

	[M]any of these affective outcomes. I think they come from the bachelor's course. It does not come with us. I do not think that Pharmaceutics 2 give much of such pleasure in laboratory work, or motivation or responsibility for own learning. Because it's not ... It's too short (T5 P2).	And you are completely exhausted when you get home. . . . So physical fatigue can be a bit demotivating. . . . I mean when you have been in a 7-hour lab, then the last hour you want to get away, ha ha. . . . I don't think I learn much in the last hour and a half . . . Because there you just focus on cleaning, and you need approval before you leave and stuff like that. So the mind is somewhere else. It's not learning (S1 DfN). I'm usually a little more careful when it comes to the lab. I'm afraid of doing something wrong, or that something will happen because I mix something. It has definitely been something that has, ha ha, done something good for me, to be in, in the bachelor's lab here, where we have had to be much more independent. At the same time, it has also been a lot of fun, because we had to go and do what we have planned, and like you have managed and structured it yourself, well, tomorrow we have to do this and that, and it just makes it a bit more fun to do the work because you can see the point of it and you can just put it into such a long-term plan (S2 B).
Transversal competences	They do group work all the time. So they have to split up. . . . But still work together, help each other, and exchange [work] around in their group (T8 P2).	(One) has to argue why one should do it one way, rather than the other way, and one has to write a report afterwards and stuff like that. Then you also get a really big transversal return (S2 DfN).

From this, we employ the SOLO taxonomy to create a set of statements from the empirical material. These statements are empirically backed intended learning outcomes, showing progression within the five clusters. The synthesized intended learning outcomes are presented in Table 4. In Table 4, the intended learning outcomes are sorted in the corresponding level of the SOLO taxonomy, indicated as U = unistructural, M = multistructural, R = relational, and E = extended abstract. Furthermore, they are divided into two columns, the courses and the bachelor's project, which provides us with another view of the difference between these contexts. The analytical argumentation is presented below for each cluster of learning outcomes.

Experimental competences

In this cluster, teachers and students in the laboratory courses mention learning outcomes related to the practical parts of the laboratory itself, such as familiarity with safety goggles, the use of glassware, and the handling of equipment akin to learning a craft. They also emphasize the need to follow experimental procedures and standard operating procedures of apparatus. Finally, they mention decision-making and designing experiments as crucial features of the bachelor's project.

Disciplinary learning

Teachers and students agree that an increased understanding of theoretical concepts is an important learning outcome of laboratory activities. Either as a simple recognition of the relation between course elements or as a complex understanding of theory-practice connections. The bachelor's project interviews expose the complexity of learning about the theory-practice relation. One teacher says that connections are established late in the process, during the interpretation of the data, while one student explains it the other way: They conduct the laboratory activities in a certain way based on conceptions of the theory. Another student says that theoretical understanding can be achieved without the laboratory but that a complete understanding of the laboratory activities requires theoretical insight. Some students mention that they write theoretical sections of assignments independently of laboratory activities but that meaningful participation and understanding of laboratory activities require conceptual knowledge. Taking this complexity into account, the progression within this domain is expressed as the increased ability to relate relevant theory to the activities in the laboratory.

Higher-order thinking skills and epistemic learning

In the laboratory courses, students are expected to participate in problem-solving with a practical character and are asked to discuss methods and explain why specific procedures are constructed as they are. However, teachers are clear that the laboratory exercises are very tightly constructed, e.g., as exercises based on Ph. Eur., leading them to say that there is less focus on problem-solving as a higher-order thinking skill. Teachers and students in both courses can envision the progression in the program, as they say, that there are not that many higher-order outcomes in the courses, but it will be a focus in the bachelor's project. However, some higher-order outcomes are also aimed at in the courses, and teachers are clear that students must apply critical thinking to evaluate their results to produce an appropriate laboratory report. Teachers interviewed about the bachelor's projects imagine that students can learn higher-order outcomes as thinking critically about their project, results, sources of error, and developing and testing ideas. Students similarly say that bachelor's projects result in critical reflections about their own choices regarding experiments.

Affective domain

A teacher from the Drugs from Nature course says that pre-lab activities force preparation, resulting in calmer students and better outcomes. Students emphasize how laboratory work adds to their motivation and enjoyment when it is fun or exciting, but also that it can take it away when it is repetitive, or they do not find it interesting. In the Pharmaceutics 2 course, concrete production of pharmaceutical products is perceived as motivating because of the clear contextualization, which provides success for the students and adds to their identity as pharmacists. When writing a bachelor's thesis, students are expected to take ownership and engage in activities that strengthen their meaning-making. The affective outcomes for students are influenced by conditions and other actors in the situation, including teachers, technicians, classmates, and established safety measures; one student summarizes it as becoming engaged when teachers themselves are engaged.

Transversal competences

Learning outcomes in this cluster are supposed to be generalizable and transferable to other contexts. Interviewees describe this as basic skills like preparing, maintaining your workstation, and following GMP. A teacher explains it as students managing their work in a way that is efficient for themselves. Communication tasks related to oral discussion and producing a written report require students to develop their argumentation. A transversal skill that almost all interviewees emphasize is collaboration. Groups must use each other's strengths and work reasonably and efficiently within a given timeframe for an assignment, which entails distributing work within your group and then collaborating on a joint report afterward.

Table 4. Aggregated empirical interview results are summarized and produced as a list of intended learning outcomes. All intended learning outcomes stem from interview data. The corresponding action verbs, e.g., identify or construct, are recommended for specific taxonomical levels in SOLO. The taxonomical level is indicated in parenthesis as unistructural (U), multistructural (M), relational (R), or extended abstract (E). Read "students..." prior to each outcome.

	Laboratory courses	Bachelor's project
Experimental	- Identify (U) and correctly apply practical conditions of the laboratory, such as clothing, glasses, and cleaning. - Imitate (U) practical skills and practice and apply them professionally and appropriately, such as weighing and changing apparatus settings. - Apply (R) experimental protocols, e.g., Ph. Eur. and SOP, to conduct experiments and analyze data in specific situations.	- Construct (R) an original project by relying on earlier laboratory skills and then independently design, plan, and conduct experiments.
Conceptual	- Recognize (U) concepts and theoretical ideas in the laboratory. - Integrate (R) content from laboratory exercises with content from other course activities.	- Create (E) own experiments by understanding and using relevant connections between theory and practice.
Higher order	- Describe (M) why the analysis conducted in a particular exercise is as it is, e.g., when it is based on the Ph. Eur. - Argue (R) if results are plausible by critically discussing procedures and identifying problems of a methodological and practical character. - Reflect (E) about the purpose of laboratory work, herein recognizing elements that would be part of a future career in pharmaceutical academia.	- Create (E) procedures and critically evaluate them. - Review (R) and explain (R) sources of error. - Hypothesize (E) why things turned out differently from expected.
Affective	- Illustrate (U) self-efficacy and confidence by adequate preparation and through opportunities to work independently. - Outline (M) own identity development in relation to laboratory work. - Examine (R) and acknowledge contributions from surrounding conditions and other actors. - Solve problems (R) like demotivation by demonstrating professionalism and actively engaging.	- Explain (R) and predict (R) your affective reactions. - Make a plan (R) and iterate on it with independence, pride, and meaning.
Transversal	- Order (U) an efficient workflow and follow GMP. - Organize (R) collaboration. - Construct (R) and present written and oral data-driven arguments in a clear manner.	- Reflect (E) on your learning while monitoring your project. - Plan (R) and create (E) a substantial project report in collaboration.

This analysis is not exhaustive, but the empirical material indicates a progression. The perception was scattered in interviews with teachers and students from three courses over a year, but after thorough analysis and theoretical application of SOLO, we see an empirically supported progression within each of the five clusters.

Discussion

The analysis show a progression in the transition from the context of laboratory courses to the context of the bachelor's project. Both teachers and students described the level of independence and framed it in terms of designing experiments and solving problems. The bachelor's project was experienced as more open-ended and with opportunities to obtain relational and extended abstract types of learning outcomes to a much higher degree than the laboratory work of the previous courses. Both teachers and students regarded this as important, interesting, and fruitful for the students learning process.

Synthesizing learning outcomes in the SOLO framework provides a theoretically strong view of progression. The SOLO framework emphasizes that the learner themselves are active in their development (Biggs & Collis, 1982), which further shows the importance of independence in learning.

The learning outcomes produced here tie the framework of SOLO together with the five clusters of laboratory learning outcomes (Agustian et al., 2022). This adds to our understanding of both frameworks as we see that multiple taxonomical steps are at play in all five clusters. Thereby, student learning can occur at multiple taxonomical levels in multiple clusters. The implication for practice is that teachers and students could benefit from being aware of the complexity of learning outcomes in the laboratory to become more reflexive teachers and learners.

Students experience ongoing choice processes and transitions as they progress through a science program (Holmegaard et al., 2014; Madsen & Holmegaard, 2022), and findings within health education have recently shown the transition experience in all years of study, concluding that teachers should understand their teaching in the context of the whole program (Birbeck et al., 2021). In addition, university courses have often been criticized for being planned in isolation (Biggs & Tang, 2011; Jessop & Tomas, 2017). Contrary to this, the courses in the third year of the pharmaceutical program at UCPH appear to be reasonably coherent as teachers in the third year have an awareness of the other course activities, their content, and aims, and there is some agreement on how progression should be implemented. Therefore, we argue that this awareness and coherence could be used as an opportunity to develop activities with more independent student laboratory work throughout the third year and thus avoid the bachelor's project as the sole carrier of the learning outcomes that this affords. These discussions should touch upon the overarching aims of the program, what kind of pharmaceutical scientists the program aims at educating, and what the program might look like in the future.

The construction of a program, the intentions held at the program level, and each course, govern the practice and the possible student learning outcomes of the program. An example of a differently constructed pharmaceutical program at Utrecht University focuses on more independent and inquiry-based learning (Meijerman et al., 2016). The argument for this type of program is based on the idea that independent, more open-ended, and inquiry types of laboratories a preferable from a learning perspective (Agustian et al., 2022; Bybee, 2006; Reid & Shah, 2007). However, we find some evidence for the importance of closed and tightly structured settings in pharmaceutical laboratory education. A plethora of intended learning outcomes are related to specific handling of apparatus, good manufacturing practice, standard operating procedures, quality assurance and batch documentation. We argue that these features are central in the nature of pharmaceutical science to a degree that distinguishes it from related fields. As central practices in the pharmaceutical landscape, we find that educating future pharmaceutical experts in these concepts is highly relevant and understand why some of our interviewees would emphasize this feature of the program. However, this point appears to be somewhat absent from the literature on pharmaceutical education, with one exception having it as a competency for experts in general health systems laboratories (Albetkova et al., 2019).

The abovementioned program also discusses the role of the teachers and the students (Meijerman et al., 2016). They see some success with having the teachers approve laboratory protocols during early and closed laboratory settings and then move into a more consultancy role of having continued discussions throughout a project in the later and more open laboratory activities. This is a different expression of progression linked to gradually creating more open activities with increased student autonomy. The relevant discussion is constructing and balancing open activities with closed contents. From a teaching perspective, this is not a simple task. With the present research, we wish to add to the ongoing debate on expository versus open-ended explorations (Agustian et al., 2022), which is relevant for all higher education programs that include laboratory work.

Limitations of this work include that only a single pharmaceutical program was studied and that few students' and teachers' participated. It could be relevant to conduct a similar investigation elsewhere, as perspectives on progression and learning outcomes might differ significantly between contexts. Another limitation is the unknown influence of Covid-19 restrictions that changed during the study.

Conclusion

In this study, we have explored teachers' and students' views on laboratory learning outcomes and how progression is expressed in the third year of a higher education pharmaceutical program. With a longitudinal approach across two courses and a bachelor's project, we find that progression is strongly linked to ideas of students becoming more independent in the laboratory. The synthesis of learning outcomes, using the theoretical framework of the SOLO taxonomy, showed that signs of progression were found in all five clusters of laboratory learning outcomes. The results nuance the five clusters by including a progression lens and show how learning outcomes derived from interviews with participants in a specific educational context can lead to an overarching discussion of a program's intentions and established discourses.

The findings further show that there is coherence between teachers' expectations and students' experiences of increased demand for independence when entering the bachelor's project. This progression is also intentional, as it follows the description in official documents.

The implications for practice includes awareness of the different learning outcomes in all five clusters. Learning outcomes can be expressed differently in specific courses and the progression of laboratory learning varies in the five clusters. All curriculum and course planning should take this into account.

The detailed analysis of this program contributes to understanding the connection between course activities, the intention of a bachelor's project, and how progression can be expressed. These insights lead to reflections on the program intentions and beliefs held by teachers and students and prompt questions on how to design for progression in higher education. In addition, the implications of choosing open or closed laboratory teaching activities warrant further discussion and research into the nature of pharmaceutical sciences with respect to teaching development. In particular, add a sense of disciplinary diversity in discussing how pharmaceutical laboratory education might look different from laboratory education in related scientific fields.

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