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Article

Problem-Based Learning in an Introductory Inorganic Laboratory: Identifying Connections between Learner Motivation and Implementation

Larissa Wellhöfer* and Arnim Lühken

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ABSTRACT: Problem-based learning (PBL) is an acclaimed educational concept for laboratory teaching in chemistry, which significantly affects learner motivation. A central aim of PBL is to overcome educational problems with "cook-book" laboratories. For example, when students receive experimental instructions and apply the instructions similar to recipes, they do not necessarily understand what they do and why. However, research in problem-based laboratories still produces inconsistent and even contrasting results. A reason for this is the research focus; the problem-based concept and the outcome (e.g., learning results) are often investigated without considering the implementation of the problem. According to self-determination theory (SDT), it is necessary for problem-based learning to invoke a sense of autonomy, competence, and relatedness in the students to foster intrinsic learner motivation. To understand better the mechanisms and potential of PBL in enhancing intrinsic motivation, it is pivotal to investigate and identify connections to the practical implementation. This study focuses on intrinsic motivation connected to implementation. The aim was to clarify central implementation strategies for PBL concepts that enhance intrinsic learner motivation. To this end, we conducted semistructured interviews with undergraduate, nonmajor chemistry students who attended an innovative, industry-based PBL-laboratory course and analyzed them using qualitative content analysis. The results suggest central implementation factors that are interconnected and led to a novel model of the autonomous scientific process. The factors that enhance intrinsic motivation in this model are the independent acquisition of information, the design and application of the experimental procedure, the gathering of feedback through experiments, and the possibility to optimize the process. Adequate strategies must be taught to the students to enable autonomy and are exemplified in this study. The students perceived the presented industry-based problem setup as an authentic, autonomous scientific process, thus appealing to their self-perception as scientists.

KEYWORDS: *Inorganic Chemistry, First Year Undergraduate/General, Problem Solving/Decision Making, Laboratory Instruction, Chemical Education Research*

FEATURE: Chemical Education Research

■ INTRODUCTION

Several concepts have been developed to remedy the educational shortcomings of traditional expository laboratory practicals, primarily emerging from a constructivist framework focusing on self-directed learning.[1−3] One widely used example is problem-based learning (PBL). PBL increases student motivation, compared to traditional lectures, according to studies in various disciplines.[4−8] However, problem-based learning has been criticized in turn; Kirschner et al. (2006) claim that PBL is a learning environment with "minimal guidance".[9] According to the cognitive load theory, problem-solving activities overburden students' working memory resources with activities unrelated to learning.[9] Supporters of problem-based learning contradict the claim that this concept provides minimal guidance and increases cognitive load, stating that the critics mistakenly equalize different concepts.[10]

The tendency to equalize different concepts and to use inconsistent terminology are an ongoing problems in chemical education research. Diverse and inconsistent teaching formats are implemented under the same name, making it increasingly difficult to assign a precise designation and the applied concept. Terms such as research-oriented, research-based, inquiry-based, or inquiry-learning, as well as learning (or teaching) in the format of research appear alternately or side by side.[11] The arbitrary use of terms continues to have

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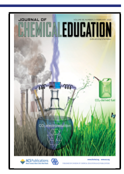

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consequences for research on the mechanisms of approaches within educational research[12] and contributes to the difficulties of obtaining comparable findings.

The inconsistent terminology and the critique on problem-based concepts point toward an important issue within educational research: research is mainly concerned with the two ends of the teaching process—theoretical conceptualization and learning outcomes—without discussing the actual processes, i.e., the implementation of the concepts. Hung (2011) attributes the inconsistent or contradictory results in PBL research to a lack of considering the implementation.[13] Therefore, it is necessary to include the actual implementation of the problem into the PBL research in order to generate a better understanding of how and why results come about.

PBL Implementation and Intrinsic Learner Motivation

An increase in learner motivation can be observed when the problem-solving process and the responsibility for the solution rest with the learner.[14] However, students do not necessarily have a higher intrinsic motivation after the introduction of a PBL concept.[15] While an increase in student ownership for their learning also increases learner motivation,[16] cognitive load and lack of guidance can quickly become overwhelming for beginners.[9] A study by Wijnia et al. suggests that for PBL to be intrinsically motivating, student autonomy and guiding elements must be balanced,[15] thus, implementation is critical. The central connection that has to be examined for a better understanding of the potential of PBL to enhance learner motivation is the implementation.

Problem-based learning is based on a theoretically sound framework designed to enhance intrinsic motivation according to Ryan and Deci's self-determination theory (SDT).[17] SDT states that events that support learner autonomy, competence, and a feeling of relatedness enhance intrinsic motivation.[18] SDT also assumes that intrinsic motivation is an inherent factor that can be enhanced or reduced by social-contextual events.[17,19,20] According to the theoretical framework, the PBL concept supports student autonomy, competence, and a feeling of relatedness.[21,22] One aspect of SDT consists of the cognitive evaluative theory (CET), developed to understand how extrinsic events, such as rewards, punishments, or feedback, affect intrinsic motivation.[23] CET focuses on the influence of extrinsic events on intrinsic motivation. These extrinsic or social-contextual events occur during practical implementation in an educational context. Therefore, CET was chosen as a theoretical framework for this study's aim to investigate connections between PBL-implementation and intrinsic learner motivation. Extrinsic rewards or feedback can cause external pressure and, thus, be controlling.[23] However, if rewards or obstacles occur naturally, they are informational instead of controlling and increase the students' perception of autonomy and competence.[17]

We aimed to contribute to a better understanding of what causes PBL to enhance intrinsic motivation by focusing on extrinsic events that materialize through implementation. The context of this work was an innovative industry-based PBL concept for an introductory nonmajor inorganic chemistry laboratory. The posed problems dealt with lithium extraction from brine and were based on current industrial methods. We strive to encourage using authentic and relevant industrial contexts for framing problems for beginner laboratories and to share this concept with the scientific community. The general PBL-concept is depicted in this work as well as the structure and content of the problems. Semistructured interviews were conducted to connect implementation to intrinsic learner motivation, transcribed verbatim, and analyzed using structured content analysis. Our study investigated, in depth, the implementation factors that enhanced the students' perception of autonomy, competence, and relatedness. Our subsequent findings contribute to the provision of more tangible guidance regarding the implementation of PBL concepts to enhance learner motivation.

The following research question guides the study:

- Which central implementation factors enhanced intrinsic learner motivation in this PBL-concept?

■ METHODS

Qualitative research concerns the subjective views of the study's participants and their communications and interactions in their everyday world contexts.[24] The decision for a qualitative research design results from the study's guiding epistemological interest in exploring the students' perception of autonomy, competence, and relatedness, in-depth, to find central connections to implementation. A qualitative research design allows the students to describe their perception of the concept freely and extensively, permitting us to find key themes that emerge from what the students deemed most important.

Methodological Framework: Qualitative Content Analysis

A qualitative research design was used in the work presented here. Codes are developed in an interplay between theory relating to the research question and the data material. The coding is defined by rules of construction and assignment and is revised and reexamined during the analysis.[25] Inductive and deductive coding of the material leads to an adjustment and addendum of the coding system until a system with clear and distinctive code descriptions, descriptive anchor examples, and firm coding rules is achieved.[26] This procedure ensures that the data are processed systematically and as clearly as possible.[27]

Setting and Participants

This study took place at Goethe-University Frankfurt in Germany. Informed consent was obtained for all participants in the study. Two students participated in the pilot implementation of the laboratory concept for 8 weeks in May and June 2020. The two students worked on the posed problems together, and a teaching assistant interviewed them after completing the laboratory sessions. Furthermore, the interview guide was piloted with these two participants. The second cohort consisted of 12 participating students in August 2020, of which ten participated in the study. All participants were nonmajors enrolled in a second-semester chemistry laboratory course. Students formed smaller groups of four people in which they worked together on the posed problems.

The qualitative data to answer the research question was acquired by interviewing students after they had completed the laboratory sessions. As the course instructor was part of the research team, a research trainee uninvolved in the teaching of the laboratory work was trained to conduct the interviews. Ten of the 12 participants consented to be interviewed. All the participants' names were substituted with pseudonyms to protect confidentiality.

PBL Process and Lab Activity

The PBL process was based on Poikela's model of problem-based learning[28] and adjusted for laboratory purposes (Figure

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J. Chem. Educ. 2022, 99, 864−873

S1 in the Supporting Information lab manual, see page S2). This model was chosen because it is detailed yet applicable and focuses on self-directed learning and versatile information sources. The specific depiction of the problem-solving process enables a structured implementation to be set up, leading to a more comprehensible research process. A detailed description of the problem-based learning process and implementation in the lab course is available in the Supporting Information (see pages S2−S4 of the lab manual). Providing exhaustive contextual information about implementation ensures comprehensibility and enhances transferability of this work.[29]

The laboratory concept includes current scientific and economic problems, in context, to induce the learners to make sense of their research activities.[30] The overarching context is the industrial lithium extraction from brine. Lithium producers have developed lengthy concentration and purification processes of lithium from the brine, which differ only in their details.[31] Despite the topicality and importance of brines for the industry, the chemical processes applied to them to extract the lithium are essentially simple precipitation reactions.[31] Thus, it is possible to keep the problem authentic and suitable for an introductory laboratory, addressing basic chemical concepts such as pH-value and solubility and acquiring basic laboratory techniques. Moreover, the experiments include classic detection reactions and current analytical methods to obtain feedback and to adapt the solution strategy.

The chosen industrial context has two significant benefits: it focuses on problems of economic relevance and it enables students to use the industrially applied approach as a possible guide for their experimental design. Due to maintaining the context as authentically as possible, it is a prerequisite that the industrial methods used in the chosen problem definition are applicable to the novice chemistry learners. Concerning the practical implementation, the instructions for the two problems were written as if an industrial company were addressing the students directly as employees.

Problems should be small-step extensions of known information material to questions that one cannot solve by existing means.[32] Table 1 provides an overview of the problems and the main features of the implementation. To solve the first problem, students have to analyze an unknown salt mixture. As support in terms of scaffolding,[10] we informed students that the different "lake samples" can each be assigned to a so-called "brine type".[33] The students should determine the brine type of the sample at hand.

The second and central problem was lithium extraction from brine. The task was to precipitate lithium carbonate from the salt solution in as high a yield as possible. The students were given a salt solution that mimicked the brine from the Salar de Atacama in Chile. Beforehand, various salt solutions were tested by the research team for comparison, with varying magnesium and lithium content, in particular. The composition of a salt solution providing consistently reproducible results included LiCl, $MgCl_2$, KCl, and Na_2SO_4, as well as the addition of $Na_2B_4O_7$ to ensure an extractable borate content (Table S4, see page S16 of the lab manual). An essential part of the second problem was designed to give students an insight into an instrumental analysis method within this context, here using powder diffraction. Students could use the information on the product purity and byproducts to optimize their experimental procedure in a continuous manner.

To enable the students to design the experimental procedure, they were taught how to research patent information. To our knowledge, patent literature is the most expedient source for this task. In order to support the students in the most ideal way, we have tested various patents and processes experimentally and written a comprehensive manual with a model solution for the experiment for the instructors, which is available for adaptation in the Supporting Information (see pages S14−S32 of the lab manual). The manual also contains detailed pedagogical suggestions to make it sufficient and self-explanatory for teaching assistants.

Table 1. Problem Definitions and Implementation

1. Problem: Analysis of an unknown salt mixture	Problem definition: determine "brine type" of the unknown salt mixture
	Salt lakes categorized into "brine types": (a) Na−CO_3−Cl−SO_4, (b) Na−Cl−SO_4, (c) Na−Mg−Cl−SO_4, (d) Ca−Mg−Na−Cl[33]
	Possible ions narrowed down: qualitative analysis of soluble and ammonium carbonate group
2. Problem: Lithium extraction from brine	Problem definition: precipitate Li_2CO_3 in as high a yield as possible
	Salt solution "Salar de Atacama" (Li^+, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-}, BO_3^{3-})
Analytics (experimental feedback)	Detection reactions (qualitative)
	Powder diffraction XRD (quantitative)
	Calculate the lithium carbonate yield using the data from the diffraction diagram and the weigh-in and weigh-out scales

Data Collection

A semistructured interview protocol was designed to explore which implementation factors enhanced the participants' intrinsic motivation in this PBL concept. The interview protocol was piloted throughout an individual pilot study of the laboratory concept with two students and revised afterward (see Supporting Information interview protocol). It was pivotal to have open and engaging questions in order to gain an in-depth insight into the students' perceptions and experiences without pushing them into a specific direction.

In designing the interview guide, no questions were included about intrinsic motivation in relation to specific situations, as the goal was to find out what the students themselves remembered and thus what was most important to them. Asking about the enjoyment of specific situations would have distorted a depiction of the outcome. During the piloting of the interview guide, students shared their experiences quite elaborately; therefore, the general structure of the interview protocol remained. Backup questions were added in case the students did not engage with the initial questions. An additional question concerning the distinction of the laboratory course to former laboratory experiences was included after piloting due to one student referring to previous school laboratory experiences, bringing interesting motivational insights to light. What students enjoyed in the laboratory course was asked last to ensure that the students had considered the whole laboratory experience from addressing the previous questions.

The interviews were conducted by a trained research assistant who was otherwise not involved in the laboratory course. The interviews were audio-recorded and transcribed verbatim and lasted for between 20 and 40 min.

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J. Chem. Educ. 2022, 99, 864−873

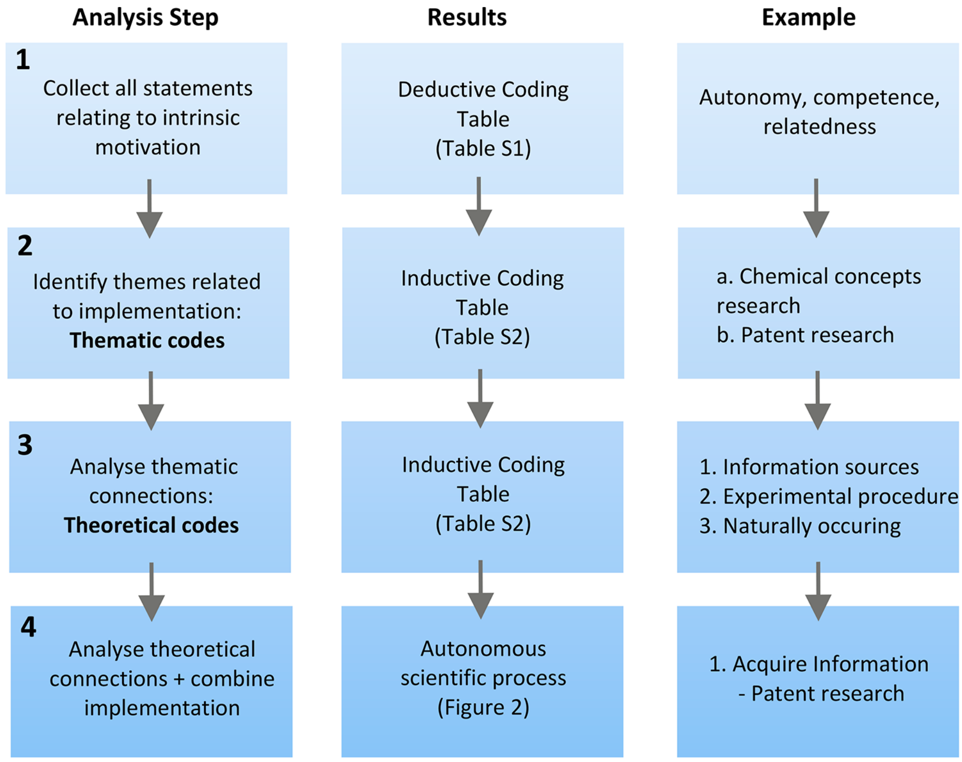

Figure 1. Overview of the coding and analysis process.

We developed the interview protocol taking into account cognitive evaluative theory[17] and questions relating to the general process of the laboratory course to find out how extrinsic events affect intrinsic motivation. Thus, we asked mainly about the enjoyment of the course and the students' processes.

Key questions in the interview included:

1. How did you go about designing the experimental procedure?
2. Where did you get your information?
3. Did you have experimental experience before the laboratory course (e.g., at school)?
   - If yes: Was this laboratory course different?
4. Have there been days when you did not understand what was being done?
5. Do you feel like you learned something in this laboratory course?
6. What did you enjoy in the laboratory course?

Data Analysis

The data analysis was conducted using the structuring content analysis method[26] and led by the research question and self-determination theory. Figure 1 shows an overview of the individual steps of the analysis and coding process. Initially, codes were formulated a priori, derived from SDT definitions of autonomy, competence, and relatedness.[17] To ensure that all statements about intrinsic motivation were systematically included in the analysis, the definitions of autonomy, competence, and relatedness served as the initial search grid from which the deductive coding table emerged (Table S1 coding tables). To be included, statements had to match at least one of the deductive code descriptions for autonomy, competence, and relatedness but could also refer to more than one of the three domains. It was not necessary to clearly distinguish the assigned codes at this point, but to ensure that a situation of interest related to intrinsic motivation occurred that was consistent with our theoretical framework.

Followingly, central themes were coded to determine the implementation factors that promoted intrinsic motivation in each incident, resulting in the formation of inductive thematic codes. Codes that emerged directly from the data material and were not deduced from SDT led to the formation of new codes. The research team developed a coding system with operational definitions for each code during this stage. Delineating the codes from each other was crucial in this step of data analysis because the underlying meanings are closely related. A research assistant with experience in qualitative research methods was given the coding system with operational definitions for the codes and a coding manual. The research team met for several debriefing sessions to discuss unclear and nonselective operational definitions with the research assistant in the first process. The trained background of the research assistant and the debriefing sessions add credibility and dependability to the work.[29,34] After an improved coding system was generated, one author and the research assistant recoded the material to create the final thematic codes (Table S2 coding tables, preceded by letters).

Subsequently, connections within thematic codes were analyzed, which led to the formation of more abstract theoretical codes (see Table S2 in the Supporting Information coding tables, preceded by numbers). The resulting inductive thematic and theoretical codes are presented together in the second coding table (Table S2 coding tables). The fourth step consisted of analyzing the systematic links between the theoretical codes in combination with the implementation factors, leading to the model of the autonomous scientific process.

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J. Chem. Educ. 2022, 99, 864−873

■ FINDINGS AND DISCUSSION

In this study, semistructured interviews were conducted to investigate which implementation factors enhance learners' intrinsic motivation in this PBL concept. The content analysis of the collected statements indicates that the central theme related to intrinsic motivation in this PBL approach is the opportunity for students to feel autonomous in their work. This result is consistent with the findings from the literature.[15,35] A balance between autonomy and control elements is necessary for students' intrinsic motivation.[17]

Autonomy was the central motivational aspect in all interviews. This was particularly evident when the students were asked about the differences between laboratory work at school and at university. Each student stated that the main difference was the ability to design the experimental procedure, and each student expressed his or her enjoyment of this. Andreas put it this way:

> *Andreas: "It was fun for me to be the master of my own work. I did not have to stick to any stupid experimental instructions but could apply my own experimental instructions and what I had researched I could apply as a scientist who has to think about his work. It was really close to reality and that is what I enjoyed the most, I really have to say."*

A systematic order emerged throughout the analysis of the theoretical codes. The theoretical codes occurred in a specific order in this setting to increase intrinsic motivation, with each step being a prerequisite for the next. For example, Sven described acquiring patent information and other sources as a prerequisite for the design of the experimental procedure:

> *Sven: "Um... I used patent literature for my experimental procedure at the beginning, but when I did not feel really safe with it and I also had the feeling that I did not really understand it, then I simply dealt with the theory of precipitation."*

The experimental procedure design and application is similarly a requirement to get feedback:

> *Manuela: "I liked the fact that you just worked practically and you could see the reaction happening. You can really recognize OK, there is now a precipitate or I have the result here or not."*

Experimental feedback proved central to the process optimization step. As Jonas described, the feedback about the low yield was what motivated him to optimize the process:

> *Jonas: "I thought on the last day I would have really liked to come again because you are in this flow with the experimental procedure but it does not work perfect yet, simply because of the low yield, so if it were up to me, the course could have gone a week longer that you can still work a bit on it, but that is then probably not possible due to the CPs or so."*

The theoretical codes were linked to their central enabling factor for implementation. The links between the theoretical codes and central enabling implementation factors were then analyzed, which resulted in the autonomous scientific process model (Figure 2).

The autonomous scientific process started with the acquisition of information about the posed problem (step 1). The enabling strategy used to teach the students was patent research. The second step was the design and application of the experimental procedure (step 2). The data suggests that the students perceived an understanding of the acquired and

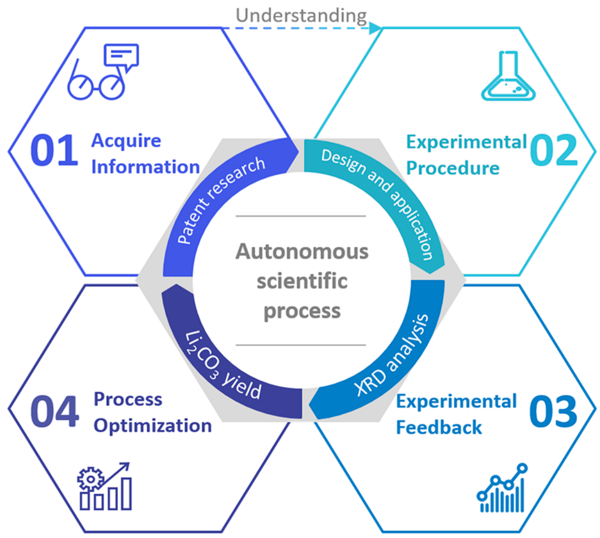

Figure 2. Model of the autonomous scientific process.

processed information as a necessity to design the experimental procedure. Again, the students received generic instruction on how to design an experimental procedure. The following step in this process was the experimental feedback (step 3). Students acquired feedback from the experiments and the powder diffraction analysis in an authentic setting, thus creating a sense of ownership of the research process. The students could analyze their products independently through qualitative and quantitative analysis and did not have to interrupt the autonomous scientific process, which was highly motivational. Feedback occurred naturally and was perceived as informational instead of controlling.[17] With this information, the students were able to optimize their scientific process autonomously (step 4). It was vital to teach the students the general strategies required to enable them to go through this autonomous process.

Information Sources

The prerequisite to designing an experimental procedure is the ability to find adequate sources and information. The key problem in this concept was designed to foster information literacy skills. Patent information for the implemented type of authentic industrial problem is a valuable information source. To acquire the ability to research patent literature was motivating to the students due to an increase in competence. When asked about acquiring information through patent research, David's answer shows how learning about a new information source was challenging at first:

> *David: "Researching with patents was completely new to me personally. I did not know that there was so much information in patents and that so much work is done with patents for scientific research. I did not know that. That was a lot at first, especially because the patents were also in foreign languages... Chinese, Korean, English. You first had to find your way around a bit. But once you had discovered your first approaches, found them, it actually went really well."*

Like David, most students were initially intimidated by patent research but overcoming this challenge led to an enhanced perception of competence. It also appeared to affect their scientific self-concept positively. Improving information literacy led to enhanced competence and autonomy and, thus, intrinsic motivation because the students felt enabled to

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navigate the chemical information landscape. Interestingly, improving chemical information literacy through patent research also appeared to enhance the perception of relatedness to the scientific community, as Andreas stated:

Andreas: "I always speak about the patent search but that is the be-all and end-all. Scientific work is only done by work of other people who have also thought about it and you orient yourself on that. That does not mean that you copy, but you try to collect as much information as you can have as a scientist, so that you can acquire new information at all."

Andreas appears confident in his word choice, explaining how scientific work and the scientific process operate, relating it to scientific literacy and the scientific community. The implementation factor that enhanced intrinsic motivation in this step was enabling the students to find adequate information autonomously.

It was considered more challenging yet possible to use prior knowledge and general chemical concepts as information sources to design the experimental procedure. Students were free in their choice of information source. Sven chose the opportunity to engage with chemical concepts at a deeper level and design his experimental procedure like this:

*Sven: "Um... I used patent literature for my experimental procedure at the beginning, but when I did not feel really safe with it and I also had the feeling that I did not really understand it, then I simply dealt with the theory of precipitation. So how is the solubility of lithium chloride compared to lithium carbonate compared to potassium carbonate compared to silver chloride and sodium chloride and when I add something, what comes out? I then simply calculated theoretically to the best of my knowledge *laughs*."*

Sven chose his information source and experimental procedure design based on the urge to understand what he was doing. The role of understanding will be elaborated further in the following section.

Understanding

Statements involving the understanding of laboratory content were closely related to the experimental procedure design. Various students referred to the necessity for them to understand what they wanted to do before performing the experiment due to the independent design of the experimental procedure; this enhanced the students' perception of autonomy and competence.

Jonas explained it like this:

Jonas: "When something goes wrong, I find it interesting to see what goes wrong and why. Because you have to work out everything yourself, you first have to understand what you want to do, otherwise it does not work. If a supervisor tells you what to do, you often do not understand it, you just do it. But because we have to work it out ourselves, we've already learned a lot during the research."

The possibility to work independently on solving a problem and understanding the process appears to create a sense of ownership of the project. Sven also felt an actual necessity to understand what was going on in order to be able to design an experimental procedure:

Sven: "We were really forced to get into the matter, to think about what is best to do with what."

Some students felt connected to the chemical scientific community through their understanding of the chemical experiments they were performing, enhancing the feeling of relatedness. While chemistry seemed "magical" to Sven before, he was now able to relate theory to the experimental phenomena he observed, thus, understanding it and being part of this hitherto unintelligible community. Sven said it like this:

Sven: "So I always thought it was great when you see videos or you see the professor in the front mixing liquids together and then a powder comes out... That was always a bit of witchcraft for me and I thought that was great that we could actually do that and I understood that."

Students perceived understanding as a necessity to design the experimental procedure, and this enhanced a feeling of autonomy and competence. Interestingly, understanding also served as an "entry card" for students into the chemical scientific community. Students felt included in the chemical scientific community by understanding the experiments, and this created a feeling of relatedness.

Experimental Procedure Design

The independent design of the experimental procedure was central to the students' motivation and formed what they generally spoke about most passionately in the interviews. Every student referred to the possibility of designing the experimental procedure as motivating; perceptions of autonomy and competence were central in this step of the scientific process. The enabling implementation factor was the teaching of a generic strategy to design an experimental procedure. The students connected the ability to research information and to understand it with the ability to design the experimental procedure and how to apply it. Andreas said it like this:

Andreas: "It was fun for me to be the master of my own work. So I did not have to stick to any stupid experimental instructions but could apply my own experimental instructions and what I had researched I could apply as a scientist who has to think about his work. It was really close to reality and that is what I enjoyed the most, I really have to say!"

Andreas' statement also shows his frustration with expository laboratories which he perceived as controlling. When asked what was the most fun in the laboratory, the most common answer was related to designing the experimental procedure.

Marie's statement followed a similar direction:

Marie: "Above all, the most fun was that we were really allowed to decide what we would do, that we were not directly given a prescription."

It is apparent that the students had different laboratory experiences until this point and appreciated the possibility of taking ownership of the experimental process. The students drew distinctions to their previous laboratory experiences in high school, where the experimental procedure was given. When asked about comparing previous laboratory experiences to this one, every student pointed out that the significant difference was the possibility to design the experimental procedure. Andreas felt very passionately about this:

Andreas: "In school we were given a sheet of paper and told to do this and this and this, so they told us what to do. If you cook according to a recipe, so to speak, as a chemist and not according to your own ideas, that is, you do not create the experiment instructions yourself, then it is like, uh, like when you stand in the kitchen and prepare noodles, nothing else in my opinion."

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J. Chem. Educ. 2022, 99, 864−873

Max's statement followed a similar direction while also describing the challenging aspect of independent work.

Max: "We had to do the experimental procedure ourselves, so we were a bit more self-reliant and had to find out for ourselves how everything worked. And you were not just told to do this and that, but you had to find your own way around. I only experimented a little bit in school and it was so boring, you were simply told what you are supposed to do. The independent work in this course was definitely a lot of fun."

The ability to design the experimental procedure enhanced the students' perception of autonomy and competence. The connected implementation factor was teaching the students a generic strategy concerning experimental procedure design.

Naturally Occurring Feedback

A central, motivating factor related to implementation was the naturally occurring feedback.[17] Students were able to go through an autonomous scientific process because they could check their progress independently. Throughout the different steps of their experimental procedure, the students used detection reactions to analyze the intermediate products qualitatively and, subsequently, they analyzed their products by powder diffraction for quantitative insights. Marie described receiving the experimental feedback like this:

Marie: "The feedback from the XRD-analysis of our sample was always cool. When we got our results and had a good result, then we had like an epiphany. Also when we did detection reactions to check ourselves what we had precipitated and if the proof was positive, then that was like an epiphany."

In combination with the aim to yield as much Li_2CO_3 as possible, the visual and analytical feedback was exciting to the students. As they did not receive feedback from their supervisors, but from their products, the feedback was informational instead of controlling.[17] Thus, experimental feedback forms an important part of the autonomous scientific process.

David referred to experimental feedback with respect to having a goal:

David: "That you really had a goal that you were working toward and you really had to work everything out for yourself and then you always saw for yourself, after every hour or so, that what you did either worked or the detection reaction did not work. Also, sometimes it looks really cool, for example, like this magnesium detection reaction with the red coloring at the bottom that was really cool, so it looked interesting."

The detection reactions and the XRD-analysis enabled the students to autonomize their scientific process. Experimental feedback was perceived as being a part of this process and, therefore, informational instead of controlling. Jonas described it like this:

Jonas: "Of course things go wrong from time to time, but I think that is part of it and I think it is interesting to see what goes wrong and why it goes wrong, and if it works out, of course, that is even better. So just that we were allowed to do everything on our own and, uh, yes I actually found that was the most fun in the lab course."

Jonas' statement shows the informational aspect of the experimental feedback. Since Jonas takes on ownership of the process, it is important to him to see what goes wrong and why. Jonas claims he was not told what goes wrong. Instead, he could gather experimental feedback himself to keep track of the progress. This form of naturally occurring feedback enhanced the students' perception of autonomy and competence.

Process Optimization

The process of yield optimization was central to the continuous problem-solving process and the students' motivation. The students' statements show that having an aim and taking on ownership to reach this aim enhanced their perceptions of autonomy and competence. Furthermore, by working with the information from the experimental feedback, students felt competent to improve their process and experimental procedure constantly:

Jonas: "We found out something new every day that... I do not want to say surprised us, but for example, with the precipitation of lithium carbonate that was like an aha-effect... It did not work at first and then we noticed at some point that if we turn the temperature another four degrees higher, then something simply precipitates. And then we noticed a few days later that it also makes a huge difference how long you keep the whole thing hot. So something like this actually happened every day that you have something you did not think of before and suddenly found that this is how it works."

Jonas' statement shows the excitement that the responsibility of undertaking the autonomous project generates. Through experimental trial and error and the possibility to check for progress and acquire analytical feedback, there emerged a sense of continuous process optimization.

Sven embedded process optimization into the teamwork component:

Sven: "When we came out of the lab on Thursday and it did not work out, when we tried something new, then everyone went looking for new information. We had a group in which we always exchanged information, saying 'I found something interesting, I found something interesting' and then during the weekend on Saturday, Sunday and sometimes also on Mondays after the Zoom meeting with the supervisor we put it together again and discussed how we wanted to do it concretely, how many experimental instructions we would do, whether we would put something together."

Sven's statement shows how his group had handled the challenges and setbacks. According to Sven, autonomy was central in his group in terms of taking ownership and responsibility for the project and also competence because the members perceived themselves capable of overcoming this challenge. Furthermore, the close connection, lively exchange of ideas, and teamwork show the students' sense of relatedness.

Sven: "It was definitely fun, to experience; OK now we had a really good sample and what can we do better and that you can also see that it is getting better. I think we learned a lot about how process optimization works."

Sven described how the feeling of having an impact on the outcome of the product was motivating; this is, again, related to competence. Once more, this indicates a close connection to the naturally occurring feedback as the extrinsic event enhancing intrinsic motivation.

Two students also claimed that they would have wanted to continue the process even after finishing the laboratory course; this provides a strong indication that intrinsic motivation is related to the process optimization.

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J. Chem. Educ. 2022, 99, 864−873

Manuel: "I think for two or three days we somehow felt that we did not move forward nor backward, but in the end, we got it solved again, but in between it was really a down phase. At the end it was better again, then we also said that we would like to improve what we have now and continue."
Jonas: "I thought on the last day I would have really liked to come again because you are in this flow with the experimental procedure but it does not work perfectly yet, simply because of the low yield, so if it were up to me, the course could have gone a week longer that you can still work a bit on it, but that is then probably not possible due to the Credit Points or so."

The common intrinsically motivating thread throughout the scientific process was the ability to work independently. The process shown in Figure 2 started with the autonomous acquisition of information (step 1). Students felt they had to understand the information they gathered to progress from information acquisition to the experimental procedure design and application (step 1−2). Interestingly, understanding also served as an "entry card" for students into the chemical scientific community. Next, the design and application of the experimental procedure enhanced motivation due to the ability to try new ideas that the problem definition enabled (step 2). Subsequently, the students acquired experimental feedback themselves, making it informational instead of controlling and, thus, enhanced their intrinsic motivation (step 3). This feedback enabled the students to optimize the process on their own terms (step 4). In summary, the feeling that transpired was "I am a scientist," which Andreas enthusiastically concluded like this:

Andreas: "When I have a problem in chemistry that I cannot solve, I now know how to research patents and find a solution to solve the problem myself, because other people have already thought about it. I have learned to work scientifically and how to research the current state of research and include it in my work, because scientific work is only done through the work of other people who have also thought about it."

■ CONCLUSION AND IMPLICATIONS FOR TEACHING

PBL holds excellent potential for laboratory teaching, especially for fostering learner motivation.[36] However, educational research in PBL-concepts often neglects implementation as a central factor. This study has presented a qualitative method to investigate how extrinsic events that materialize throughout implementation affect intrinsic motivation in an introductory PBL-laboratory. Analysis of the students' interviews suggested that it is essential for the students to go through an autonomous scientific process in order to enhance their intrinsic motivation; i.e., the progression of acquiring information, designing and applying the experimental procedure, acquiring experimental feedback, and finally, optimizing the process enhanced intrinsic motivation (Figure 2). Feedback plays an imperative role in this cycle because it occurs naturally and is, thus, perceived as informational instead of controlling by the students.[17] On the basis of our findings, we recommend starting with an adequate problem definition according to the autonomous scientific process. First, the problem should engage students in targeted information sources. Second, the problem should permit various solution strategies and, thus, experimental procedure designs. Third, the problem should include a means for experimental feedback that students can acquire, and last, the problem should include the possibility to optimize the solution strategy. Students have to feel competent to solve the posed problem or else they will feel overwhelmed. Therefore, student autonomy has to be enabled by teaching. Instructors should provide students with adequate generic strategies that refer to the problem content and the stage of the autonomous scientific process; strategies for information acquisition, designing an experimental procedure, experimental analytics to acquire feedback and optimizing a process must be taught in relation to the concrete problem content.

Educational research is always complex and many factors influence student learning outcomes. Implementation is a critical factor in the impact of PBL, but it has been neglected so far. The further incorporation of implementation into PBL research could help to clarify some of the conflicting findings in this field of research and continue to improve PBL laboratory settings.

■ LIMITATIONS

This qualitative study aimed to gain a better understanding of how implementation factors enhance the students' intrinsic motivation in PBL, focusing on the practical implementation of the problem. The bases for this study were the students' perceptions. Therefore, we formulated open questions to gather the essential implementation factors involved in the perception of the students. However, other factors that may enhance or diminish intrinsic motivation, especially people-related factors, such as the group's constellation or the instructor's behavior, were not included in this study. Recent findings show the importance of these factors,[19] and we plan future studies on people-related influences on intrinsic motivation in connection to this concept. In addition, this study consisted of one cohort in one specific PBL-setting and our findings may not be applicable to other student populations. Further studies, including the practical implementation of problems, are necessary in order to gather generalizable results. In addition, according to our data, the model of the autonomous scientific process includes those implementation factors that enable autonomous scientific process and are central for enhancing intrinsic motivation. Further studies are necessary to test this model in different PBL-settings and with different student populations. Nonetheless, our model represents an important starting point for connecting practical implementation of problems with intrinsic motivation.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.1c00808.

Example interview protocol for the study (PDF) (DOCX)

Coding tables (PDF) (DOCX)

Lab manual including PBL process and detailed implementation (PDF) (DOCX)

■ AUTHOR INFORMATION

Corresponding Author

Larissa Wellhöfer − *Departement of Chemistry Education, Goethe University Frankfurt, 60438 Frankfurt am Main,*

Germany; orcid.org/0000-0001-7373-6922;
Email: wellhoefer@chemie.uni-frankfurt.de

Author

Arnim Lühken − *Departement of Chemistry Education, Goethe University Frankfurt, 60438 Frankfurt am Main, Germany*

Complete contact information is available at:
https://pubs.acs.org/10.1021/acs.jchemed.1c00808

Notes

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