Chemical Information Literacy in a Problem-Based Beginner Laboratory

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Larissa Wellhöfer

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This dissertation provides a condensed overview of the research findings. The complete and detailed results have already been published in the following academic journals:

1. Wellhöfer, L.; Lühken, A. Problem-Based Learning in an Introductory Inorganic Laboratory: Identifying Connections between Learner Motivation and Implementation. *Journal of Chemical Education*. 2022, *99 (2)*, 864−873.
2. Wellhöfer, L.; Lühken, A. Information Is Experimental: A Qualitative Study of Students' Chemical Information Literacy in a Problem-Based Beginner Laboratory. *Journal of Chemical Education*. 2022, *99 (12)*, 4057-4067.
3. Wellhöfer, L.; Machleid, M.; Lühken, A. "I don't know, ask the chemists -. I think it's kind of a consensus among them" – Information Practice in a Problem-Based Beginner Lab. *Chemistry Teacher International*. 2023. (Accepted for publication)

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1. Introduction

This dissertation addresses a core aspect of chemistry education research: learning in the chemistry laboratory. While there is consensus that laboratory learning is central to students' education, there is no agreement on what students are supposed to learn in the laboratory and why it is so important (Hofstein, 2004; Hofstein & Lunetta, 1982). As a result, researchers have increasingly sought to understand what students learn in the lab, what they should learn, how they learn, and how laboratory learning can be improved.

The constructivist understanding of learning has led to an increasing demand for inquiry-based laboratory concepts, such as PBL laboratories, which differ from traditional expository concepts (Di Fuccia et al., 2012; Eilks & Byers, 2010; Ralle et al.). PBL labs prioritize research processes and utilize the experiment as a research tool to promote student-centered learning. The aim is to move away from predetermined experimental instructions, and place the responsibility for designing the experimental procedure onto the students (Claire Mc Donnell, Christine O'Connor and Michael K Seery*, 2007). While PBL labs can be beneficial to student learning in the laboratory, they also bring new difficulties that require further exploration (Keen & Sevian, 2022; Sandi-Urena et al., 2012).

In beginner chemistry laboratories, students encounter a complex learning environment that can cause additional confusion due to unfamiliarity with non-traditional lab concepts and implicit expectations (Chopra et al., 2017; Seery et al., 2019). Human interaction is the primary determinant of the complex, collaborative, and context-dependent learning scenario in the laboratory (Jobér, 2017; Keen & Sevian, 2022). To understand students' struggles in undergraduate chemistry laboratories, Keen and Sevian (2022) proposed a sociocultural framework, which includes a domains-of-struggle framework characterizing students' struggles in four domains: cognitive, psychomotor, epistemological, and socioemotional. However, further research is needed to understand the beginner PBL laboratory as a complex learning environment, where students engage with textual, social, and physical information in specific ways, including the role of physical learning beyond isolated "practical skills" (Carnduff & Reid, 2003; DeKorver & Towns, 2015; Flaherty et al., 2017; Hofstein, 2004; Keen & Sevian, 2022).

Therefore, this work aims to contribute to the understanding of learning in PBL beginner laboratories, as the benefits and challenges of using PBL in the chemistry laboratory context are still not fully understood.

In the context of PBL laboratories, students are expected to design their own experimental procedures, a task that requires gathering information from various sources. Consequently, an information problem arises in PBL labs, making them inherently connected to information literacy (Lloyd, 2010b). In order to study learning in PBL labs, it is helpful to adopt an information literacy framework, which can provide a deeper understanding of how students access and utilize information sources in laboratory settings.

Information literacy is a sociocultural practice that facilitates the knowledge of information sources within a given environment and an understanding of how these sources are constructed through discourse (Lloyd, 2010c). Information literacy is constituted through the connections that exist between people, artifacts, texts, and bodily experiences that enable individuals to develop both subjective and intersubjective positions (Ibid.). Figure 1 shows the information modalities that are relevant to information literacy, based on a model by Lloyd (2007) that has been adjusted to fit the specifics of chemistry practice (Lloyd, 2007a).

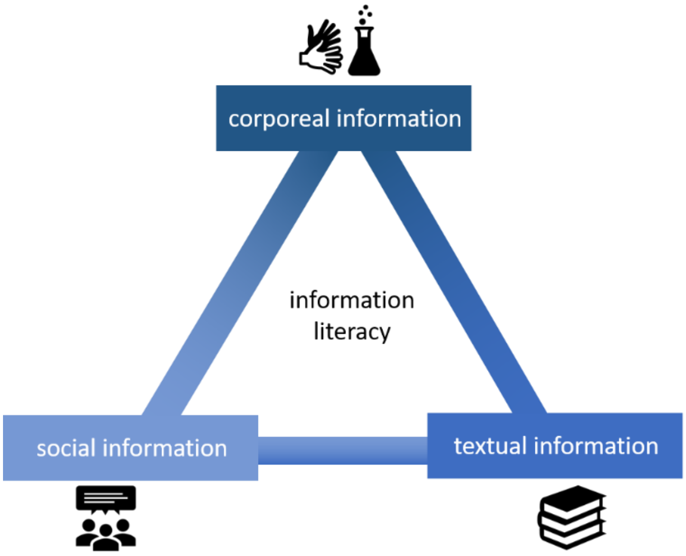

Figure 1. Information modalities relevant to chemistry practice based on the information literacy model from Lloyd(2007).

In order to become a member of a new community of practice, individuals must develop an understanding of the information resources that are valued in the community and how information can be obtained from the knowledge base (Lloyd, 2007a). In the case of beginner PBL laboratories, investigating how students engage with information can provide insight into their learning process and how to best support them. This study adopts an information literacy framework to examine the intertwined connections between textual, social, and corporeal information modalities that arise during the students' first PBL laboratory experience. The overarching research question that guides this work is:

- **How is information practice represented and developed by participants in a problem-based beginner laboratory?**

The contribution made to answering this question aims to provide further insight into the difficulties, advantages, and possibilities of learning in the laboratory. The underlying qualitative perspective that pervades the three publications forming the basis of this work is instrumental in highlighting the "lived experience of practice" and developing a deeper comprehension of the role of context and social setting in shaping ways of knowing (Lloyd, 2021). This view challenges the conventional understanding of information literacy, which has traditionally focused on textual information and the quantification and measurement of correct or incorrect information retrieval (Diekema et al., 2011; Tuominen et al., 2005a). Engaging with information in a community of practice is a highly intricate process that cannot be readily measured. Thus, the choice of a qualitative research design for this study was informed by its epistemological interest in students' perceptions and the continuous exploration of their lived experience through discourse interpretation during laboratory practice. The methodology utilized throughout the publications delineates the various facets of information practice that were of interest in this dissertation.

Within the field of research on learning in the PBL beginner laboratory, this dissertation aims to contribute to the existing knowledge base by answering specific research questions and shedding light on various aspects of learning in this context. Empirically, the study utilizes results from two content analyses and a documentary methodology approach, including audio-recorded practice and interview transcripts. The purpose of this framing text is to present the individual publications and their connection to one another; thereby providing overarching implications for teaching that arise from integrating the findings of the three studies, and developing a comprehensive framework for incorporating the information literacy findings in PBL teaching.

To achieve this objective, the next section presents the theoretical background on the interconnection between information literacy and PBL and the underlying sociocultural research understanding that guides the studies. The individual publications and their respective results are then presented, followed by a contiguous discussion of the findings to provide actionable implications for teaching. Finally, the conclusion provides an outlook on further research possibilities.

2. Theoretical background

2.1. The Relationship between Problem-Based Learning and Intrinsic Motivation

PBL concepts are informed by constructivist teaching and learning theory, focusing on the construction of knowledge through meaning-making (Di Fuccia et al., 2012; Eilks & Byers, 2010; Ralle et al.). PBL laboratory practicals essentially differ from expository concepts by shifting the responsibility for designing the experimental procedure towards the student. The experiment becomes a means of problem-solving. Research has shown that students are more motivated when they are responsible for solving problems during the learning process (J. Savery & T. Duffy, 1995). However, the introduction of a PBL concept does not necessarily result in higher intrinsic motivation among students (Wijnia et al., 2011). While learner motivation can be enhanced by increasing student ownership of their learning (Savery, 2013), cognitive load and lack of guidance can make it overwhelming for beginners (Kirschner et al., 2006). Studies on PBL often neglect the importance of implementation, despite its crucial role in shaping the effectiveness of this instructional approach (Hung, 2011). Notably, a study by Wijnia et al. highlights the significance of achieving a balance between fostering student autonomy and providing appropriate guidance to increase intrinsic motivation in PBL contexts (Wijnia et al., 2011). Therefore, it is necessary to pay close attention to the implementation of PBL and the incorporation of elements of guidance.

PBL is a theoretically sound framework to increase intrinsic motivation according to self-determination theory (SDT) by Ryan and Deci. SDT posits that events that support learner autonomy, competence, and relatedness can enhance intrinsic motivation (Ryan, Richard M., and Edward L. Deci, 2000). SDT assumes that intrinsic motivation is an inherent factor that can be influenced by social-contextual events (Ryan, Richard M., and Edward L. Deci, 2017; Wang et al., 2019; Woon Chia Liu et al., 2014). According to the SDT framework, PBL can promote student autonomy, competence, and relatedness (Hmelo-Silver, 2004; Savery, 2006). One aspect of SDT is the cognitive evaluative theory (CET), which explains how extrinsic events, such as rewards, feedback, or punishments, can affect intrinsic motivation (Ryan, 1982). CET focuses on the impact of social-contextual events on intrinsic motivation during practical implementation in an educational context. Extrinsic rewards or feedback can be controlling, causing external pressure, but if they occur naturally, they can be informational and increase students' perception of autonomy and competence (Ryan, Richard M., and Edward L. Deci, 2000). Therefore, CET was chosen as a theoretical framework to investigate the connection between PBL-implementation and intrinsic learner motivation in the first publication.

2.2. The Complexities of Information Literacy in PBL

In a PBL lab, learners must consider what they wish to achieve through the experiment, why it is necessary and how they want to do it (McDonnell et al., 2007), instead of following a recipe-like experimental procedure (Clark et al., 2016). To design the experimental procedure, the learners require additional information. An essential part of a PBL lab is to determine what type of information is needed, where and how to get it, how to evaluate it, and, finally, how to use it to plan the experimental procedure. These aspects constitute the basic parts of the concept of information literacy (Grafstein, 2002). The connection between PBL and information literacy is rooted in the original definition of information literacy by Paul Zurkowski in 1974. Zurkowski defined information literate people as those "trained in the application of information resources to their work," who have "learned techniques and skills for utilizing a wide range of information resources" and "primary sources for molding information solutions to their problems" (Zurkowski, 1974). This definition highlights the importance of utilizing information resources to solve problems, which is a central component of PBL.

The Association of College and Research Libraries (ACRL) established a definition of information literacy in 2000 as "recognizing when information is needed and knowing how to locate, evaluate, and use it effectively" (Association of College and Research Libraries, 2000). This definition has been widely influential and formed the basis for a set of standards, objectives, and instructional suggestions in educational settings (Sühl-Strohmenger, 2012; Virkus, 2003). However, some critics argue that the ACRL standards reduce information literacy to easily measurable, text-based skills such as searching specific databases or proper citation (Diekema et al., 2011; Kapitzke, 2003; Tuominen et al., 2005a). In response to changes in the information ecosystem, the ACRL published a revised definition in 2015 that is more comprehensive and reflective. The updated definition states that information literacy is a set of integrated abilities that includes reflective discovery of information, understanding how information is produced and valued, and using information to create new knowledge and participate ethically in learning communities (Association of College and Research Libraries, 2015).

The ACRL revised its former information literacy standards for higher education, creating a new framework that takes into account important developments in information literacy education research. Instead of a list of standards and skills, the framework is based on "interconnected core concepts, with flexible options for implementation"(Ibid.). The framework is informed by threshold concepts, which are "those ideas in any discipline that are passageways or portals to enlarged understanding or ways of thinking and practicing within that discipline"(Ibid.). The development of this framework highlights the complexity of information literacy as a contextual and social practice. The idea of threshold concepts emphasizes the situatedness of information literacy within "communities of learning"(Ibid.).

An important aspect of the framework is the concept that "authority is constructed and contextual" (Ibid.). This concept depicts that the expertise and credibility of information creators are reflected in their information resources, and the evaluation of these resources is dependent on the specific information need and context in which the information will be used. Different communities of practice may recognize different types of authority, and the level of authority required may be determined by the information need in question, indicating that authority is constructed and contextual. The threshold concept refers to novice learners who can develop a critical mindset by understanding the concept of authority in information sources. They should examine all types of evidence critically, regardless of their form, such as a blog post or a peer-reviewed conference proceeding, by asking relevant questions about their origins, context, and suitability for the current information need. This approach can help novice learners appreciate the expertise that authority represents while also being wary of the systems that have elevated that authority and the information produced by it (Ibid.).

Research on the benefits of combining PBL and information literacy in an educational setting has been a cross-disciplinary topic for some time (Cheney, 2004; Dodd, 2007; Kim et al., 2022; Pelikan, 2004; Roberts, 2017; Santharooban & Premadasa, 2015). More recent studies in chemistry education aim to leverage the inherent connection between PBL and information literacy to develop critical thinking and deepen students' understanding of underlying processes (Cheney, 2004; Cowden & Santiago, 2016; Shultz & Li, 2016; Shultz & Zemke, 2019). Community experts offer guidance to teach students how to navigate an increasingly complex information environment and prepare them for lifelong learning beyond university (Baykoucheva et al., 2016; Cowden & Santiago, 2016). However, previous studies on PBL and information literacy in chemistry education did not seek to understand and describe the social and contextual information processes that students engage in during PBL laboratories. To advance knowledge in this area, more research is needed that highlights the contextual and social dimensions of information literacy practice. The link between PBL and information literacy holds great potential for a better understanding and teaching of PBL and information literacy, and it is necessary to shift the focus from measuring and improving information literacy to understanding how the information practice is shaped that occurs during a PBL lab.

2.3. A Sociocultural Approach to Information Literacy Research: Understanding the Contextualized Practice

Information literacy has been theoretically framed as a social practice for almost 30 years (Hjørland & Albrechtsen, 1995; Rath, 2022). A sociocultural approach to information literacy research considers information literacy to be a socially shaped and contextualized practice (Lipponen, 2010; Montiel-Overall, 2007). The manner in which information is produced, shared, and valued depends on a shared understanding of the context and the social site (Lipponen, 2010; Lloyd, 2006). Becoming information literate involves developing a set of abilities and skills (contextual knowledge) to draw meaning from the knowledge base through engagement and experience with information (Lloyd, 2006). In this view, information literacy as a practice refers to the knowledge and ways of knowing that are valued and agreed upon in a situated social setting. According to Lloyd (2021), information literacy is a contextual process of knowing, where certain information modalities (e.g., textual versus social) and information skills (e.g., citation) are privileged over others, as construed by the social community (Lloyd, 2021). The socio-cultural realities of the social site influence the preference for specific practices over others (Lloyd, 2010a). How information is acquired, shared, valued and transmitted to newcomers depends on the particular community and its participants (e.g., nurses, librarians, firefighters) (Lloyd, 2021). These developments have been widely discussed and acknowledged in the scholarly literature (Cox, 2012; Head et al., 2013; Lloyd, 2010b; Ross Todd, 2017; Tuominen et al., 2005a). However, there is still a lack of understanding of information literacy as a social practice in the context of chemistry education, even though it could be helpful to gain a better understanding of laboratory learning.

Lloyd (2010b) provides an example of how information literacy can differ across social settings. For instance, the scientific way of practicing information literacy may differ in different communities of practice, where the practice of information literacy may emerge corporeally and favor knowledges that are developed through physical experiences and are therefore embodied. In this understanding, knowledge is locally situated, "representing the collective, embodied and informed work of people who populate and engage with the material objects of the space, e.g., a workplace, a school, or a football field" (Lloyd, 2010b), or a chemistry laboratory. The privileging of certain information modalities and ways of interacting with them are traditionally inherent in the social site and will be referred to as “privileged ways of knowing” (Lloyd, 2021). Thus, it is problematic to see information literacy as a generic set of skills, because there will always be the question of “What/whose view and ways of knowing are being privileged?” (Ibid.). The aim of the second publication is to attain a more profound comprehension of the information process and the “privileged ways of knowing” that take place in the PBL beginner laboratory. This will facilitate an improved depiction of the information practice and provide a basis for instructional recommendations (Tuominen et al., 2005b).

Lloyd (2010) refers to Schatzki's site ontology (2002) to explain the theoretical framing of information literacy as information practice (Lloyd, 2010b; Schatzki, 2002). This theoretical framing depicts practice as the central feature of social life (Ibid.). Finding and making sense of information in a particular context requires the experience of authentic practice (Lloyd, 2007a). Lloyd proposes that researchers should choose the sociocultural affordances of the practice as the unit of analysis to research information literacy, instead of information skills because these affordances lead to the development of information skills (Lloyd, 2010c), an attribute that is widely acknowledged by the literature (Association of College and Research Libraries, 2015; Hosier, 2019; Rath, 2022).

2.4. Connections between Workplace-Related Information Practice and the Chemistry Laboratory

Each community of practice has its own complex ways of using or disseminating knowledge and information (Tuominen et al., 2005a). The practice term is especially used in the context of professional or workplace learning (Green, 2009; Head et al., 2013). This work follows a framework of workplace-related information practice and adapts it to the chemistry laboratory. The chemistry laboratory practical has many similarities with workplace-related information practice: "In workplaces where there is an emphasis on practical and embodied understandings and more value placed on experiential knowledge and know-how, information literacy will reflect the informal nature of learning within site" (Lloyd, 2010b). Furthermore, there is a focus in the literature on new employees entering a workplace practice and the social sharing of information with experienced practice members who serve as information resources (Brown & Duguid, 1991; Wenger-Trayner, 2008), which provides a useful theoretical frame for these studies' intent.

Professional practice requires more than the application of theoretical knowledge (Reich et al., 2014). The sayings and doings of practice become meaningful when they are enacted as "knowledgeable activities" or "knowing-in-practice" (Price et al., 2019). Knowing-in-practice is characterized by developing knowledge collectively in an ongoing way determined by specific situations. In their study on workplace learning in emergency departments, Manidis and Scheeres (2012) examined interprofessional practice around a patient's bedside. The case of an elderly patient, Jane Edna, who spent over 11 hours in an ED, was analyzed in detail. The researchers mapped the 51 separate visits by 22 individuals involved in her care, including doctors, nurses, and allied health professionals, who all brought their own professional knowledge to the bedside. However, they had to continuously ask the same questions to the patient to "know-in-practice" how to assess the situation in relation to their particular field and expertise. In this context, knowledge of the patient and how to treat her is developed collectively and continuously, and is rooted in the practice of multiple practitioners (Manidis & Scheeres, 2012).

2.5. Tacit and Explicit Knowledge in Information Practice

People learn through participation about how to act, as well as how to communicate, via information that is often coded and specific to the community (Lloyd, 2010c). Through participation, people engage with tools, objects and activities that are valued in the practice, display their affiliation to the group and are guided by experienced members of the group (Ibid.). When beginners participate in the community and interact with other members, they ascertain how to decode forms of communication, the "sayings of practice," and eventually become equal members by establishing a shared understanding (Ibid.). Novice practitioners encounter both subtle forms of tacit information and codified explicit information (Lloyd, 2010b). On one hand, explicit information in the chemistry information practice can be distinctly expressed, for example, in codified rules, lab manuals and textbooks, or by written and verbalized guidelines (Ibid.). On the other hand, the concept of tacit knowledge refers to the knowledge of a person that is expended in the flexible process forms of perceiving, evaluating, expecting, thinking, deciding or acting, but cannot, not completely or adequately be explicated by the subject (verbalizable, objectifiable, formalizable) (Porschen, 2008).

Kirschner (1992) identified the experiencing of scientific phenomena in order to accumulate tacit knowledge as a central aim of the laboratory practical in education: "What is attempted is not the gaining of insight or understanding of phenomena through practicals, but rather getting a feel for phenomena. It is the obtaining of an implicit, often indescribable, feeling as to what is happening or what is supposed to happen, as opposed to the explicit knowledge of how something works or why" (Kirschner, 1992). Keen and Sevian (2022) analyzed how rules and routines can lead to a struggle in the laboratory: "because they are how the community and participants implicitly and explicitly negotiate their beliefs about the structure, content, and process of learning chemistry" (Keen & Sevian, 2022).

It is the aim of the third publication to explore how the experience of scientific phenomena and the experience of rules and routines unfold in discourse and constitute the information practice of students in the laboratory. Thus, attention can be drawn to the importance of implicit, explicit and embodied aspects of the information practice for learning.

3. Cumulative part of the dissertation

In the following section, the individual publications are presented that this cumulative dissertation is based on. The first publication is [1] Wellhöfer and Lühken (2022a), which analyzes the problem-based laboratory context and the problem implementation in relation to learner motivation. This work lays the foundation for the research interest in two ways: first, it lays the empirical-analytical foundation for the central connection between PBL and information literacy, which is fundamental to all further work. Second, it sheds light on how it is possible to approach the complexity of implementation by using content analysis to explore the motivational effects of PBL. The work yields the autonomous scientific process as a model that is largely a process of engaging with information. [2] Wellhöfer and Lühken (2022b) deepens the understanding of the learning process in a PBL beginner lab by connecting the different phases of the PBL lab work to information literacy, with a special focus on the pivotal phase during which the students are planning the experimental procedure. This article yielded a model of the information process students engage in during a PBL lab and it depicts how students engage with different textual sources and their reasoning behind this. [3] Wellhöfer, Machleid and Lühken (2023) complements the previous findings by exploring laboratory practice and focusing on the connection between the corporeal and social information modalities. This article further adds more depth to the results by drawing on the documentary method. Overall, the publications show decisive aspects of the connection between PBL and information literacy for the students' learning experience in a beginner laboratory.

The three publications are presented below. The presentation is done in three steps: In each case, the problem and the central concern of the study are briefly outlined (1). Subsequently, the methodological structure of the paper (2) as well as the central results are presented (3).

3.1. The Role of Implementation for Intrinsic Motivation in a PBL Lab

The content of this chapter has been published:

Wellhöfer, L.; Lühken, A. Problem-Based Learning in an Introductory Inorganic Laboratory: Identifying Connections between Learner Motivation and Implementation. *Journal of Chemical Education*. 2022, *99 (2)*, 864−873. Copyright 2022 AmericanChemical Society.

(1) Research on PBL lab practicals yields inconsistent results and, as a result, varying suggestions for teaching (Hmelo-Silver et al., 2007; Kirschner et al., 2006). This inconsistency may be due to inconsistent terminology and a focus on both ends of the PBL process: the theoretical concept and the learning outcomes (Hung, 2011). Therefore, it is necessary to include concrete implementation

in research to produce comprehensible results. PBL can be either intrinsically motivating or overwhelming, depending largely on the implementation (Wijnia et al., 2011). For PBL to be intrinsically motivating, student autonomy and guidance elements must be balanced (Ibid.). According to Ryan and Deci's self-determination theory (SDT), socio-contextual events that support learners' perception of autonomy, competence, and relatedness can enhance intrinsic learner motivation (Ryan, Richard M., and Edward L. Deci, 2000, 2017; Wang et al., 2019; Woon Chia Liu et al., 2014). Conversely, extrinsic events such as rewards or feedback may be perceived as controlling and cause pressure (Ryan, 1982). However, if feedback occurs naturally, it is likely perceived as informational, which supports perceptions of autonomy and competence (Ryan, Richard M., and Edward L. Deci, 2017). The PBL concept offers a theoretically suitable framework to enhance students' intrinsic motivation. Study 1 analyzes the extrinsic events that enhance intrinsic learner motivation during practical implementation, in order to gain a deeper understanding of how we can translate this potential into practice. The aim of this study was to find out how implementation factors were connected to motivation in this PBL beginner laboratory. The following research question guided the study:

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

(2) This study was conducted at Goethe-University Frankfurt, Germany in August 2020, and it involved ten undergraduate non-majors who participated in their first chemistry laboratory practical. Before the study began, all participants were informed about the study's purpose and provided written consent. A detailed description of the PBL lab course is provided in the Appendix (Study 1 SI Lab Manual).

To explore how the implementation of PBL laboratory practicals connects to intrinsic learner motivation, semi-structured interviews were conducted with the participants after they completed the practical. The interview guide used in this study can also be found in the Appendix (Study 1 SI Interview Protocol). The questions were designed to elicit the participants' recollections and perspectives on the practical without leading them to specific implementation factors.

The audio recordings of the interviews were transcribed verbatim, and the data was analyzed using structured content analysis (Kuckartz, 2016). Figure 2 summarizes the data analysis process.

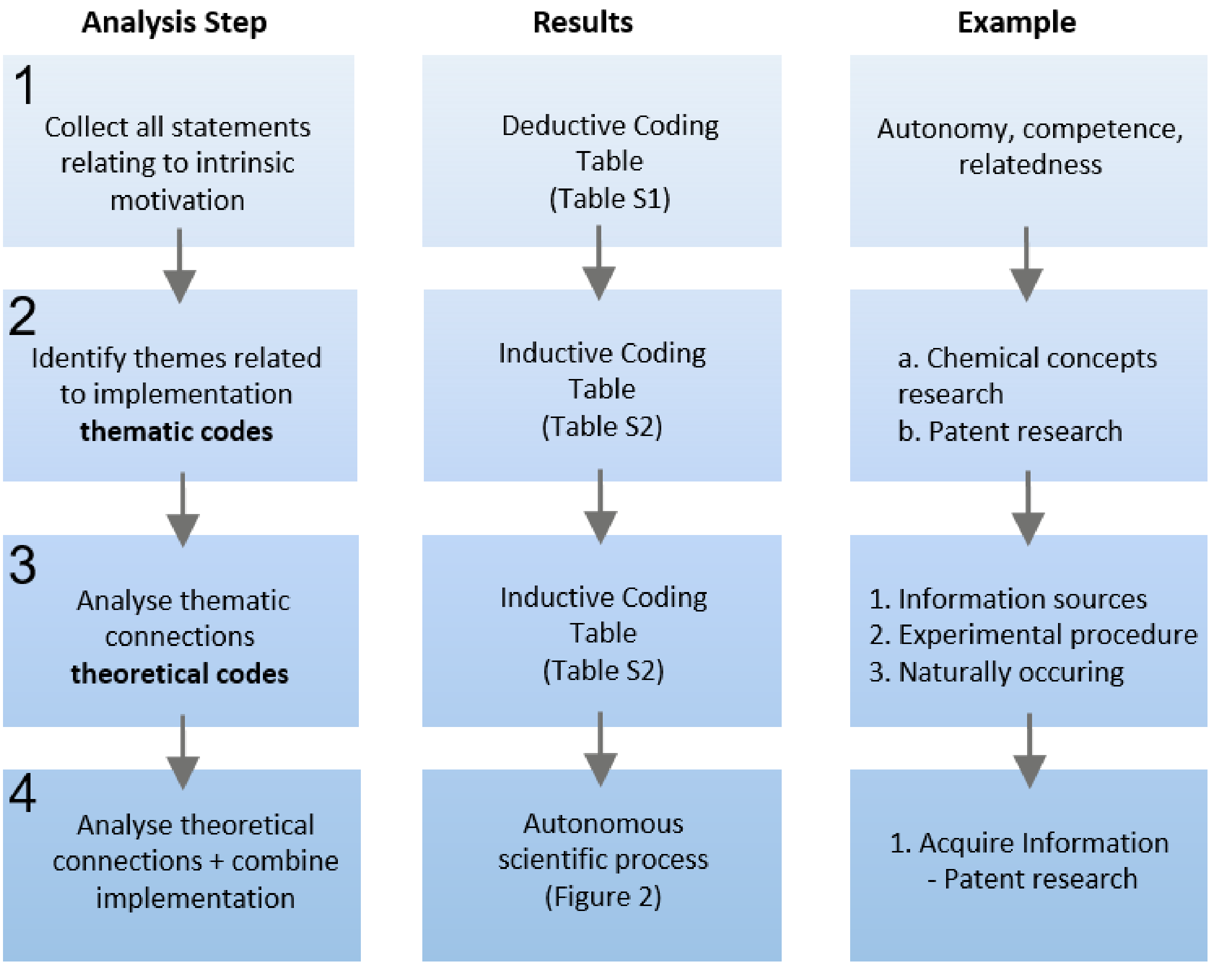

Figure 2. Overview of the coding and analysis process.

The data analysis consisted of four steps. In step one, a deductive search grid was used to collect all statements related to the theoretical definitions of autonomy, competence, and relatedness according to SDT. These statements were used to create an initial deductive coding table (Study 1 SI Deductive Coding Table). In step two, themes related to implementation were identified using an inductive approach, which resulted in an initial inductive coding table (Study 1 SI Inductive Coding Table). In step three, the connections between the themes were analyzed to identify higher-level correlations between the individual implementation factors, following a temporal progression. Finally, in step four, the superordinate categories were connected to the concrete implementation factors, resulting in a model of the autonomous scientific process (Figure 3). The findings and development of the model will be further discussed in the next section.

(3) The findings of this study suggest that implementing strategies to enhance students' perception of autonomy is key to promoting intrinsic motivation. Autonomy, defined in this study according to Ryan and Deci as “self-determined, volitional action in accordance with one's own authentic interests and values" (Ryan, Richard M., and Edward L. Deci), was found to be a common factor in enhancing intrinsic motivation among students. This finding is consistent with existing

research on the topic (Black & Deci, 2000; Wijnia et al., 2011). The study identified thematic codes representing different implementation factors that enhance intrinsic motivation in students, which were then connected in a systematic order to form theoretical codes. These theoretical codes were then used to create the model of the autonomous scientific process, which outlines the generalizable theoretical codes central to enhancing intrinsic motivation, along with their specific enabling implementation factors relevant to this PBL scenario (Figure 3).

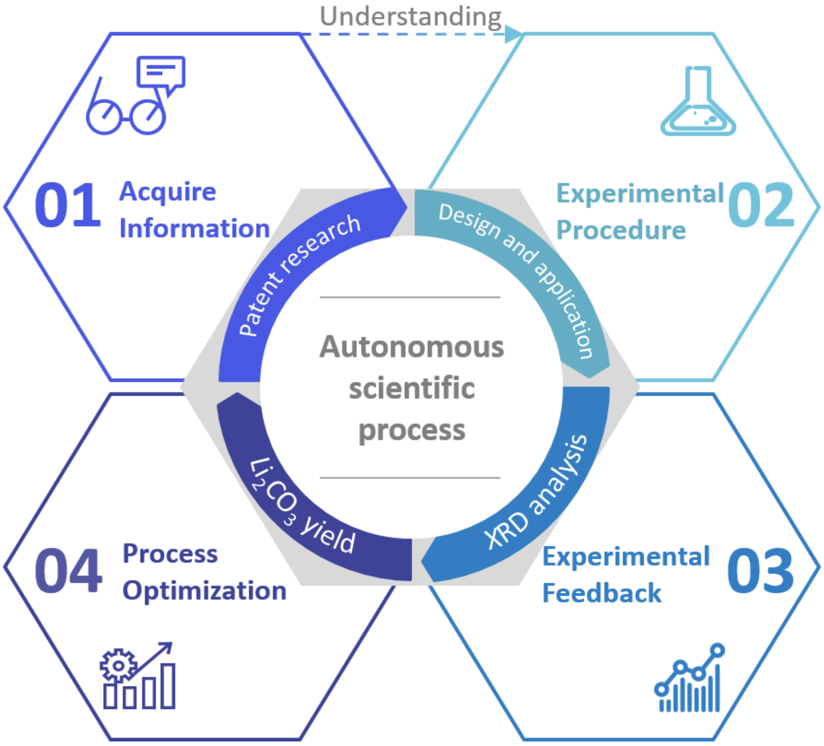

Figure 3. Model of the autonomous scientific process.

The first step of the process was information acquisition, which students found motivating when they were able to take ownership of the research process and design their own experimental procedure. To enable this ownership, they needed to acquire their own information through patent literature research. Additionally, students reported that understanding the experimental procedure was a prerequisite to designing it, which enhanced their feelings of autonomy and ownership.

The second step was the design and application of the experimental procedure, which all students found enjoyable. To enable this step, they needed to be taught about experimental procedure design and application.

The third step was experimental feedback, which students found motivational when it occurred naturally in the problem-solving process and was not artificially given by supervisors. Qualitative analysis and quantitative XRD analysis in this course enabled students to gather experimental feedback. Some students even reported perceiving obstacles as motivating because they occur naturally and are perceived as informational instead of controlling.

The fourth step that students found motivating was the ability to optimize the process autonomously. To enable this step, students needed information about their current Li_2CO_3 yield.

The model is transferable for other instructors, who can adjust the implementation factors to the individual problem scenario at hand. The results suggest that enabling students to do these four steps autonomously can enhance intrinsic motivation in PBL labs: acquire information, design and apply the experimental procedure, acquire experimental feedback, and optimize the process.

3.2. Connections between Information Literacy and Learning in a PBL Lab

The content of this chapter has been published:

Wellhöfer, L.; Lühken, A. Information Is Experimental: A Qualitative Study of Students' Chemical Information Literacy in a Problem-Based Beginner Laboratory. *Journal of Chemical Education.* 2022, *99 (12)*, 4057-4067. Copyright 2022 AmericanChemical Society.

(1) The link between PBL and information literacy has great potential for improving laboratory learning, and has been the subject of increasing attention among chemistry education researchers (Shultz & Li, 2016; Shultz & Zemke, 2019). The development of information literacy research and education has undergone significant changes, as evidenced by the influential Association of College and Research Libraries (ACRL) guidelines for teaching information literacy. While the original ACRL standards (Association of College and Research Libraries, 2000) focused on measuring information literacy skills related to textual information acquisition, the revised information literacy framework (Association of College and Research Libraries, 2015) acknowledges the context-dependent and fundamentally social nature of information literacy. However, previous studies on PBL and information literacy in chemistry education have not explored the social and contextual information processes that students engage in during PBL. Study 1 highlighted the importance of autonomous information acquisition and experimental procedure design, as well as the informational role of experimental feedback. Study 2 builds on those findings to provide a more detailed exploration of how students engage with information during planning and execution of the experimental procedure. A sociocultural framework for information literacy research emphasizes practical experience and challenges the traditional approach that information can only be acquired, manifested and researched through textual resources. To advance knowledge in this area, further research is needed to describe the social and contextual dimensions of information literacy practice in chemistry, with a focus on how information processes occur in practice during a PBL lab.

The intent of Study 2 was to improve the understanding of the information process that students engage in during this PBL beginner lab to further a description of the information practice in relation to laboratory learning.

The following research questions guided this study:

1. **How can we describe the in-practice and perceived information process students engage in during a PBL beginner lab?**
2. **How do privileged ways of knowing in relation to textual source quality shape the information process?**

(2) To answer the research questions, different types of data were collected over the course of three cohorts using a qualitative study design. Data collection and analysis were an iterative process, evolving over the course of the three cohorts to get closer to the research topic. The goal of this study design was, first, to understand how students deal with information in practice, since many social aspects of the information process occur subconsciously and cannot be retrieved in retrospect. Secondly, the intent was to explore the inner world of the students and their perception of certain aspects. Figure 4 shows the data collection and analysis.

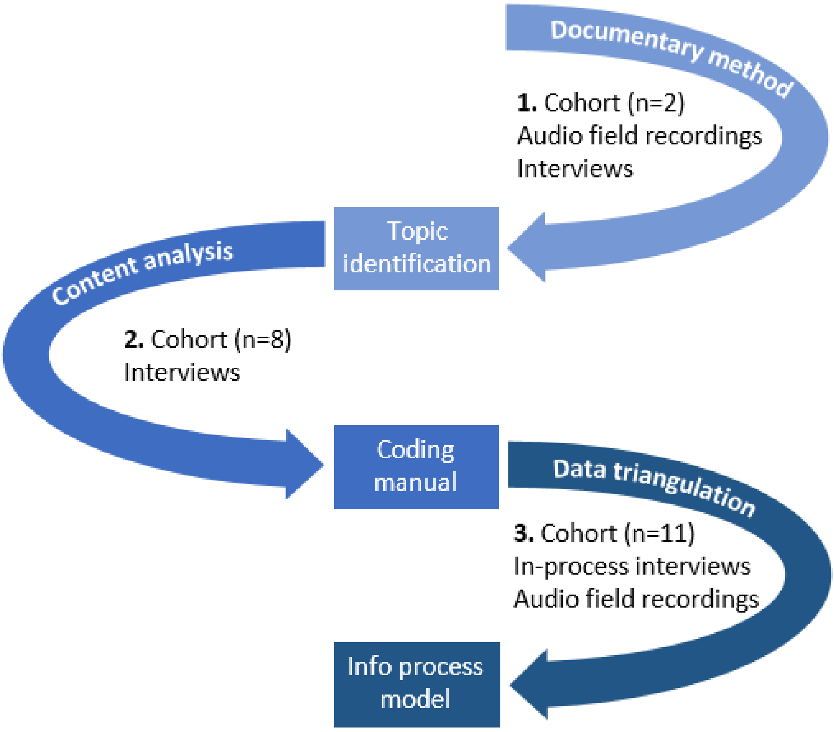

Figure 4. Overview of data collection and analysis.

Data collection for this study involved three cohorts of students, and a variety of qualitative research methods were used to answer the research questions. Before the study began, all participants were informed about the study's purpose and provided written consent. The goal of the study design was twofold: to gain insight into how students deal with information in practice and to explore their perceptions of the information process.

The first cohort consisted of two students who were interviewed about the creation of experimental instructions. Furthermore, the students' on-site experimental procedure design was recorded. Initially, the documentary method was used for data analysis. Initially, this method was used to identify themes that may be subconscious to the participants in relation to the information process. This approach generated a table of central themes (Study 2 SI Central Themes Table), with information evaluation emerging as a key topic that guided further adjustments. To gain a more comprehensive view of the perception of the students, semi-structured interviews lasting 20-30 minutes were conducted, guided by findings from the audio recordings on how the students perceived the process and what they deemed important. The interview guide is available in the Appendix (Study 2 SI Interview Protocol). The themes that emerged from the documentary method served as the basis for formulating the deductive codes used to analyze the interviews, while inductive codes originating directly from the data material were also developed. Combining both deductive and inductive codes resulted in an initial coding manual.

The second cohort consisted of eight students who participated in an interview study after the lab course. During the analysis of the second cohort interviews, the study focused on the use and understanding of non-scholarly and scholarly sources, particularly in terms of privileged ways of knowing. The interview data were analyzed using structured content analysis (Kuckartz, 2016; Mey & Ruppel, 2018; Philipp Mayring, 2019). The previously generated coding manual was applied deductively at first, and inductive coding of the interview data diversified and specified the coding manual. During data analysis, it became clear that certain aspects of the information process were only accessible in the moment they occurred and could not be reconstructed retrospectively, as previous literature has suggested (Lloyd, 2021). Because the interview study left some aspects of the information process unanswered, the data collection was adjusted accordingly.

For the third and final cohort, the findings from the previous data collections were combined and integrated. The third cohort consisted of 11 students in June 2021, who were interviewed multiple times during the laboratory sessions. In addition, the students recorded their experimental procedure planning sessions, providing deeper insights into the information process. The coding system was adjusted over the course of the three cohorts until a system with clear code descriptions, anchor examples, and sound coding rules was achieved (Study 2 SI Information Process Coding Table). We collected all experimental procedures (n=25) from students and analyzed the data using structured content analysis. Ultimately, all data was triangulated to gain a comprehensive understanding of how students engage with information in practice.

(3) The information process

Data analysis yielded a model of the information process that the students engaged in throughout the course. (Figure 5)

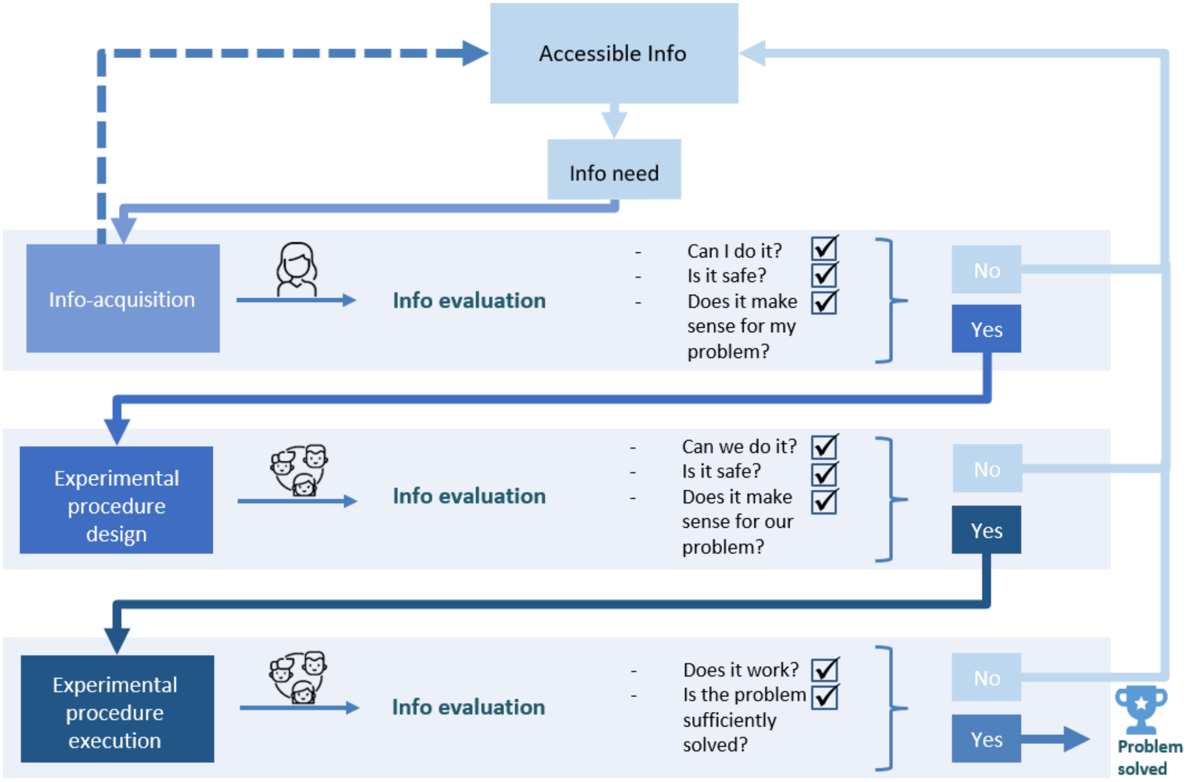

Figure 5. Information process model.

In this PBL lab, designing an applicable, problem-oriented experimental procedure was crucial to solving the problem and drove the entire information acquisition process. The process began with students using the information already accessible to them, often by searching for information using Google. They would use the strategy of "Googling around" to establish an information base and then repeated the information acquisition process until they had enough information to evaluate.

To evaluate the information obtained, students asked themselves three main questions:

"Is it useful for my problem?"

"Can I do it?" (relating to cognitive understanding, available equipment, and psychomotor ability)

"Is it safe?"

By posing these three questions, a more specific information need is derived. The required information was then searched for either online or in books. The information acquisition process was an iterative process where newly acquired information led to newly accessible information, which, in turn, led to new and more precise information needs.

The information process is a crucial component of PBL that shows how students use information in practice to solve problems. In PBL, the focus shifts from evaluating sources based on general criteria to using them as collections of information that can be applied and performed in experiments.

When students were interviewed about the information process, they explained their reasoning for using what they considered "good" or "bad" sources, but in practice, the emphasis was on the content itself. By using authentic problems, PBL allows learners to shift their focus from finding specific sources to using information to learn (Diekema et al., 2011). The students examine any information, regardless of the source, in terms of its feasibility and usefulness for experimentally solving a problem, which is a crucial feature of PBL compared to expository laboratories.

At the beginning of information acquisition, students often feel overwhelmed in their groups because the process is unclear, and assigning tasks and using the group's power without a basis of information can be challenging. This uncertainty is especially true when there has not been substantial experimental experience for the students yet.

Once the students have evaluated the information individually, they share their ideas for designing the experimental procedure with the group. Then, they evaluate the information at the group level, where different people review each other's ideas. If any criterion is not met, the information acquisition process is repeated. However, if all three criteria are approved, the students test the information by trial and error in the experiment. If the experiment does not work as expected, or if more information is needed, the students obtain new information, and the information process starts again with the accessible information. On the other hand, if the experiment provides all the necessary information to solve the problem, then the information and problem-solving processes have been successfully completed.

Experimentation is crucial for evaluating obtained information and ultimately solving problems. The students asserted that they could only determine the reliability and effectiveness of the gathered information by putting it into practice. They have reasons to believe that it will work, such as whether it makes sense, is safe, and is feasible. However, they require hands-on experience to confirm its validity. If the experiment fails to deliver the desired results, it could mean that the information was incorrect, or the students made an error.

This process highlights that students consistently assess information with experimentation in mind. The information must be suitable for the experiment and critically evaluated. Ultimately, though, it is the testing that serves as a fundamental aspect of inquiry learning. The emphasis lies in employing information for experimentation, which sets PBL and inquiry-based approaches apart from expository formats. This distinction displays the ownership and autonomy inherent in these methods.

Privileged Ways of Knowing: Quality of Sources

Part of this work investigated the students' perceptions of privileged ways of knowing concerning the quality of textual sources. The coding table is available in the Appendix (Study 2 SI Quality of Sources Coding Table). During practice, students did not discuss generic source quality criteria; hence, no data could be obtained from the on-site audio recordings. In practice, feasibility and problem-orientation of the information is decisive for the students. In the interviews, the students were explicitly asked about source quality's role during the experimental procedure design to gain a deeper insight into the students' perception of privileged ways of knowing. The sources are mainly categorized into “non-scholarly” and “scholarly” sources, which is a common distinction in the literature to categorize student's information literacy skills (Shultz & Li, 2016) and is also used by the participants in this study on their own initiative.

Students generally referred to non-scholarly sources as "bad sources" and scholarly sources as "good sources," while generally using both to find information, nonetheless. A common strategy was to search for information content helpful for problem-solving in non-scholarly sources for comprehension and application and then attempt to find similar information in scholarly sources to be able to quote a "good" source on the experimental procedure. The notion that non-scholarly and scholarly information is used in practice was supported when cited sources included in the students' experimental procedures were analyzed. Twenty-five experimental procedures were collected in total: four cited only non-scholarly sources, five cited only scholarly sources, fifteen cited both, and one was handed in without the citation of sources. However, listening to the audio recordings in practice, there appeared to be a predominant use of content from non-scholarly sources.

One advantage of non-scholarly sources was their comprehensibility; sources such as forum information gave the impression that the content came from people facing similar problems. This information was expressed in more straightforward terms and is more understandable. However, the source's low-threshold nature also relates to the student's perception of the author, who seemingly experienced similar beginner problems. Disadvantages of the non-scholarly sources stated by the students included safety concerns; the students feared that non-scholarly sources might not be as safe as scholarly sources. Another disadvantage was that the content might be unreliable and would not work in the lab. Aside from this, most concerns revolved around the supervisors not being satisfied with the choice of sources, which again reinforces the argument that scholarly sources are a form of privileged ways of knowing in this field.

There is a difference between how students engage with information in practice - for instance, the questions they ask and the experimental and social factors involved - and the theoretical picture they have in mind when using the term "information." Although what students say retrospectively about source quality may not influence their practical decisions, discrepancies between their evaluations of source quality and their actual source usage align with other reported findings (Griffiths & Brophy, 2005; Kyung-Sun Kim & Sei-Ching Joanna Sin, 2011; Martin, 2008). These results highlight the difficult position students are in: while they may perceive non-scholarly sources as unreliable and fear not meeting their supervisor's standards, such sources have advantages that lead them to use them. In contrast, students have a high degree of trust in scholarly sources, which are difficult to comprehend and obtain.

Historically, information literacy research and education have mainly focused on codified information retrieval and easily measurable skills (Diekema et al., 2011; Tuominen et al., 2005a). Current developments in information literacy teaching and research emphasize the importance of including social and contextual aspects (Association of College and Research Libraries, 2015). This work contributes to this shift by shedding light on the complex ways in which students navigate the information practice of chemistry. This knowledge can serve as a starting point for supporting their information problem-solving process.

3.3. The Social and Physical Aspects of Information Practice for Beginners in a PBL Lab

The previous studies focused in depth on problem design and implementation in a beginner lab as well as the planning of the experimental procedure in relation the information process and the used sources. These studies established the experiment as a central information source and yielded key aspects of information literacy practice in PBL laboratories. However, this work complements these findings by examining the discourse between newcomer students and experienced TAs in their first university laboratory session. By exploring the social and corporeal aspects of information in the laboratory practice, we gain valuable insight into what it means for students to enter a new community of practice.

The content of this chapter has been accepted for publication:

Wellhöfer, L.; Machleid, M.; Lühken, A.: "I don't know, ask the chemists -. I think it's kind of a consensus among them" – Information practice in a problem-based beginner lab. *Chemistry Teacher International.* 2023.

(1) The beginner laboratory can pose challenges for students, particularly in non-traditional formats. To shed light on these challenges, an information practice framework can help understand

how learners acquire knowledge through social, textual, and corporeal modalities within the community of practice. In this study, the aim is to explore the information practice of novice learners entering the chemistry community by drawing on practice theory and comparing their experiences to those of experienced members. The results of this work will contribute to a better understanding of what it means to become information literate in chemistry, the specific role of social and corporeal information, and how instructors can support students in this process. The following research question guides the study:

- **How is information practice represented and developed in a problem-based beginner laboratory?**

(2) The study was carried out in a PBL beginner laboratory at Goethe-University Frankfurt, Germany. The researchers chose to collect data during the first lab session of two groups of non-major chemistry students, with Group A comprising of three students and one TA, and Group B comprising of four students and one TA. The chemistry laboratory is a context in which group-specific “sayings and doings of practice” (Lloyd, 2012) are very present. The learning about procedures, the way things are done, and the classification of phenomena that are physically experienced through experiments is a vital part of what newcomers learn when they enter the laboratory practice. The practical understanding of phenomena is often not easily describable (Kirschner, 1992). The reconstruction of orientation frames and tacit knowledge, which entails "that we know more than we know how to say" (Polanyi, 2009) represents a vital task of the documentary method (Liebig, 2007). Following this, the documentary method was the method of choice for this case study's interest to explore the different characteristics of the information practice in the chemistry beginner lab. The tables containing the data analysis related to the topics of safety, disposal, and acidification can be found in the Appendix (SI Table Safety; SI Table Disposal; SI Table Acidification). Usually, the documentary method uses group discussions for data collection (Bohnsack, 2001). However, the aim is to keep the discourse situation as authentic as possible (Meyer & Verl, 2019). In this study, the information practice in the laboratory was of interest. Thus, there was no need to create an artificial interview setting. Instead, the first lab session of two groups of students was recorded on-site and built the data basis for this study.

(3) The next sections depict the representation of information practice for explicit information, specifically focusing on the topics of safety and disposal. In the subsequent section, the role of tacit and corporeal information is illustrated, with a particular emphasis on the topic of acidification. The representation and development of information literacy practice were analyzed, drawing on the key aspects of safety, disposal, and acidification. What these topics have in common is that they exemplify group-specific knowledge (Kleemann et al., 2009).

The Topics of Safety and Disposal: Explicit Information Needs

The results of Study 3 show that theoretical knowledge in the form of textual information is not sufficient for students to act independently in practice. To develop "knowing-in-practice" regarding disposal and safety, students require action-guiding social information from experienced members of the practice community in addition to textual information. Furthermore, physical experience in different scenarios is essential for students to develop this knowing-in-practice. Figure 6 illustrates the information practice of students in their first PBL beginner laboratory session. The model begins with an information need related to disposal or safety. Initially, students prepare an experimental procedure using textual information, as we demonstrated in studies one and two. However, in the laboratory, a new information need arises that is related to the social modality, in our case, the TA. The TA provides action-guiding information that enables students to act and gain physical experience. The dotted line in the model represents the need for students to experience many scenarios before they can act independently and develop knowing-in-practice. These scenarios have various particularities that are difficult to anticipate in theory, as shown in Study 3 or Appendix SI Table Safety and Disposal.

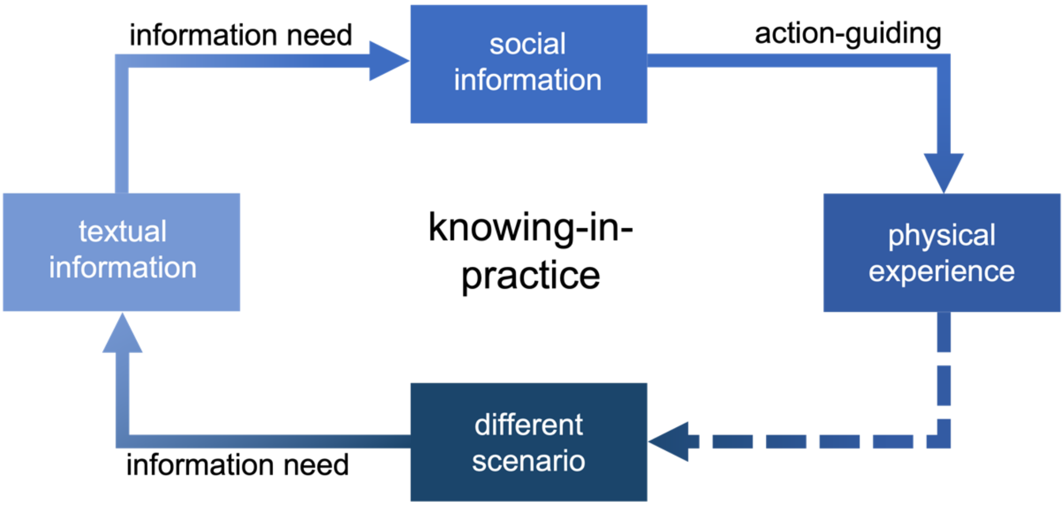

Figure 6. Illustration of the students' information practice in the case of explicit information needs, exemplified by safety and disposal.

The following section will briefly describe the results related to the two distinct group-specific topics that emerged from the data: disposal, safety. The two topics, disposal and safety, are illustrated in Figure 6 and highlight further aspects of laboratory information practice. The topic of disposal exemplifies how practice requires the application of knowledge to various lived scenarios that may not have been anticipated by students during theoretical preparation. In practice, new information needs arise, and students require social information or demonstrations from experienced TAs, to become equal members of the practice community. The topic of disposal also demonstrates how students develop their information practice throughout the session, from asking the supervisor directly without actionable suggestions to asking for feedback on suggestions and eventually engaging in group discussions that result in independent action. This development occurs through action and negotiation, as students gain experience and learn to make situational decisions independently.

The topic of safety highlights how knowing-in-practice in the chemistry laboratory is guided by general guidelines that are adapted situationally. When it comes to safety, specific decisions must be made that adhere to general guidelines that the chemistry community agrees upon intersubjectively. However, how these guidelines are applied appears highly subjective, as each nuanced situation differs from another (Elmborg, 2006). The results show that the students' attempts to actively participate in the information practice, by making suggestions to the TA and seeking guidance, are often met with the TA's passing on of "doings of practice" regarding safety. The students without question adopt the TA’s suggestions, even when an explanation for the safety measures is not provided. The supervisor, acting out of their responsibility for safety, often rejects the students' situational assessment and refers to general guidelines that correspond to a higher safety standard. Despite contradicting the students' theoretical preparation and subsequent safety concept, the TA's guidance is unquestioningly adopted by the students.

The "sayings and doings of practice" are shaped by both intersubjective and subjective components (Lloyd, 2007b). In the case of disposal and safety situations, theoretical rules are often insufficient to address the versatility of situations that require a situational decision (knowing-in-practice), as shown in the results. These situations create an information need that cannot be solved through textual resources alone, but rather require social guidance that is action-guiding, followed by physically lived experience.

The results highlight the different characteristics of information practice in a chemistry beginner laboratory, exhibiting differences between experienced community members and complete novices entering a new community of practice. The guidance provided by TAs varies from situation to situation and from TA to TA, sometimes with an explanation and sometimes without.

In contrast to textual information, differing and cautious suggestions from TAs are often adopted unquestioningly by students.

The use of general guidelines contributes to the socialization of students in the community of practice and provides a framework for situations and decisions to be bundled together (such as not wearing gloves and always going to the fume hood with sulfuric acid), which can be a relief in the complex learning environment of the beginner laboratory. The unquestioned transmission of rules of conduct exemplifies how members are socialized into the practice community, how they are passed on, and how the students will likely pass them on in the future.

The Topic of Acidification: Tacit Information Needs

The importance of physical experience and tacit knowledge in learning the ways of a community of practice is emphasized by Lloyd (2010b): "They learn not only about the actual performance of practice (e.g., the doing of practice), but they also engage with nuanced information that is difficult to articulate (e.g., the saying of practice)."

In the laboratory, learning occurs through physical experience of the routines, procedures, and experiments that constitute the doings of practice. This includes the crucial aspect of "getting a feel for phenomena" (Kirschner, 1992), which is closely tied to tacit knowledge. Tacit knowledge, however, can be difficult to articulate and verbally pass on.

In this study, the role of tacit knowledge in the beginner laboratory is exemplified by the topic of acidification (Appendix SI Table Acidification). The discourse shows how the TA herself knows what acidification means (to her) in a specific situation, enabling her to determine if a sample is "still too neutral" or "strongly acidic." However, she cannot explicate what acidification means in a general sense; she has a feel for the phenomenon.

We illustrated the students' information practice in the case of tacit information needs in a model based on our results concerning acidification (Figure 7).

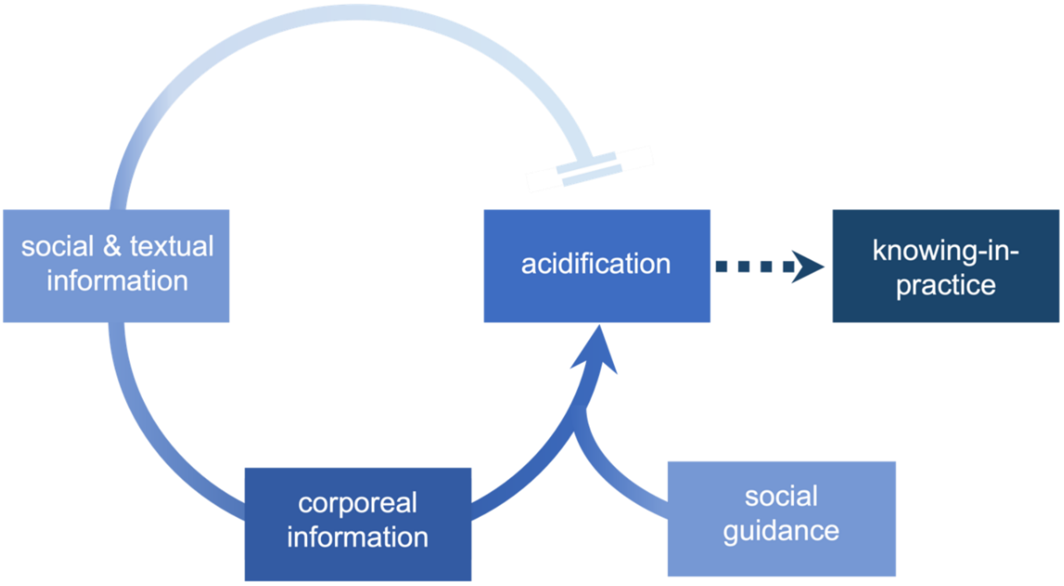

Figure 7. *Illustration of students' information practice in the case of tacit information needs, exemplified by acidification.*

The students initially relied on textual information that was insufficient in guiding their practical application of the concept of acidification. The term "acidification" appeared to be group-specific knowledge that was difficult for outsiders to understand. Even asking the TA did not provide a clear understanding of the practical application of the concept. The TA's instruction was rooted in tacit knowledge that could not be easily articulated.

However, the combination of corporeal information and social guidance enabled the students to experiment and gather information through trial and error. The students attempted to acidify their sample and measured the pH value, which the TA then classified as "too neutral" or "strongly acidic", providing social guidance that enables them to eventually succeed in the attempt to acidify their sample. The students learned through this entwining of cognitive and corporeal sources of information, and gradually developed a feel for the phenomenon of acidification.

As shown in Study 3, the integration of social, textual, and corporeal information through practical experience needs to be repeated in different scenarios for students to become independent actors. The practice community's common reference frame is established through individuals engaging in practice together, with newcomers learning the sayings and doings of the practice and eventually becoming information-literate members who can act independently and decide situationally (knowing-in-practice) (Lloyd, 2010a). The acquired information, whether predominantly tacit or explicit, requires social guidance and physical experience for the students to develop knowing-in-practice. In the case of acidification, for instance, the students need an experienced member to classify their findings and understand the concept's practical application. In both cases, multiple experiences are necessary to develop a shared understanding of the community's concepts and practices in the chemistry information landscape.

4. Discussion and Implications for Teaching

The results in the three papers concerning the textual, social and corporeal information modalities, yield different aspects of how they could be beneficial to laboratory teaching. The overarching research question "How is information practice represented and developed by participants in a problem-based beginner laboratory?" guided our exploration of them from a sociocultural perspective. This involved focusing on different aspects of practice that manifest through discourse, as well as the individual perception and experience of the students.

The results of the studies suggest teaching information literacy in a holistic manner, including all three information modalities (Figure 1). In the upcoming sections, implications will be suggested on how to include textual, social, and corporeal information into teaching to support the student's information literacy and integration into practice, by connecting the results from the different studies.

Reconstructing aspects of the chemistry information practice shows how demanding the process is for beginner students. They learn how to integrate textual, social, and corporeal information modalities, how they play together, and how they are valued within the social site. Students encounter group-specific knowledge in the form of "sayings and doings of practice" that experienced members find self-evident and use to mark belonging to the group. Through this process, students learn to communicate and act in a way that integrates them into the community of practice. The different studies provide insights into various aspects of the information practice, which will serve as the basis for the subsequent implications for teaching. The next section will explore how the findings on students' use and perception of textual non-scholarly and scholarly sources can help to connect social and textual information.

4.1. Authority of Sources: The Connection between Social and Textual Information

The incorporation of primary chemistry literature in PBL beginner labs can be challenging for students, as they may struggle to understand the content and lack the experience to evaluate its usefulness. As a result, students may feel overwhelmed and unable to find actionable information to build a knowledge base. As observed in Study 2, students turned to non-scholarly internet sources such as forums and Wikipedia, despite being aware of the potential drawbacks of these sources. Moreover, students were aware that non-scholarly sources were not preferred by supervisors, which may result in an internal conflict for them. However, despite the drawbacks, the students did not desist from using non-scholarly sources. Incorporating non-scholarly sources into teaching can help students understand the pros and cons of different information sources and develop critical evaluation skills.

An example of non-scholarly sources the students used for information acquisition were forum entries (Study 2). The students referred to them as possibly unreliable information, showing their general scrutiny of this type of non-scholarly internet source. However, they still used information from forum entries because it was easy to understand and appeared to be provided by people with similar beginner problems. Hence, they knew about the disadvantages but used them anyway. The benefits the students identified was that the forum information was easily understandable and actionable.

The use of forum entries as a non-scholarly information source can have similar advantages and disadvantages as information shared with peers; it can be entirely false, or it can be helpful for learning and support in a manner that is closer to the students' understanding and reality. Forum information highlights the connection between social and textual information because it is very close to peer information; it is very apparent, also to the students, that a person has written this text. Thus, the use of forum information in information literacy instruction can serve as an introduction to teaching all types of textual sources as fundamentally social.

Teaching the students that textual forum information was written by somebody and is therefore fundamentally social may seem trivial at first. However, the results of Study 2 show that students tend to have a fundamental trust in scholarly sources and a fundamental distrust in non-scholarly sources. As such, to teach students to evaluate information critically, they need to go beyond binary thinking of "good versus bad sources." An approach by Li et al. involves researching assignments that require students to edit Wikipedia entries, which can offer valuable insights into the intricacies of information creation and production (Li et al., 2016). This approach, along with the discussion of forum information, may serve as a starting point for comparison with scholarly information, helping to clarify that even a peer-reviewed article is written by someone and enabling the evaluation of the diverging authority of various sources.

4.1.1. From Non-Scholarly Sources to Professional Information: A Deliberate Intermediate Step

The students in the study employed a strategy to help them address their need to use non-scholarly sources while anticipating their supervisor's dissatisfaction with them. They searched for information in non-scholarly sources and then cited "good" (scholarly) sources. This demonstrates the students' participation in the information practice by showing that they know how to find valuable and comprehensible sources for problem-solving and how to privilege certain ways of knowing, as determined by experienced members of the practice (Lloyd, 2010b). The students' coping mechanism illustrates the group-specific and intersubjective value placed on certain information resources above others by the group. This also shows their understanding of the historical, ideological, and contextual aspects that constitute participation in the practice (Tuominen et al., 2005a).

Advancing from non-scholarly sources to more professional information is crucial for students to fully integrate into the information practice and draw meaningful knowledge from the group's approved knowledge base. Difficulties with the language used in primary sources can often lead to cognitive load (Lloyd, 2010b). Therefore, deciphering the specialized language in primary sources should be viewed as a learning process. Following the results of Study 2, the students' information acquisition in non-scholarly sources and subsequent searching for similar information in scholarly sources to cite them can be understood as a deliberate intermediate step in the information literacy development. This process enables the supervisor to serve as a corrective for the students until they can access primary literature directly, which is a form of social consultation inherent in the community of practice (Hosier, 2019). However, the results do not indicate to what extent students would engage with the content of the scholarly sources or whether they would only look for key terms to verify whether the content fits the general information they previously acquired through non-scholarly sources.

4.1.2. Problem-Based Learning in PBL Beginner Labs: Aligning Problems and Information Paths

The results indicate that beginner students sometimes use non-scholarly sources for understanding and scholarly sources for citation. To further challenge students and enhance their intrinsic motivation, problems can be designed that can only be solved with certain sources. In acquiring textual information to design the experimental procedure, students gain a sense of competence and autonomy (Study 1). Therefore, when designing problems for a PBL lab, the problem and information paths must align. By deliberately addressing specific information pathways that students should learn, obstacles that arise are more likely perceived as informational rather than controlling (Ryan, 1982). This kind of problem design is consistent with CET (Ryan, Richard M., and Edward L. Deci, 2000). Students can then learn in a meaningful way that certain sources are more useful or even necessary for certain problem-contexts. In the PBL lab these studies are based on, almost all students viewed patent literature as a prerequisite for acquiring vital information to solve the second problem. The ability to navigate the patent literature reinforced students' sense of autonomy and competence (Appendix Study 1 SI Inductive Coding Table).

However, some students found the need to use patent literature overwhelming (see Study 2), which highlights the challenges of a novel and complex learning environment, especially for beginners (Seery et al., 2019). Additionally, students may struggle with nontraditional lab formats and experience a general state of confusion (Chopra et al., 2017). Therefore, requiring complex primary literature, such as patent literature, in a beginner PBL laboratory may be excessively difficult. However, for more advanced students, designing problems that target specific information skills and are otherwise unsolvable can be a meaningful task. The problem designed in the referenced studies can serve as an example of this approach (Appendix Study 1 SI Lab Manual).

4.1.3. The Socially Constructed Authority of Information Sources in PBL Beginner Labs

Information literacy instruction can help students understand textual sources as fundamentally social by contextualizing them to specific problems. This can be achieved by considering the socially constructed authority of a source and the authority required by the specific context at hand (Association of College and Research Libraries, 2015). To become information literate, people must be able to make contextual decisions about the required authority of a source in question. The authority of information sources is determined by the knowledge and credibility of their author, and the required authority of a source depends on the situation, where "information needs can help determine the degree of authority required"(Ibid.). Each of us unconsciously evaluates and weighs the required authority of sources for information needs. In Study 2, students were more likely to refer to scholarly sources for questions of safety related to their experiments. The required source authority for safety questions was intuitively higher for them than in other contexts.

Creating an awareness of the social and context-specific nature of information for different kinds of information problems could help students make competent decisions and reduce the internal conflict they experience when they consider a source unsuitable but use it anyway. This understanding is a practical and fundamental introduction to the idea that source authority is socially constructed and context-dependent.

4.2. Social Guidance in Laboratory Practice

The previous section explored possible instructional approaches to help students evaluate textual sources concerning their contextual suitability by understanding sources as a socially constructed authority. These approaches have implications for teaching, particularly regarding students' planning of the experimental procedure, which is a critical aspect of PBL laboratories.

When students encounter a PBL laboratory for the first time, they face a complex and potentially confusing learning environment. Therefore, it is important to identify information pathways that can support their initial laboratory experience and avoid those that might hinder it.

4.2.1. The Importance of TA Instruction in PBL Laboratories

The results of Study 3 suggest that, in laboratory practice, the TA provides social information that is more influential than the textual information students may have prepared beforehand. The TA's instructions and demonstrations often differ from what students anticipate based on their theoretical knowledge, and their guidance is critical to the students' practice. Consequently, the results show that students generally accept the TA's instructions without questioning them, even without an explanation.

Therefore, it is important to consider the TA's role as a social information resource when applying the findings of Study 3 to teaching. The information required by students to plan an experimental procedure is very practical, focusing on feasibility and safety. When students enter the laboratory, they learn about the fundamental sayings and doings of practice, including how things are done and communicated in their group.

Graduate student TAs are typically the primary resource and central contact person for students in laboratory courses (Cortes et al., 2014). New TAs who are close in age to the students may prioritize maintaining their authority and demonstrating their competency in answering questions (Robinson, 2000), but this may lead them to avoid clarifying when they do not know the answer or explanation to certain questions, resulting in insufficient explanations of procedures. However, clear explanations are identified as a central aspect of TA instruction by both students and TAs (Herrington & Nakhleh, 2003). Therefore, it is necessary to create an awareness of these "obvious" things that TAs may have adopted themselves in practice without fully understanding them, and to stress the importance of not skipping steps when explaining certain procedures.

Tacit elements of practice are challenging to describe for the TA, and this lack of understanding may be passed on to the students, who may also not know why things are done in a particular way.

Including a reflection on the group-specific aspects of practice that experienced members consider self-evident but that are completely novel to newcomers in TA training can be helpful. Peer leaders have reported that laboratory courses are relevant to learning about their own learning (Gafney & Varma-Nelson, 2007). However, awareness of the group-specific sayings and doings of practice is a prerequisite for reflecting on one's own learning. Teaching these practices from a practical perspective could be beneficial. For example, incorporating a reflection on excerpts from Study 3 on topics such as disposal, safety, and acidification in TA trainings could increase awareness of the challenges newcomers face in understanding the sayings and doings of practice. By showing TAs excerpts that depict the discourse around acidification samples as "very neutral" or "strongly acidic," they can become more aware of their own practice and how they pass it on, which ultimately benefits both students and TAs.

TA training focuses on TAs' subject knowledge regarding procedures, experiments, safety, chemistry concepts, and teaching capabilities (Herrington & Nakhleh, 2003). Reflections are already implemented in TA training or teaching internships (Atieh & York, 2020; Cortes et al., 2014; Wheeler et al., 2019). However, without awareness of group-specific "knowing-in-practice," TAs cannot improve their explanations. Thus, incorporating a reflection on the group-specific aspects of practice that experienced members consider self-evident but that are completely novel to newcomers could improve TA training by providing a more practical and holistic perspective that benefits both students and TAs.

The aim of teaching information literacy in a beginner chemistry laboratory is not to convert tacit knowledge into explicit knowledge or to create general rules of conduct. However, the literature indicates that the beginner laboratory is a challenging and potentially overwhelming environment for students (Chopra et al., 2017; Kirschner et al., 2006). In a PBL laboratory, students are expected to independently solve problems by searching for information, while TAs are supposed to guide students without providing answers (Clark et al., 2016). However, specific areas of direct instruction in PBL laboratory teaching could help lighten the cognitive burden on students (Kirschner et al., 2006). For instance, in the scenario of acidification discussed in this study, a demonstration by the TA could have been helpful.

To reduce difficulties that are not productive struggles, more research is needed on how the chemistry community's group-specific knowledge is represented in practice. This research can help identify when a situation can be considered a "productive struggle" (Keen & Sevian, 2022) and when it is unnecessarily difficult for students (Chopra et al., 2017). The aim is to encourage inquiry while reducing unnecessary difficulties.

4.2.2. Information Literacy Instruction: A Holistic Approach to Critical Evaluation

In contrast to their evaluation and scrutiny of textual information, the students in the study did not question or seek clarification from their TA when given instructions (social information). For example, one student was frustrated by the chemistry literature when the formulations changed between percent and mole, showing that students scrutinize the ways of expression in the literature (Study 3). However, no student scrutinized the information given by the supervisor, whether or not it included an explanation. This highlights the risk of social information being accepted and internalized without question when internalized principles are passed on.

Information literacy research and education often aim to improve the critical evaluation of written sources (Li & Liu, 2022; Yevelson-Shorsher & Bronstein, 2018). However, teaching students to understand information literacy as a holistic practice and apply the same critical mindset to social information could also be beneficial. As previously mentioned, an effective strategy for teaching students to scrutinize social information involves imparting the understanding that all textual information is inherently social. Ultimately, students should understand that all authority of sources is constructed, and it is up to them to evaluate the required authority in a specific context (Association of College and Research Libraries, 2015).

To build information literacy instruction from the start as a connection of social, textual, and corporeal information may also help reduce hierarchy and intimidation in the lab and cultivate an environment that welcomes questions, a positive error culture, and a constructive dialogue between TAs and students. In practice, the authority of sources becomes evident in the in-practice discourse, where instructions for action are followed without question (Study 3). While this can be beneficial and necessary for lab work to be feasible and safe, it could also be helpful to raise awareness of social information as information that comes from a source. TAs as sources of information obtain an authority that students should learn to critically evaluate.

4.2.3. Acknowledging the Importance of Corporeal Information and Tacit Knowledge in Laboratory Practice

To address students' feelings of insecurity in a beginner laboratory, it is important to raise awareness of the need for corporeal information and physical experience for conceptual understanding from their perspective. In instances where the required information is not available in writing or is rooted in tacit knowledge, students may know that something is missing, but they cannot identify what it is. This is because the information must be enacted to become meaningful. By making the learning experience transparent to students, such as through the Transparency in Learning and Teaching (TILT) approach (Winkelmes, 2014), educators can discuss with students how and why they learn in a certain way, including the necessity of physical experience for understanding laboratory practice.

4.3. The Experiment as the Center of Information Literacy Instruction

Combining the findings from the three studies, we can implement the knowledge gained into information literacy education. Study 1 highlights the importance of experimental feedback for motivation, while Study 2 shows that students' primary concern is to find safe, feasible, and useful information to plan and conduct the experiment. Finally, Study 3 demonstrates the necessity of physical experience and trial and error through the experiment.

These findings propose making the experiment the focus of instruction in information literacy education, including teaching students how to retrieve, use, and evaluate information for and from the experiment. Moreover, they suggest connecting information modalities (textual, social, corporeal) to the experiment to foster a more comprehensive understanding of the field of study, reduce feelings of insecurity in the laboratory, and enhance learning outcomes. The role of the experiment will be further examined from an information literacy practice viewpoint in the following section.

4.3.1. Enabling Student Autonomy and Competence in Problem-Solving through Information Literacy Education

The experiment is a particular information source that delimits the chemistry practice from other practices and holds great potential for information literacy instruction. Experimental feedback can be used for problem design to enhance intrinsic motivation (Study 1). Through the experiment, the students can gather the central information for problem solving autonomously. Thus, obstacles and challenges are more likely to be perceived as informational instead of controlling.

Laboratory practice also creates an opportunity for students to perceive themselves as part of the chemistry community of practice. One student noted how he used to think of chemistry as magical, but through the lab experience, he learned to relate theory to experimental phenomena and become part of the hitherto unintelligible community (Study 1). The students felt that understanding the experiments was a necessity to design the experimental procedure, which enhanced feelings of autonomy and competence, and also served as an "entry card" into the chemical scientific community, creating a sense of relatedness.

To achieve this, the problem should be designed aligned with the autonomous scientific process (Study 1). Students must feel competent to solve the posed problem or else they will feel overwhelmed. Therefore, student autonomy must 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. An elaborate example for problem design in this manner is given in the Appendix (Study 1 SI Lab Manual).

4.3.2. Trial and Error Through Experimentation: Instrumental in Learning and Motivation

Trial and error through experimentation emerged as a crucial aspect of the students' learning process across the different articles. The process of trying, failing, and adjusting experimental procedures was found to be instrumental in the students' motivation and conceptual understanding, often leading to "epiphanies" (Study 2). Ultimately, the critical information for problem-solving was acquired through the experiment, making the process a source of excitement and motivation for the students (Study 1). However, laboratory practice showed that when supervisors encouraged students to "just try it" without providing adequate social guidance, the students struggled (Study 3). This highlights the fundamental importance of information gathering in the laboratory, and the students' demand for missing information to be able to act competently. As such, instruction should emphasize the value of experimentation, the process of trial and error, and the crucial role of social information in guiding students towards successful experimentation.

The ability to test information in experiments is a key contextual feature of chemical information literacy practice. Information (textual, social) can be retrieved by the students in preparing the experimental procedure and it can be physically tested through the experiment, generating new, corporeal information. If an instructor designs a problem that can be solved using non-scholarly sources, and students test the experimental procedure for safety, feasibility, and usefulness, it should be up for discussion as to why the non-scholarly source is not contextually appropriate. If it works and it is the easiest option, it might make sense for the students to use non-scholarly sources. As we have discussed earlier, beginners may find it challenging to rely solely on scholarly sources. Therefore, their use of non-scholarly sources can be a valuable starting point for discussing the pros and cons of different information sources. It is crucial to emphasize the importance of deliberate problem design, which considers the possible and probable information pathways and adapts them to the prior knowledge and skill level of the learning group. If educators intend for students to use specific sources as a learning outcome, these sources must be essential for solving the problem at hand, as demonstrated in Study 2.

Rather than reinforcing notions of generally "good" or "bad" sources, information literacy education can be used to inform students about evaluating authority of sources context-specific, derived from the specific information need. Students evaluate the required source authority intuitively when the topic of safety in the laboratory is involved (Study 2). We can encourage this further by using naturally occurring scenarios during experimentation to further their awareness of source authority, for example: While non-scholarly sources were the students’ first information acquisition strategy, they were unsure about them and attributed arising difficulties to the sources rather than their own performance during experimentation. By designing their own experimental procedure, the students can experience themselves which sources to evaluate more thoroughly. The students are willing to scrutinize their information retrieval strategy if it does not generate the aspired results (Study 2). This can be used to start a discussion as to why certain sources might be more reliable than others, i.e., the diverging levels of authority inherent in different sources. Also, it can show them from the beginning that experimental procedures are, like every textual information, fundamentally social, and thus, not infallible.

From an information literacy perspective, the students' ability to scrutinize the experimental procedure in case of unsatisfactory results is a conceptual advantage of PBL labs compared to expository lab formats. In PBL labs, students receive feedback from the experiment and consider whether they executed the experimental procedure correctly or if the information they acquired was incorrect. This highlights that the experimental procedure is not an infallible document provided by a superior, but rather a work that obtains a certain level of authority depending on the author. This connection between textual and social information is tested in the experiment by obtaining corporeal information.

By emphasizing this point in instruction, students can better understand the authority and limitations of experimental procedures in comparison to expository lab formats, where students may not question the procedures they receive. Overall, this approach can enhance students' understanding of information in the context of laboratory experimentation.

4.3.3. The Necessity of Corporeal Information and Physical Experience in Knowing-In-Practice

From the students' perspective, an awareness of the need for corporeal information and physical experience to "know-in-practice" could help alleviate feelings of intimidation in the lab. The required information is often not available in writing, and there may be no precise answer from the supervisor, as the necessary information may be rooted in tacit knowledge. For example, acidification in a lab (Study 3). The students know that information is missing but may not be able to identify what it is, as the information must be enacted to become meaningful. Raising awareness of corporeal information and the necessity for physical experience could help students better understand their learning process. Additionally, models for explicit and tacit information needs could be used to visualize the different necessary information modalities for students and clarify the role of corporeal information in knowing-in-practice. This transparency approach could help students understand that the laboratory learning experience requires physical experience to become meaningful in practice.

The laboratory is where students participate in practice and learn to “know-in-practice”, which requires physical experience (Study 3). It is a place where students gain a feel for phenomena (Kirschner, 1992) and can lay the foundation for a more holistic understanding of information literacy. In conclusion, this section provides implications for teaching based on our findings that include the corporeal, social, and textual information modalities and how they are connected in practice. By incorporating a holistic understanding of information literacy and the importance of physical experience, instructors can help students better understand their learning process, foster feelings of motivation and autonomy, and help them become part of the chemistry community of practice.

5. Outlook

The first study aimed to explore how implementation factors can enhance students' intrinsic motivation in PBL, specifically in relation to the practical implementation of the problem. The study gathered data from student perceptions through open-ended questions. While this study provided insights into the implementation factors that impact intrinsic motivation, it did not include other factors that may also influence motivation, such as group dynamics and instructor behavior. Future research should investigate these people-related factors in relation to intrinsic motivation. Additionally, the study was limited to one cohort in a specific PBL-setting, and its findings may not be generalizable to other student populations. More research is needed to test the model of the autonomous scientific process, which includes the implementation factors that enable autonomous scientific process and enhance intrinsic motivation. Further studies should explore this model in different PBL-settings and with different student populations. It would also be beneficial to design and test problems for PBL-settings according to the model of the autonomous scientific process to determine if it increases student motivation. Nonetheless, this study provides a valuable initiation for understanding the connection between practical problem implementation and intrinsic motivation in PBL.

In the second study, a qualitative sociocultural approach was used to describe the information process in a PBL beginner lab, which is not commonly found in chemical IL research. The study provides a comprehensive insight into the information process by utilizing various data types and refining the research process across cohorts. However, this study is only a starting point in understanding the complex social and contextual dimensions that shape the information landscape, as other factors like supervisor behavior, problem design, and group dynamics were not considered. Additionally, as the study was conducted in one PBL setting, the findings may not be generalizable to other settings. Nonetheless, the information process model developed in the study includes essential aspects of IL that are necessary for problem-solving. A distinctive benefit of the study is the combination of in-practice audio recordings and interviews with students, which has great potential for further research in uncovering the discrepancy between what students believe is "good" information and what is useful to them in practice. Future studies are needed to test and potentially diversify the model in different PBL settings, with a mixed-methods approach that includes both quantitative and qualitative data collection. Although the study raises additional questions, it serves as a solid starting point for future research in chemical education.

In the third study, the lens of practice theory is used to understand information literacy, acknowledging it as a complex, contextual, and fundamentally social practice. The focus is also on highlighting the value of practice theory in comprehending and instructing information literacy and, ultimately, learning. However, the physical aspect of the learning experience in regards to chemical information literacy has been overlooked in both educational and scientific discussions thus far.

Still, it should be noted that this study only provides initial indications of the usefulness of the practice theory approach. To obtain a broader picture of information practice in the field, further studies are necessary. One of the primary limitations of this study is its reliance on a single group of students, emphasizing the need for comparisons with other groups. Future research could utilize the documentary method to uncover additional group-specific themes that shape the chemistry information practice, further understanding when corporeal, social, or textual information is necessary for learning, and improving instruction and learning in the laboratory. This study presents an in-depth qualitative analysis that does not claim to be generalizable. While the models proposed in this study offer insights into the different information modalities, they are limited to safety, disposal, and acidification. Therefore, further research is required to provide a more complete picture of how social and physical experiences shape information practice in the laboratory. As information literacy's contextual and social aspects gain recognition in educational research and practice, this study presents a valuable beginning for future research to expand upon.

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7. Appendix: Publications

7.1. Study 1

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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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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

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.

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

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.

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.

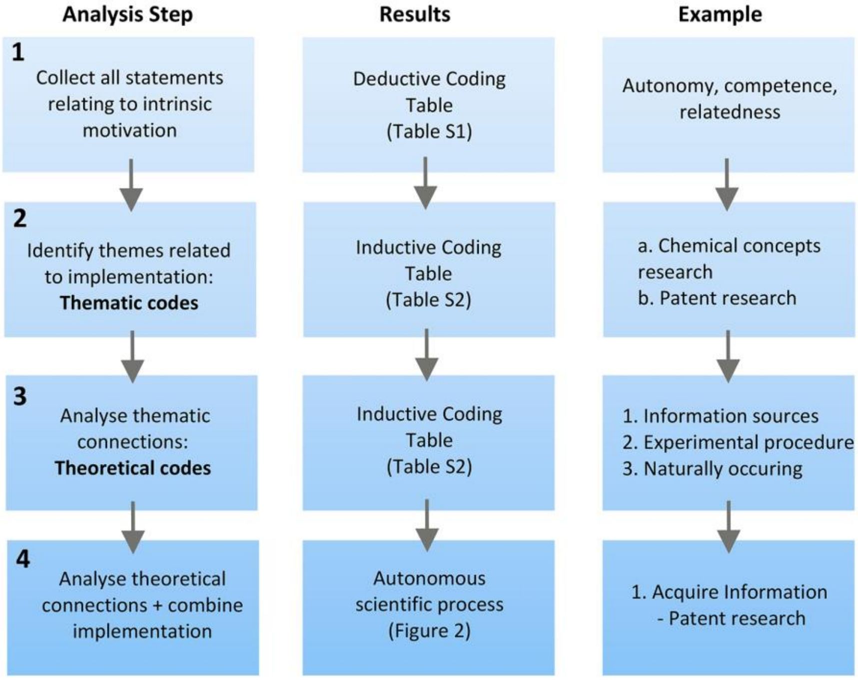

Figure 1. Overview of the coding and analysis process.

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.

■ 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).

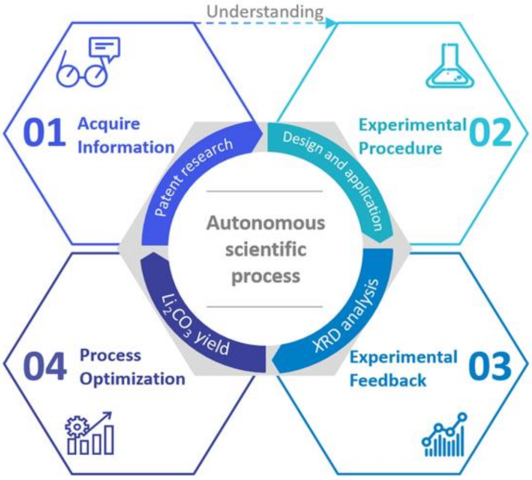

Figure 2. Model of the autonomous scientific process.

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 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 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."*

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.

> *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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7.2. Supporting Information Study 1

7.2.1. SI Lab Manual

Problem-based learning in an introductory inorganic laboratory: Industrial lithium extraction

Lab Manual

Script for teachers

Institute for Chemistry Education
Goethe-University Frankfurt
Summer semester 2021

Content

Introduction

The following laboratory and seminar concept is intended to provide supervisors with an overview of the lab course content. In addition to technical content, students will learn to work efficiently within the context of a problem-based entry-level laboratory in this course. It is assumed that students have not previously completed a laboratory practical. The lab course is problem-based and is based on current procedures in industry. Basic laboratory techniques and chemical analysis will be demonstrated using industrial lithium extraction as an example. The course is organized as a blended learning concept: It consists partly of face-to-face sessions in the lab and partly of virtual content to be worked on at home.

The contents of the practical course can be divided into two problems, which have to be solved experimentally. The problems build on each other with respect to their degree of difficulty. The first problem is easier than the second one and should familiarize the students with the problem-based concept. Most of the time will then be spend on the more elaborate second problem. Within the first problem, students are asked to determine the composition of an unknown salt mixture using qualitative analysis. In the second problem, the students will be given a salt mixture of known composition that mimics lithium-containing brine and will be asked to extract lithium carbonate from it in as high a yield as possible. Students will work in groups of up to five on the problems and may also design the experimental design as a group. The course is designed so that only the laboratory appointments are face-to-face sessions. The seminar and all included and subsequent content will be held and worked on virtually.

On the one hand, the self-learning phase consists of digital content in the form of screencasts or online courses, which serve primarily to convey information (input). On the other hand, students are expected to implement what they have learned by uploading a draft of their experimental design online to the learning platform in the form of a file discussion (output). For this purpose, they will be given an experimental procedure template that includes certain criteria and must be completed and uploaded as a file discussion at a specific time during the week. Students must print their digitally completed experimental procedures and bring them to their lab appointments. After the experimental instructions have been signed by an assistant, the student may begin the lab activity. The seminar will be held weekly via Zoom and will be especially useful for networking and sharing within each group, as well as with all students in the larger group. Content developed online can be discussed together regarding problems that have arisen, ideas, tips, or safety issues.

The eLearning component should enable students to design the experiments as independently as possible. For the problem-based concept it is fundamental that the experiment instructions are not given but are developed by the participants themselves. Informative screencasts and online learning courses were designed to enable students to design experiments independently. The digital content is not intended to prescribe explicit content, but to enable students to independently find, use, and evaluate information for experimental design. One advantage of the digital component is the ability for instructors to gain advance insight into students' ideas and prepare accordingly. Students may have dangerous, unfeasible, or off-the-wall experimental design ideas. Supervisors can correct experimental procedures prior to lab appointments and provide appropriate feedback.

Structural organization of the lab course

The lab course consists of face-to-face sessions in the lab two times a week and a weekly seminar session held virtually via Zoom. The overall timeframe is one month, so approximately eight lab sessions. In addition, there is a weekly exchange between the head supervisor and the individual groups. Students can participate in a consultation session with the lab supervisor to clarify questions or discuss ideas.

In the seminar, the problem is first communicated and discussed in the entire group. To be able to solve the problems, experiments must be carried out and the students organize themselves within their individual groups to create the corresponding experimental design.

The experimental design must always be uploaded (if changed) to the learning platform as a file discussion on the days before the lab session no later than 5pm, including appropriate hazard assessments. Students can participate in a consultation session with the lab supervisor to clarify questions or discuss ideas. Work in the lab always takes place from 9:00 am to 2:00 pm.

The problem-based laboratory concept

The PBL process was based on Poikela's model of problem-based learning[1] and adjusted for laboratory purposes.

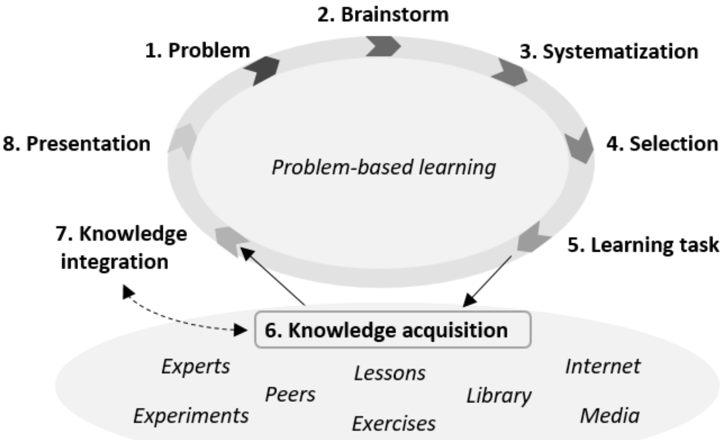

Figure S1. Problem-based learning process adjusted for laboratory purposes. The process is based on a model by Poikela (2006).

This PBL process was chosen because it is detailed yet applicable and focuses on self-directed learning and versatile information sources. The detailed depiction of the problem solving process enables a structured implementation. Phase one of the problem-based learning cycle aims to generate a shared understanding of the posed problem (see Figure S1). The problem was derived contextually by starting with a short documentary in the seminar discussing lithium carbonate's economic and ecological relevance and also the problems for the population living in areas where companies extract lithium carbonate from brine. The problems in this course were worded as if students were working for a chemical company in order to increase their authenticity.[2]

In phase two, the students brainstormed problem-solving approaches in their groups based on their prior knowledge. In the third phase, students categorized similar ideas in order to structure them. Subsequently, during the fourth phase, the students negotiated which ideas they wished to pursue. In the fifth phase, the students aimed to formulate a straightforward learning task considering the necessary knowledge in order to solve the problem. The fifth phase ended with the first tutorial. Throughout the tutorial sessions, the students received input on different information sources and information-finding strategies necessary to solve the problems. In a problem-based learning setting, information literacy skills are essential but often need guidance.[3,4] Strategies and resources for information acquisition need to be taught and cannot be assumed.

The central problem in this concept was designed to foster information literacy skills. We, therefore, chose a problem that was not quickly solved by a simple internet search. The problems were designed to require multiple sources of information to solve them. Patent information for this type of authentic industrial problem is an essential chemical information resource for students to learn. In addition to the content taught in the tutorial sessions, online courses and explanatory videos were available on the learning management platform. Information sources should be versatile and, besides textual resources, students were encouraged to ask each other and experts, e.g., professors.

During the sixth phase, the students acquired new knowledge to plan the experiments necessary to solve the problems. The self-study phase generally took place at home where the students completed the first version of their experimental design using a template and uploaded it to the learning platform. The group's teaching assistant checked the experimental procedure and gave feedback on safety or implementation issues. The seventh phase concerned the implementation of the acquired knowledge by creating the experimental procedure and applying it in the laboratory. The seventh phase transitioned back into knowledge acquisition if the experimental design did not produce the desired results and had to be adjusted. The students had a separate area in the laboratories where they could resume their research if necessary. The experiments, thus executed, also served as central informational feedback in this concept. During the eighth phase, students interpreted the problem-solving process considering the original problem. Assessment consisted of the impression throughout the problem-solving cycle (30%) and the final presentation (70%). The final presentation was a pitch presentation in front of the hypothetical company board, still in the context of industrial lithium extraction. The groups pitched their experimental procedure, explaining how and why they achieved their results and eventually why the company should take on their procedure as a large-scale process to extract lithium from brine. They were encouraged not only to explain, but also to justify and market their experimental procedure. The assessment, thus, remained in the same context while also testing the primary learning goal of this PBL-laboratory: for the students to create an experimental procedure to solve a problem and show that they understood what they were doing.[5]

PBL lab activity

The depicted concept includes current scientific and economic problems, in context, to induce the learners to make sense of their research activities.[6] 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.

Learning objectives and educational considerations

The overarching goal of the problem-based sequence of the laboratory practicum is to give students responsibility for experimental design and thus to perceive the experiment in its original function. Typically, students in entry-level labs are given experimental instructions, which leads to low learning efficiency because students do not need to understand what they are doing and for what reason during the experiment. To enable students to design experiments independently, the focus is on teaching chemical information literacy. If students are able to identify information needs, find, use, and evaluate information, then they will be able to manage their experimental design independently.

Since the problem-based chemistry sequence is newly developed and it is an entry-level lab, it was especially important to establish clear learning objectives here. To ensure that the individual problem components also covered the learning objectives established in other entry-level chemistry labs, the curriculum matrix shown below was used. On the left side are the subject-specific learning objectives, and on the right side are listed the problem components with which the learning objectives are to be achieved.

Table S1. Curriculum matrix with regard to scientific learning objectives. The scientific learning objectives (laboratory techniques and separation processes, as well as measurement techniques and analytics) were derived from other "classical" entry-level practical courses. It should be ensured that the same learning objectives can still be facilitated with the problem-based concept.

Scientific learning objectives	**Problem component**		
	Analysis of an unknown salt mixture	Lithium extraction	Lithium analysis
	Laboratory techniques and separation processes		
Keeping a lab journal	√	√	√
Stoichiometry	√	√	√
Preparing solutions	√	√	
Neutralize	√	√	
Disposal	√	√	
Vacuum filtration	√	√	
Filtration	√	√	
Centrifugation	√		
Liquid-liquid extraction		√	
Recrystallization		√	
	Measurement techniques and analytics		
XRD/EDX			√
Detection reactions	√		
Flame spectroscopy	√		
pH value determination	√		

The learning objectives regarding knowledge acquisition and chemical information literacy were further developed based on the competence areas of the educational standards chemistry of the Hessian core curriculum (Chemie | Hessisches Kultusministerium 2017).

Table S2. Curriculum matrix regarding knowledge acquisition and chemical information literacy. The learning objectives regarding scientific knowledge acquisition are the focus of the problem-based concept. The learning objectives for chemical information competence (finding, evaluating and using information) are a necessary prerequisite for independent problem solving. The two aspects of knowledge acquisition and information competence complement each other.

Knowledge acquisition and chemical information literacy	**Problem component**		
	Analysis of an unknown salt mixture	Lithium extraction	Lithium analysis
	Scientific knowledge acquisition		
Problem-solving skills	√	√	√
Plan scientific investigations, conduct, evaluate and interpret results	√	√	√
Work safety	√	√	(√)
	Chemical information literacy		
Find, evaluate and use information	√	√	√
Present and communicate information	√	√	√

Problem implementation

Detailed descriptions of the problems, as well as experimental and educational implementation suggestions are provided in the upcoming sections.

Table S3. Overview of problems

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[7]
	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

1. Problem: Analysis of an unknown salt mixture

Problems should be small-step extensions of known information material to questions that one cannot solve by existing means.[8] Thus, the first problem, "Analysis of an unknown salt mixture", was supposed to familiarize the students with the problem-based concept and prepare them structurally and practically for the following problem: "You work as part of a team for a lithium factory, and you have the order to examine samples from different salt lakes to discover possible new lithium sources. Unfortunately, your spectrometer has broken, and you need to find a way to detect which ions make up the sample. To extract lithium from brine, you need salt lakes with specific mineral compositions. How can you determine the composition of a sample?" As support in terms of scaffolding.[9] we informed students that the different "lake samples" can each be assigned to a so-called "brine type".[7] Students have to determine the brine type of the sample present. 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 whereby so-called "subtypes" such as Na-CO_3-Cl, Ca-Na-Cl...[7] are also possible. Thus, the possible ions are limited.

Nevertheless, this covers a large part of the ions that are important later on in the course. The students become familiar with designing the experimental procedure while engaging with a problem with uncomplicated content and implementation. Practically, the students learn about precipitation reactions and detections in a specific context, using the partaking ions. Students perform the appropriate experiments and can later draw on this prior knowledge. In addition, different information paths are suitable for this problem and the second problem. While the further course focuses on online sources, information acquisition for the first problem requires the library. Thus, different possibilities for finding chemical information are covered all together.

Group organization:

Two samples must be examined per group. The following "special roles" must be fulfilled in each group:

- Safety officer(s): at least one person is responsible for preparing hazard assessments.
- Physical literature research: at least one person is responsible for researching physical literature.

Instructions:

Students will be given the following notes:

- Salt lakes can be divided into so-called brine types (Lerman and Baccini 1978, p. 239). Fortunately, all your boss wants to know at first is what brine type your sample is. Possible brine types are: a) Na-CO_3-Cl-SO_4, b) Na-Cl-SO_4, c) Na-Mg-Cl-SO_4, d) Ca-Mg-Na-Cl

- Your boss is skeptical that you can detect exactly what is in the sample. So design your experiment as comprehensible and convincing as possible. You must be able to detect all the ions contained. Guessing is not an option ;-)
- Of course you have to take care of safety during your work. So think about your risk assessment!
- At the end of your work you will submit a scientific protocol. You will learn how to write such a protocol during the next tutorials.

Presentation of results:

- The presentation of the results is done in the form of a protocol.

1.1. Preparation of samples

Since the salts are inexpensive, non-hazardous and environmentally friendly, it is not necessary to pay attention to particularly small amounts of original substance for the students. In order to enable unambiguous results and flexible work with the original substance, 1-2 g of the respective salt can be provided.

For example, for the brine type Na-CO_3-Cl-SO_4 the following mixture could be prepared: 2 g $NaCO_3$, 2 g NaCl, and 2 g $NaSO_4$.

1.2. Experimental development

The experimental procedure for the first problem consists of classical detection reactions of the ions in question and can be found, for example, comprehensively in Jander and Blasius (2005)[10], or other textbooks on qualitative analysis.

A separation step of qualitative analysis can be carried out by separating Ca^{2+} ions from the remaining cations present. The alkaline earth ions can be precipitated as carbonates in the separation step with $(NH_4)_2CO_3$. Since the solubility products of the alkaline earth carbonates are relatively large (pKL ≈ 9), precipitation should not be done from too dilute a solution (although this will hardly matter at the amounts used here). If Mg^{2+} is present, reprecipitation may make sense because Mg^{2+} is readily trapped by carbonate precipitate.

1.3. Educational suggestions

Since this section serves, among other things, as practical and experimental preparation for the upcoming, more demanding section, it is advisable to insist that the students work cleanly. The experimental instructions should therefore be checked for completeness and in the laboratory. It is particularly important in this section to guide the students to work precisely and cleanly in order to avoid cognitive overload later on. In addition, the separation of Ca^{2+} as a separation step including reprecipitation is suitable to point out the property of Mg^{2+} to be included in other precipitates. This fact will be of great interest in the further course of lithium extraction. Teachers and assistants are again especially urged here to weigh when students need hints and guidance, especially regarding accurate and neat work. Unless accurate work can be traced, neither experimental instructions nor prompts should be accepted.

2. Problem: Industrial lithium extraction

Lithium extraction from brine represents the main part of the laboratory practical. Since the industrial process was newly developed as a teaching and laboratory concept, this section is described in more detail.

2.1. Industrial lithium extraction from brine

The overarching context is the industrial lithium extraction from brine. Lithium occurs on Earth in two different industrially relevant forms: lithium-bearing mineral rock and lithium dissolved in saline brines. The processes used for the large-scale industrial extraction of lithium depend on the type of occurrence. Lithium mining represents a significantly smaller share due to cost reasons.[11] Lithium extraction is a current topic of significant industrial and economic interest, while, as a controversially discussed topic, it also offers a wealth of information material. Furthermore, it combines ethical and ecological topics, such as electromobility and the effects on the local population[12] with the typical chemistry problems of the cost-effectiveness and the efficient extraction of valuable raw materials. Although the composition of brines varies with climatic conditions, water depth, and other factors, typical maximum concentrations of about 1500 ppm (0.15%) of Li^+ are found. Due to this, lithium producers have developed a lengthy concentration and purification processes of lithium from the brine, which differ only in their details.[12] 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.[12] 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.

2.2. Problem description: "Lithium extraction from brine."

The second and central problem is lithium extraction from brine: "After you and your team have examined various salt lake samples, you finally come across a lake in which lithium is present in high quantities! Initial equipment has already been installed on-site and the evaporation process for initial testing has been completed. You receive a sample of concentrated brine from the lake. Your task is to extract Li_2CO_3 from the salt mixture in as high a yield as possible." The students are given a salt solution that mimicks 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 task is to precipitate lithium carbonate from the salt solution in as high a yield as possible. Students design experimental procedures for extracting lithium from simulated brine.

Lithium processing primarily consists of a combination of precipitation reactions. To enable the students to design the experimental procedure, they are 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 designed this model solution for the experiment for the instructors. This sample solution is not a guide for the students but, rather supposed to summarize the essential steps and enable the teachers to offer flexible assistance and scaffolding.

The third problem component of the second problem is designed to give students an insight into an instrumental analysis method within this context, here using powder diffraction. Firstly, the students receive a brief introduction into the method during the seminar. Subsequently, they continually submitt their respective lithium carbonate products for measurement throughout the duration of the laboratory practical and obtain a diffraction diagram with percentage information on the product purity as well as the by-products. Students can use the information on the product purity and by-products to optimize their experimental procedure in a continuous manner.

Detailed descriptions of the problems, as well as experimental and educational implementation suggestions are provided in the upcoming sections.

2.3. Industrial practice and educational suggestions

Lithium deposits in brine from dried-up salt lakes are first pumped into evaporation ponds, where first sulfates, then chlorides and finally also more soluble hydrates precipitate with increasing concentration. Lime water ($H_2O + CaO$*) and washing soda (*Na_2CO_3*) are added to the concentrated solution while stirring, and precipitated carbonates and hydroxides are separated by filtration. Further addition of* Na_2CO_3 *and heating of the solution lead to the formation of solid* Li_2CO_3*. After filtration and drying, the desired product is further purified or converted to other target products.*[13]

To adapt this process for educational purposes, first a salt solution had to be found which sufficiently simulates a concentrated lithium brine after evaporation. From this, sulfates could first be precipitated by addition of precipitation reagents before extraction of any borate ions present. Any alkaline earth ions still present could then be precipitated as carbonates or hydroxides before the product lithium carbonate (Li_2CO_3*), which is poorly soluble in heat, was precipitated from the solution. In order to achieve high yield and purity, all steps were optimized with different reagents at varying concentrations. Products and intermediates formed were analyzed by classical detection methods such as flame staining and additionally by X-ray powder diffraction. In addition to the development of an exemplary solution, all experiments and analysis methods are also classified in the respective didactic background and considered within the problem-oriented concept.*

The industrial implementation of Li_2CO_3 precipitation as described has been published in principle by companies. However, for a high yield and purity of the final product it can be assumed that a detailed knowledge about the concentration of reagents used, adjusted pH values and possible following purification steps is required. These parameters are usually classified as trade secrets by lithium manufacturers and are therefore hardly accessible. In order to counter this circumstance and still enable the students to solve the problem independently, it is necessary to teach to students how to work with patents. For this purpose, online courses were created that focus on working with patents for experimental design. Videos and texts were used to convey the content. In addition, the seminar exemplifies how to search for patents on a specific topic. Students are given an overview of how to work with patents, where important chemical information may be contained, and how to search for patents. On the one hand, this is important for the teaching context in that the problem is industry-based and students actually rely on information from patents to solve the problem. On the other hand, patents in general are an important source of chemical information and learning about patents is also important in general. Efficiently and effectively searching for patents, and making use of the information contained in documents, is a key aspect of chemical information literacy.

The second problem statement is: After you and your team investigated various salt lake samples, you finally came across a sample in which lithium was present in high quantities! Initial equipment has already been installed on site and the evaporation process for initial testing has been completed. You receive a sample of concentrated brine from the lake. Your task is to extract a Li_2CO_3 from the salt mixture in as high a yield as possible.

Group Organization:

The following "special roles" must be fulfilled in each group:

- safety officer(s): at least one person is responsible for preparing the risk assessments.
- patent literature research: at least one person is responsible for researching patent literature.

Notes: Students will be given the following clues:

- Divide your problem (as in the previous case) into meaningful subsections: First, you have to convince your supervisors with an experimental set of instructions.
- In the next days you will learn a method to determine the purity of your sample and thus the yield using instrumental analysis.
- At the end of your work, you will "pitch" your developed process in the form of a presentation to the board of directors to decide whether this procedure will be adopted on a large scale in your company.

Presentation of results:

The presentation of results will be in the form of a presentation ("pitch").

In terms of content, the requirement for the students here is, on the one hand, to reproduce the basic precipitation reactions for the precipitation of Li_2CO_3, in which the students virtually take on the role of a scientist in a company developing a recovery process and in doing so have to combine their existing knowledge with new literature. On the other hand, in addition, the ability to determine the yield and purity of the product produced can simulate process optimization. Students who progress faster can use their own knowledge and access to more concrete literature such as patents to adjust various details in order to improve product parameters according to logic and trial-and-error principles. This is to ensure a scope for heterogeneous learning groups.

For the purpose of testing working solution methods in the practical course, detailed sources in the form of US patents according to Brown et al.[14] and Wilkomirsky[15] were available. These focus primarily on borate removal, but also treat other steps of precipitation in quite some detail, citing, among other things, pH and concentration ranges of the reagents used in each step. However, it should again be noted that working with patents must be explicitly taught, as they contain a great deal of information in language that is difficult to decipher. This can be perceived as very challenging, especially at the beginning of a degree program. On the one hand, the patents provide a detailed insight into the intricacies of the industrial implementation of lithium extraction. This can help to generate ideas, especially in process optimization. On the other hand, the patents hold some pitfalls, starting with a legal style of language that is sometimes difficult to understand. In terms of content, moreover, large ranges are always given for parameters such as concentration or pH, since conditions in patents are usually intended to be protected to the maximum extent possible. Therefore, the information given there often only provides a starting point for further optimization, an exact value can hardly be taken from the documents. There is also always the question of whether the parameters specified for industry can actually be successfully applied on a laboratory scale. Anticipating such difficulties is important prerequisite. They are to be regarded as a fruitful basis for discussions with the students, developing more and more from school teaching experiments to "real" scientific problems.

A basic solution principle based on successive precipitation reactions that allow Li_2CO_3 to be precipitated from a salt solution containing various components is obtained. The sequence of reactions as well as reaction parameters can be variable and are given differently in different sources depending on the composition of the salt solution and industrial circumstances. The basic principle mainly includes four steps including precipitation of the desired main product:

1. The brine worked out in the practical course is explained in more detail in section “Salt solution composition” and consists of the following cations and anions: Li^+, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-}, BO_3^{3-} and other hydrated borates. After their preparation, borate must first

be removed, since this could later bind lithium in the form of lithium borate and thus either impair the yield or lead to borate impurities in the final product.

On a large scale, an acidic pH of 0 to 5 is first set for this purpose in order to convert borates quantitatively into boric acid according to scheme (1) and to precipitate a large part of them (Wilkomirsky 1999).

$$Na_2B_4O_7 \cdot 10H_2O \ + 2\,HCl \longrightarrow 4\,H_3BO_3 + 2\,NaCl + 5\,H_2O \tag{1}$$

In the technical process, precipitated boric acid is then filtered off and the remaining borate content in solution is removed in an extraction step. A mixture of a primary alcohol (e.g. 2-ethylhexanol) in kerosene is usually used for this purpose, although the composition of the extraction mixture can vary greatly (range 1:5 to 5:1).[16] Thanks to better solubility of boric acid in the mixture, it can be completely removed from the aqueous phase by repeated extraction. Preparation of the extraction reagents is easily possible by adding NaOH.[16]

Students learn about the solubility of substances in different media and the theoretical background of extraction as a substance separation method, which go hand in hand with the practical understanding of the correct allocation of the two phases. In addition, the hazardous nature of boric acid must be known.

2. In the further process, particularly magnesium and calcium interfere, since these elements form compounds with carbonate that are even more difficult to dissolve than the actually desired lithium. The boron-free brine obtained must therefore be freed from Mg^{2+} in a second step by a precipitation reaction. In most cases, 20-30% Na_2CO_3 solution is used for this purpose, resulting in the precipitation of poorly soluble magnesium carbonate at a pH of 7-9.[16]

$$MgCl_2 + 2\,Na_2CO_3 \longrightarrow MgCO_3 + 2\,NaCl \tag{2}$$

Very wide ranges are given for the exact reaction parameters of temperature (15 - 95 °C) and duration (5 - 120 min), which could have only a minor significance for the laboratory scale in comparison to the large-scale optimization of the process. According to Wilkomirsky, this reaction makes it possible to precipitate up to 95% of the Mg^{2+} present and to separate it by filtration in a subsequent step.[15]

3. Subsequently, residual Mg^{2+} and, if present, Ca^{2+} remain in the aqueous solution and must be quantitatively removed from the brine to ensure high product purity. A further precipitation reaction enables their precipitation as a solid by a calcium hydroxide suspension, which consists of $Ca(OH)_2$ in a proportion of 5 - 50% by weight. At an alkaline pH (8 - 10), both calcium carbonate and magnesium hydroxide precipitate during the reaction.[13,15]

$$\longrightarrow$$

$$MgCO_3 + Ca(OH)_2 \qquad Mg(OH)_2 + CaCO_3 \tag{3}$$

$$MgCl_2 + Ca(OH)_2 \qquad Mg(OH)_2 + CaCl_2 \tag{4}$$

$$CaCl_2 + Na_2CO_3 \longrightarrow 2\,NaCl + CaCO_3 \tag{5}$$

Subsequently, by decantation or filtration, a brine can be obtained which exclusively contains the ions Li^+, Na^+, Cl^-, SO_4^{2-} and CO_3^{2-}. In addition to the solubility product, the educational background for students in steps 2, 3 and 4 is primarily of a practical nature. The task here is to prepare solutions and to work as precisely quantitatively as possible in order to precipitate all desired compounds without already binding lithium in the precipitate due to an excess of precipitating reagent. Another aspect at this point is the fact that all steps involve working in highly concentrated salt solutions. This is of great importance in both the technical and student implementation of the reactions. As will also be discussed again in the coming section, in such solutions it is possible that even supposedly well soluble substances such as NaCl precipitate when further Na^+ ions are added. A comparison of the solubility and understanding of the solubility products of all compounds is therefore absolutely necessary for further problem solving. In the technical approach, the brine is usually diluted again after a precipitation step in order not to increase the Lithium concentration too much.

4. In a final reaction, the desired product lithium carbonate can ultimately be precipitated from the brine. Here, too, the solubility and its temperature dependence play a role. It is exploited that the solubility of Li_2CO_3 decreases with higher temperature. Accordingly, when the solution is heated, the product precipitates almost quantitatively (typically 80-90%) compared to related alkali carbonates.[15] The temperature of the solution must be in the range of 50 °C to 95 °C, and the pH is necessarily in the basic to strongly basic range (8 - 12). Under these conditions, the lithium previously dissolved as chloride precipitates.

$$2\,LiCl + Na_2CO_3 \longrightarrow 2\,NaCl + Li_2CO_3 \tag{5}$$

In the industry, precipitation is followed by several processing and drying steps before the product is delivered directly in pure form or converted into other marketable lithium compounds. However, these steps are of little importance for the laboratory experiments, since only the classic product drying and yield determination are to be carried out here.

3. Experimental procedure and results

This section presents the experiments that make it possible on a laboratory scale for undergraduate students to precipitate Li_2CO_3 from a previously given salt solution. For this purpose, the industrially known precipitation reactions were adapted to the student chemistry laboratory and various conditions were tested to maximize the yield and purity of the product as much as possible. In the following, the most promising solution for precipitation established in this lab will be presented before discussing a selection of alternative variants that, with limitations, can also lead to positive results. The elaborated experiments are first presented in detail with respect to their set-up, execution and the observations and results obtained. In addition, comments are made on any practical problems that may occur and approaches to interpreting or eliminating these deviations. For each experiment also a short classification in the educational background of the laboratory concept is given in connection with the knowledge presumably required by the students and the accompanying learning prospects.

During the testing of the experimental setups, all products and relevant intermediates were tested for their constituents by means of classical detection methods and their exact composition was analyzed via X-ray powder diffraction.

3.1. Salt solution composition as a simulation of processed brine

The starting point for the student experiments should be a salt solution that simulates the components of a brine containing lithium after the evaporation process. The evaporation processes with precipitation of large parts of NaCl and $MgCl_2$ can be well omitted to reduce practical processes in the laboratory, since the evaporation of large amounts of water is industrially extremely slow and for this reason cannot be reasonably reproduced in the laboratory.

For comparison, different compositions of salt solutions were tested, varying in particular the Magnesium and Lithium content. However, since the experiments with a higher $MgCl_2$ content resulted in an increased chloride ion concentration, this approach led not only to increased chemical consumption but also to a strong precipitation of chlorides during the precipitations, which should be avoided. In addition, no calcium salt was used in comparison to conventional brines, since Ca^{2+} only occurs in very low concentrations in natural brines[16] on the one hand, and on the other hand calcium sulfate precipitates when Ca^{2+} and SO_4^{2-} are added simultaneously, which can no longer be soluted. The composition of a salt solution providing consistently reproducible results therefore included, in addition to LiCl, $MgCl_2$, KCl and Na_2SO_4 as well as an addition of sodium tetraborate to ensure an extractable borate content (Table S4).

Table S4. Components of the salt solution for simulating a brine. The amounts of substances of the salts used as well as their mass and concentration when dissolved in 25 ml of distilled water are indicated.

Component	**Amount of substance [mmol]**	**Mass [g]**	**Concentration [mol/l]**
LiCl	35.4	1.5	1.415
$MgCl_2 \cdot 6\ H_2O$	7.4	1.5	0.295
KCl	17.4	1.3	0.698
Na_2SO_4	7.0	1.0	0.282
$Na_2B_4O_7$	0.4	0.15	0.016
Solution in dist. H_2O			V = 25 ml

With the exception of calcium, the prepared salt solution contains all ions that also occur in natural, industrially used brines. The amounts of the salts used were chosen with the aim of ensuring the most positive results possible for the experimenters. Therefore, a very high Li^+ concentration was chosen in order to still allow a sufficient yield of Li_2CO_3 even in case of losses. The volume of 25 ml was chosen with the aim of providing a well-manageable amount of liquid that could still be processed with common separating funnels in the upcoming extraction step when a high volume of extractant was used. While for these reasons the mass fractions of the respective ions in the total solution are not comparable with conventional brines, the mass ratios in the solution are relatively consistent with the ion ratios for industrially used brines after evaporation (Table S5).

Table S5. Ion ratios after evaporation from industry and simulation in comparison. Shown are the ratios of the individual components of a brine relative to lithium after the evaporation process. The ratios given for industry are based on internal information from an expert at Albemarle GmbH and are derived from the weight percentages of the individual ions in the processed brine.

Ion ratio	**Albemarle**	**Simulated brine**
Mg/Li	1/4	1/6
Na/Li	1/67	1/2
SO_4/Li	1/333	1/5
K/Li	1/143	1/2
B/Li	1/8	1/73
Ca/Li	1/125	-

While the magnesium ratio of the laboratory brine is quite comparable with the actual one, clear differences are nevertheless noticeable with the other ions. Since a precipitation of sulfate became necessary in the course of the experiments and this can be well combined with chemical detections in the separation step, a relatively large amount of SO_4^{2-} in the form of Na_2SO_4 was used for demonstrative purposes. This equally led to an increase in the Na/Li ratio. The B/Li ratio of the salt solution, on the other hand, is lower than indicated on a large scale. The reason for this is the educational goal of learning a liquid-liquid extraction with subsequent borate detection. This works already with the addition of only a spatula tip of sodium tetraborate to the initial solution. However, since borate cannot be reliably removed quantitatively with only one extraction, as little as possible must be weighed in to avoid excessive borate contamination of the final product. From the salt solution given in Table S4, all the experiments described below were carried out.

3.2. Precipitation of sulfate anions as calcium sulfate

At the beginning, an upstream step was introduced because it became clear in the course of the experiments that sulfate significantly reduces the Li_2CO_3 yield of the experimental cascade due to the formation of mixed lithium salts.

The experiment is performed on a stir plate in a beaker with the initial solution (brine). At neutral pH, a 2 M $CaCl_2$ solution is added until a precipitate is formed (Figure 2, left). The solution can then be filtered in a filtration rack or similar filtration setup and the clear solution can be used for further processing (Figure 2, right).

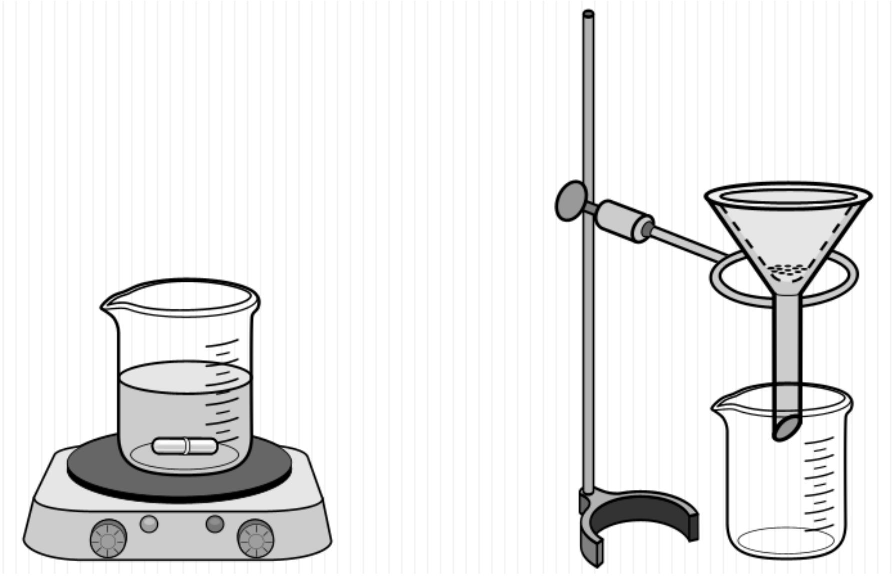

Figure S2. Schematic experimental setup for precipitation of CaSO4. Left: First, calcium sulfate is precipitated from the initial brine under stirring. Right: The resulting solid can then be separated by filtration.

In performing the experiment, 3.5 ml of freshly prepared 2 M $CaCl_2$ solution is used, which is thus added quantitatively to precipitate the sulfate ions present. The formation of a white precipitate can be observed with a slight time delay after a few minutes of stirring. The precipitate can then be separated by filtration using a glass funnel or, alternatively, using a Büchner funnel with a coupled water jet pump. Since the solution is often contaminated by residues in the wash bottle, filtration via a glass funnel is preferable. Resulting $CaSO_4$ can either be dried for analysis or discarded. The clear solution is then subjected to borate removal.

In the present simple precipitation reaction, sparingly soluble calcium sulfate ($K_{L,\,298K}$ = 2,45 x 10^{-5} mol^2/l^2) [17] is post-formed in the salt solution:

$$Ca^{2+} + SO_4{}^{2-} \longrightarrow CaSO_4 \tag{6}$$

Since the solubility product of the compound is exceeded when calcium ions are added, the compound precipitates completely. None of the other ions present in the solution forms a sparingly soluble precipitate with Ca^{2+}. Analysis of the precipitate via X-ray powder diffraction showed the presence of $CaSO_4$ as anhydrate, dihydrate ($CaSO_4$ * 2 H_2O) and hemihydrate ($CaSO_4$ * ½ H_2O).

Educational remarks

On the one hand, this precipitation reaction is trivial, but it has immense educational value within the problem-based laboratory concept. In the literature search, the precipitation of calcium sulfate can be found only with difficulty, since it is not carried out industrially. Nevertheless, it is well known chemically that the sulfates of some alkaline earth metals form poorly soluble compounds ,[18] so students may well assume that the reactions are influenced by sulfate ions present. In addition, it should be known from classical chemical analysis that the precipitation of sparingly soluble sulfates is often applied as a clear and easy to perform detection. For example, in the anion separation pathway, sulfate is detected as $BaSO_4$ by precipitation using barium chloride solution ($BaCl_2$).[10] This knowledge could be very helpful for students in the problem-based laboratory to make this transfer of an industrial application to a chemistry laboratory. Without this step, severe yield losses were observed during this work because the mixed salt $KLiSO_4$ is formed during carbonate precipitation in the alkaline milieu. A large portion of the Li^+ present is bound in this compound, which cannot be precipitated later as Li_2CO_3. Therefore, it can be assumed that this step is required at the latest in the optimization process for a sufficient yield and can be tapped by the students themselves as a reasonable step.

While sulfate is often precipitated industrially with the less expensive $CaCl_2$, the reaction also works analogously to the aforementioned sulfate detection with 2 M barium chloride solution, but the salt solution must first be acidified with HCl for this purpose. An advantage of this variant is that an indication of the product $BaSO_4$ can already be obtained by a follow-up experiment in the laboratory - this should not dissolve in concentrated HCl.

Concerning the general conduct of the experiment, it should be noted that quantitative work seems to be quite important here. The addition of a strong excess of $CaCl_2$ solution resulted in yield losses that cannot be explained in detail. It could be assumed that an excess of Ca^{2+} ions forms $CaCO_3$ or other poorly soluble compounds at a later point, so that less carbonate is available for the binding of Li^+.

3.3. Extraction of borate using organic solvents and borate detection

The brine, which is now free of sulfate, can be freed from borate according to the technical model by extracting it with an organic mixture after acidification. The special feature of this reaction is that it introduces a new separation method and additionally combines it with an easy-to-perform but impressive detection reaction to make the results of the extraction directly visible.

The experimental setup first includes a well-fixed separating funnel, the volume of which has to be chosen depending on the planned addition of the organic extraction mixture (Figure S3, left). For the extraction, the clear salt solution must first be acidified with a few drops of concentrated HCl. The pH value should then be around 1-3. The entire solution is then poured into the separating funnel. Meanwhile, a mixture of 20% (v/v) 2 ethylhexanol in gasoline is prepared and the mixture is added to the salt solution in a ratio of 2:1, corresponding to a volume of about 40-50 ml. The two phases are then mixed several times, venting the separatory funnel a few times due to the volatility of gasoline. The heterogeneous mixture is then observed for a few minutes until a clear phase separation can be seen. The aqueous phase (below) is then collected in a beaker and can be subjected to the following precipitation reactions.

Acidification of the salt solution during the extraction step causes conversion of all borates to boric acid according to reaction scheme (1). This can then be dissolved in the organic mixture by phase mixing and thus removed from the aqueous solution.

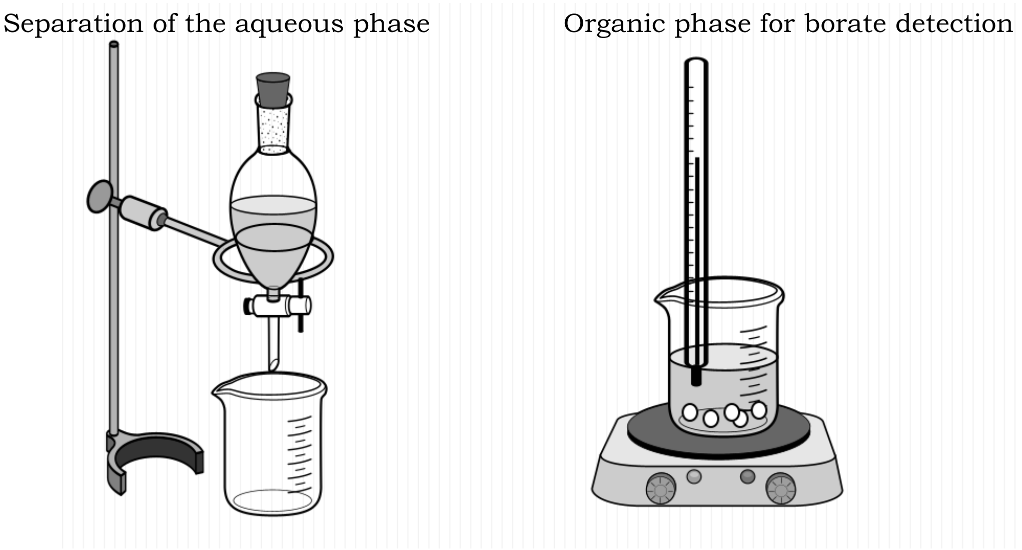

Figure S3. Experimental setup for the extraction of borate and borate detection from organic phase. To extract boric acid from the aqueous salt solution, an organic mixture of 20% (v/v) 2-ethylhexanol/gasoline is added to the solution in a 2:1 ratio and mixed in the separatory funnel. The aqueous phase can then be separated (left). The organic phase can be evaporated separately in a beaker under the fume hood for borate detection. Care should be taken to increase the temperature slowly (thermometer) and to add boiling stones to avoid boiling distortions (right). The solid residue can then be tested for borate.

Borate can also be detected from the organic phase. To do this, 20-30 ml of the mixture should first be taken and evaporated in a beaker on a hot plate under the fume hood (Figure S3, right). Care should be taken to raise the temperature of the hot plate only very slowly to the boiling point of the higher boiling 2-ethylhexanol (184 °C).[19] Since the hot plate can be inaccurate, the adjustable temperature may be significantly higher (up to 250 °C). A temperature check with the thermometer may be useful at the beginning, but is not possible later due to the decreasing volume. The beaker is removed as soon as white residue and no liquid can be seen at the bottom.

During heating, the low-boiling gasoline component evaporates first (20-80°C depending on the gasoline used) and then 2-ethylhexanol. Boric acid dissolved in the mixture remains as a white solid. This can be used for classical borate detection.

For the detection of borate as a trimethyl ester, the white residue must be scraped out of the test tube with a spatula. A little visible substance on the spatula is sufficient, which is then spread into the center of an evaporating dish. The test tube is rinsed with a few ml of methanol to dissolve borate residues and the methanol is transferred to the evaporating dish. A few drops of concentrated sulfuric acid (H_2SO_4) are then added and the organic phase is ignited with a lighter. A green flame coloration confirms the presence of boric acid trimethyl ester ($B(OCH_3)_3$). For safety, it is possible to perform a negative control in parallel. This can be done, for example, with a spatula tip of $Na_2B_4O_7$ and ethanol in place of methanol, which should not result in a green coloration of the flame. Optimally, however, a negative control must be performed with the same substance under investigation, which is not possible in this case due to the small amount of substance.

In the detection described, boric acid is reacted with methanol under catalysis of hydrophilic sulfuric acid to form its trimethyl ester (Scheme 7), which leads to green coloration when the organic phase is ignited.

$$B(OH)_3 + 3\ CH_3OH \xrightarrow{H_2SO_4} B(OCH_3)_3 + 3\ H_2O \quad (7)$$

Experimental and educational remarks

At this point, it should first be noted that borate removal is a didactic simplification. The goal of this experiment is simply to dissolve a large portion of the boric acid in the organic phase and detect borate from it. Complete borate extraction was not demonstrated during the course of this research practical. Although it can be surmised that better results can be obtained with multiple extractions and varying mixtures such as a higher isooctanol content or a higher solvent:brine ratio. However, possible borate contamination could only be guessed from typical amorphous elevations in the X-ray powder diagrams of some intermediate precipitates and would therefore have no direct effect on the final product, also because only very small amounts of $Na_2B_4O_7$ are used in the starting brine. Accordingly, a single extraction followed by borate detection without a larger-scale optimization of this step should be reasonable and time-saving for students with the same gain in knowledge. Moreover, borate detection from the organic phase was also successful with 25% and 30% 2-ethylhexanol/gasoline and solvent:brine ratios of 1:1 and 3:1.

The main didactic focus of this experiment can be seen as the experimental performance and the prior discussion of safety requirements. First and foremost is the question of which substance can be used to replace the kerosene present in the literature. A direct product of petroleum distillation is therefore the similarly produced gasoline, which, like kerosene, is a mixture of various alkanes, aromatics and olefins.[20] In addition to addressing this issue, the substances used also offer considerable risk potential. Students must be aware of the importance of safety aspects in advance: During the entire process, it is necessary to operate under a fume hood, as gasoline is carcinogenic; wearing protective gloves is also recommended. During the evaporation of the solvent mixture, it is essential to avoid boiling distortions. Further risk potential is posed by the boric acid formed and the ester $B(OCH_3)_3$, which is formed when borate is detected. These compounds are highly damaging to fruit, which is why contact must be avoided at all costs - including during disposal.

In addition to the safety aspects, the experiments can be well combined with basic chemistry, which is often already taught in school. For example, the question of the solubility of boric acid in organic solvents or the influence of sulfuric acid on the chemical equilibrium during borate esterification can be discussed.

3.4. Precipitation of magnesium ions as $MgCO_3$

The precipitation with washing soda (Na_2CO^3) can be adopted from the concentrated salt solution as described in the literature. The experimental setup is analogous to the sulfate precipitation. Before the actual precipitation, the solution must first be neutralized. This can be done by stirring with a small amount of diluted KOH or NaOH. When these are added, a slight turbidity initially forms due to precipitating hydroxides, but this disappears again after a few minutes if a pH value of 7 is not exceeded.

Optionally, the salt solution can be slightly diluted to prevent the precipitation of potassium or sodium chloride in the following. In this case, a dilution of 2:1 caused a higher Li_2CO_3 yield, but at the same time still a NaCl/KCl precipitate in the carbonate precipitation. The dilution step can therefore not ultimately be evaluated as useful.

Subsequently, 3.2 ml of a 2 M Na_2CO_3 solution is added to the neutral solution while stirring. Alternatively, a 20% solution can be used in direct accordance with the literature. It seems to be important at this point to have a precisely known concentration in order to add the amount of carbonate to the solution that corresponds to the amount of Mg^{2+}. The pH of the solution can be checked afterwards and should be around 9-10.

The addition directly results in a strong turbidity of the solution, which can be removed from the stir plate after a short time until the precipitate has settled. The solution can then be filtered and subjected to the next precipitation step.

During precipitation, sparingly soluble white $MgCO_3$ should form according to (8). ($K_{L, 285K} = 2,6 \times 10^{-5}\ mol^2/l^2$).[17]

$$Mg^{2+} + CO_3{}^{2-} \longrightarrow MgCO_3 \tag{8}$$

In fact, diffractometric analyses showed that the precipitate is largely NaCl and KCl. These are most likely precipitated by the high salt concentration. The addition of similar ions (Na^+ from Na_2CO_3 and K^+ from KOH) could lead to the maximum solubility of the mentioned salts being exceeded in the volume and therefore they precipitate. If the precipitate is dried and a little acid is added to it, a clearly recognizable gas evolution occurs. This indicates that carbonates are present in the intermediate despite the analytical results. It is likely that magnesium carbonate is formed to a large extent, which may not be detectable by X-ray powder diffraction due to an amorphous structure.

Educational remarks

The educational focus of the reaction in this case is exclusively the solubility product. It should be clear to all students even before the experiment is carried out that a sparingly soluble salt is again formed in order to precipitate magnesium ions quantitatively. For this reason, an exemplary calculation task can be carried out at this point for the purpose of understanding the solubility product more precisely (also mathematically), if the organizational procedure of the day's experiment is compatible with this. For example, the solubility products of $MgCl_2$ and $MgCO_3$ could be given. The students would then be asked to calculate the mass of the dissolved substance in 100 ml of a saturated solution of the respective substance. With such a calculation, it becomes clear that the more soluble chloride is dissolved in a saturated solution with a very large mass, while the carbonate is present only in trace amounts in the solution, as the majority is present as a precipitate that is undissolved. Such a task complements the observations made during performance by once again supporting the sense and effectiveness of precipitation of a poorly soluble salt from the theoretical side with illustrative numerical data.

In addition to the treatment of the solubility product, the experiment could also be extended practically by detecting magnesium from the precipitate. An analysis via X-ray powder diffraction does not seem very useful due to the NaCl and KCl present, as a discussion of the analysis requires deeper knowledge of the method. Instead, after drying, for example, detection on magnesium could be done with magneson as an organic color varnish, if this is already known from the previous part of the lab. A risk with such an extension, however, is the presence of calcium. If $CaCl_2$ was added in slight excess in the first step, Ca^{2+} ions present may interfere with the magneson detection. For this reason, the step was not carried out in the experimental design.

3.5. Precipitation of magnesium residue as magnesium hydroxide

After $MgCO_3$ precipitation, the remaining clear solution can be freed from Mg^{2+} residues as described in the literature by precipitating them with a base as hydroxide. The precipitation takes place in the typical apparatus (see 2.4.2, Figure 2). Subsequently, about 5 ml of a diluted base such as NaOH / KOH or about 10 ml of the filtrate of a previously freshly prepared 20% limemilk ($Ca(OH)_2$) is added while stirring.

The pH value of the solution increases again to 11-12. With KOH an incipient formation of a white precipitate can be observed, which can be filtered off. When the limemilk is added, only a very slight turbidity can be observed. The white precipitate formed here can be filtered, but is not sufficient for analysis.

In this reaction, any magnesium still present should be precipitated in the form of the sparingly soluble $Mg(OH)_2$ ($K_{L,291K} = 1{,}2 \times 10^{-11}\ mol^3/l^3$) [17] (reaction equation 9).

$$Mg^{2+} + 2\,OH^- \longrightarrow Mg(OH)_2 \tag{9}$$

In fact, analyses of the dried precipitate showed that in the case of the precipitate after addition of KOH, it was not the hydroxide, but instead a mixture of KCl and NaCl. This can probably be attributed again to the precipitation by equionic addition, as already described in the previous chapter. Since magnesium should have been precipitated almost quantitatively in the previous step, it can be assumed that the amount of resulting $Mg(OH)_2$ in the mixture is too small for clear detection.

In contrast, despite the lack of analysis after addition of $Ca(OH)_2$ solution, it can be assumed that the precipitate is small amounts of $Mg(OH)_2$ with $CaCO_3$ formed according to reaction schemes (3) and (5). Neither precipitation reagent appeared to have any effect on the yield and purity of the final product during the experimental optimization.

Educational remarks

The precipitation of the Mg residues as hydroxides is mainly relevant on a large-scale technical level and is only required for the practical experiments to reproduce this process. On a large scale, this ensures an extremely high purity of the Li_2CO_3 obtained at the end, since even the smallest amounts of magnesium are precipitated. In the laboratory, the precipitation reaction had no influence on the yield and purity of the product. Nevertheless, it is useful in the sense of the problem-based approach and can be discussed with respect to the precipitation reagent used.

In industry, for example, precipitation is carried out exclusively with $Ca(OH)_2$. One reason for this could be that this is the least expensive alternative compared to other hydroxides such as KOH or NaOH. However, when lime milk is used on a laboratory scale, lime water can be disadvantageous because the concentration of OH^- ions cannot be accurately determined due to the poor solubility of calcium hydroxide. Only a small portion of the solid actually dissolves in water. In addition, the limemilk must be filtered, since precipitate formation could no longer be observed if it were added directly to the salt solution. However, since only remaining residues are to be precipitated with this variant, filtered milk of lime can certainly be added in slight excess in this step without knowing an exact concentration. In addition, $Ca(OH)_2$ has the advantage that carbonates still present in the solution are precipitated as $CaCO_3$ and cannot already precipitate at this point as Li_2CO_3. KOH or NaOH as precipitation reagents offer the advantage of precisely known concentration, but can be confusing due to the precipitation of large amounts of KCl and NaCl instead of $Mg(OH)_2$ and produce results that are difficult to explain without further analysis.

3.6. Precipitation of lithium carbonate

Precipitation of the product Li_2CO_3 takes place with further addition of Na_2CO_3 and heating of the solution. This process takes advantage of the fact that lithium carbonate is more sparingly soluble in heat (13.3 g/l) than at room temperature (7.2 g/l). Since the temperature is an important parameter in optimizing the process, it is constantly monitored by means of a thermometer in a stirring apparatus on a hot plate (Figure 4).

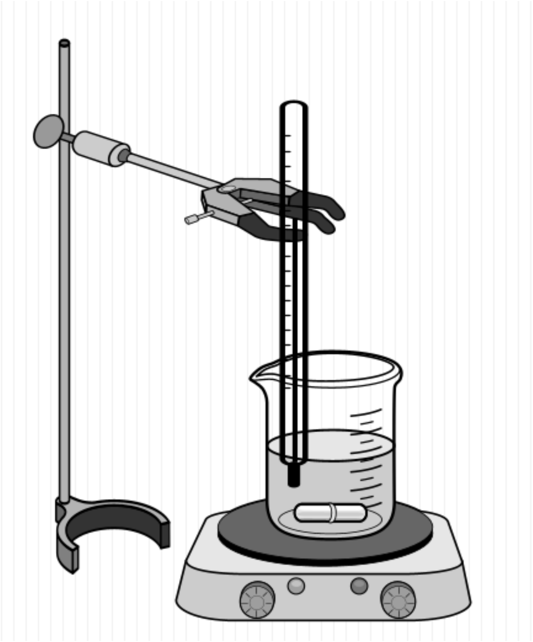

Figure S4. Experimental setup for the precipitation of Li2CO3 in the heat. The experimental apparatus consists of a hot plate on which the clear salt solution is heated under the fume hood (boiling base) after the addition of washing soda (Na_2CO_3) with stirring and constant temperature measurement.

For the precipitation of Li^+, 2 M Na_2CO_3 solution is first added quantitatively, corresponding to about 9 ml, to the clear brine. The mixture is then slowly heated in the beaker while stirring. If the solution becomes turbid, heat it a little further and wait until clearly white solid is visible in the solution. The solution is then filtered while hot and all solid residues in the beaker are additionally rinsed into the filter with warm water. A Büchner funnel with connected water jet pump or a conventional glass filter can be used for this purpose. The filter paper used is first weighed in the dry state for yield determination.

The solid, which is as dry as possible, is then dried on the filter paper for 1-2 h in a drying oven at 80 °C and can be placed in a desiccator overnight for better drying. The dried solid is finally weighed on the filter paper, the mass of the product is determined and finally the yield is calculated.

The precipitation of lithium carbonate is based on the poor solubility of the product at high temperatures. Precipitation could be observed mostly from about 40°C, further precipitation precipitated up to a temperature of about 80 °C. The yield of Li_2CO_3 during the experimental optimization was 51.2% for the solution route described here, but varied between 25% and 40% with variations and repetitions of the experiments.

Initial detection for lithium from the product can be done via flame staining, preferably using a platinum wire. For this purpose, a spatula tip of substance is dissolved with some diluted HCl in a porcelain dish, the Pt wire is dipped and then held in the burner flame. A red coloration in the aftermath indicates the presence of Li. For more detailed analysis, a few spatula tips of the product can be placed in a snap cap vial and analyzed by X-ray powder diffraction.

Experimental and educational remarks

The background concept in this case is the temperature dependence of the solubility. Here it should be noted that lithium occupies a special position, since it is the only one, compared to all other alkali and alkaline earth metals, to form a carbonate which is poorly soluble at high temperatures. During the experimental design, however, it was found that even from pure KCl and $MgCl_2$ solutions little K_2CO_3 or $MgCO_3$ precipitates when treated in the heat itself. Thus, slight impurities of the product by these components during analysis can also be explained, especially if a slight excess of carbonate is added to the precipitate.

Experimentally, the drying, yield determination, analysis and the resulting questions about further purification of the final product and process optimization are of particular importance to the students in this experimental step. The related considerations and their implementation require already acquired basic chemical knowledge and complete the procedure of lithium extraction in the problem-based concept. At this point, some challenges in the mentioned steps are highlighted before a concrete example of yield determination is given.

Before precipitating Li_2CO_3, students must first determine the amount of Na_2CO_3 solution needed to precipitate the amount of Li^+ present. It must be taken into account that, according to the molecular formula of lithium carbonate, one mole of carbonate anions is needed to precipitate two moles of lithium cations (Li_2CO_3 with $n(Li^+):n(CO_3^{2-}) = 2:1$). Thus, if a substance amount of 0.0354 mol LiCl or Li^+ is given in the salt solution, $\frac{0,0354}{2} = 0,0177$mol carbonate anions are required to precipitate the entire lithium portion. On the other hand, if a molar ratio of 1:1 is incorrectly assumed, twice the amount of CO_3^{2-} would be added. Although this excess does not cause any major complications in the first instance, it can, under certain circumstances, cause any potassium present to also precipitate as K_2CO_3 and contaminate the product to a greater extent.

Reliable yield determination of the product also requires conscientious drying. For this purpose, it is advisable to remove the precipitate from the drying oven after various time intervals (e.g. 30 min and 60 min), to cool it briefly and to weigh it. Complete drying can only be assumed if the mass of the precipitate no longer changes. Optimally, the precipitate can then be dried overnight in the desiccator and weighed again the next day to correct the yield if necessary. Nevertheless, an approximate yield can be determined after drying for about 60 min in the drying oven (80 °C). When determining the yield from the mass of the precipitate obtained, the empirical formula of Li_2CO_3 must also be taken into account. The determined amount of substance of lithium carbonate contains twice the amount of Li^+ ions, whose proportion of the initially present amount of Li^+ is determined as yield (see 2.4.6.2).

The analysis of the substance can subsequently be used to obtain information about the impurity of the Li_2CO_3 obtained and to correct the yield (see 2.4.6.2). For the analysis, the well-known method of flame staining is recommended initially, since lithium in particular, with its red spectral lines, can be clearly detected here. However, due to sodium impurities, the orange Na flame often covers the lithium coloration of the flame. During the experimental optimization, this could be minimized by using a platinum wire. Here, although the characteristic Na coloration is initially visible in the flame, after a short time this disappears and a clearly recognizable red coloration (Li) appears. As an extended detection method, the precipitate was also transferred to LiCl with concentrated hydrochloric acid, the solution extracted in a test tube with 1-pentanol and the organic phase evaporated. Since, compared with other alkali and alkaline earth metals, only LiCl dissolves in 1-pentanol, pure LiCl can be obtained by evaporation. This subsequently gives the typical flame coloration. In the course of this work, the described detection required a lot of substance, moreover, it can be assumed that it is very time-consuming for the students. Since flame staining with a Pt wire also shows the Li flame without prior extraction, it is advisable to dispense with this extended detection. In any case, X-ray powder diffraction is a reliable method of subsequent detection. Particularly due to frequently occurring chloride impurities, the question arises for the subsequent process optimization as to whether repeated washing of the precipitate is capable of removing these residues produced by the drying process. In the course of this preparation, 1-4 washing steps with 80 °C hot water were carried out to investigate this. It was found that washing the precipitate significantly increased the purity of the product (about 90% to 98%), but rapidly decreased the yield. Regardless of the number of washing steps, the yield was only about 10-14%. With a general product purity of approx. 85-90%, it is therefore more advisable to dispense with washing the product.

Yield determination, analysis and corrected yield

In this section, an example of the yield determination as well as its correction after analysis is carried out is given for illustration.

As indicated, the product obtained is first dried and weighed in order to determine the yield.

In the present case, $m = \mathbf{0,67\ g}$ of white solid was dried on the filter paper. According to $n = m/M$ n=m/M considering the molar mass of Li_2CO_3 $(M(Li_2CO_3) = 73{,}891 g/mol)$, this corresponds to an amount of substance of $n(Li_2CO_3) = 0{,}0091\ mol$. This in turn corresponds to twice the amount of substance of lithium ions, since according to the empirical formula they are present in a ratio of 2:1, i.e.: $n(Li) = 0{,}0181\ mol$.

The yield is then calculated as the proportion of the lithium precipitated in this way to the total amount in the solution, which is given here as $n_{ges}(Li) = 0{,}0354\ mol$

$$yield\colon\ \Phi = \frac{n(Li)}{n_{ges}(Li)} * 100 = \frac{0{,}0181\ mol}{0{,}0354\ mol} * 100 = \mathbf{51,13}\%$$

The dried solid can finally be analyzed via X-ray powder diffraction. As a result of this measurement, a diagram is obtained in which the reflection intensity after diffraction of X-rays at the crystal lattice is plotted against the diffraction angle. The combination of reflection positions is characteristic for a certain crystal structure of a material. Thus, the reflections can be assigned to the crystalline constituents present in the precipitate. By determining the area under the peaks of a substance, it is also possible to determine the mass fraction of the respective constituent and thus de facto the purity of a product. With the aid of the information on the purity of the product, a corrected yield can subsequently also be calculated according to the following scheme.

For the precipitate obtained, the compounds shown in Table 3 were determined by X-ray powder diffraction with their respective mass fractions.

Table S6: Compounds determined by X-ray powder diffraction and their proportions in the product precipitate. The indicated mass fraction results from integration of all peaks characteristic for a substance and the proportion of the obtained area to the total area of all peaks present in the diagram. Unidentified peak area" refers to all peaks that cannot be clearly assigned to a substance.

Compound	**Mass fraction (%)**
Li_2CO_3	91,7
NaCl	1,9
KCl	0,5
K_2CO_3	0,2
„unidentified peak area“	5,7

Taking this information into account, the purity of the Li_2CO_3 obtained can be given as 91.7%. From this information, a corrected yield Φ_{corr} can be calculated, since it is now known that only 91.7% of the mass of the precipitate is actually pure Li_2CO_3. With 0.67 g of precipitate obtained as mentioned, this then gives a corrected mass of the product of

$$m_{corr}(Li_2CO_3) = 0{,}67\ g * 0{,}917 = 0{,}61\ g$$

Finally, a corrected substance quantity of lithium of $n_{korr}(Li) = 0{,}0165\ mol$ can be determined from this data in analogy to the calculation shown above. This finally gives the actual yield taking into account the product purity.

$$\Phi_{corr} = \frac{n_{corr}(Li)}{n_{ges}(Li)} * 100 = \frac{0{,}0165\ mol}{0{,}0354\ mol} * 100 = \mathbf{46{,}61}\%$$

The calculation of the corrected yield trains the mathematical understanding of the students in particular and also serves to illustrate the effects of an impurity. In addition, the students can thereby once again deal in more detail with the analysis method carried out.

4. Suggestions for experimental implementation

To establish a direct link between the experimental elaboration of lithium precipitation and the practical implementation in the PBL-based student laboratory, the sequence of an exemplary laboratory day will be described in summary.

As mentioned above, the PBL concept requires a high level of student initiative even before the experiments are conducted. Therefore, the central point of the beginning of the day must be the seminar preceding the practical, in which the preparation already done by the students is discussed.

The literature found and the solution concept worked out from it by the interns must be presented in the seminar and discussed, checked and supplemented under supervision. The actual topics will depend on the students, but could be, for example, initially the presentation of search methods for reliable literature on the topic of lithium extraction or the critical examination of the process and application of lithium in general. Subsequently, the focus should be on presenting developed concepts and discussing them with the help of supplementary literature and chemical background knowledge.

Ideally, upon entering the laboratory, each student will have a fairly detailed plan of the experiments they wish to perform to precipitate lithium from the brine presented in the seminar. Since the elaborations are discussed beforehand, the experiments should be roughly based on the experimental elaboration described in chapter 2.4. The procedures can be very different, for example precipitation reagents can vary, their concentration, the way they are added (as solution or solid to the brine), the mixing ratios and total volumes of solution used in the extraction, any buffer mixtures used to adjust the pH more precisely, or even the separation methods (filtration, Büchner funnel, decantation) and any purification steps of the precipitates.

During the course of the day, all experiments should be run at least once. If the approaches are very different, it may also be useful to run them in parallel so that a direct comparison of the processes is already possible at the end of the day. At the beginning, the students receive the salt solution in the laboratory, from which they are to precipitate Li_2CO_3 in the course of the day. Since the focus is on obtaining the end product, but detection reactions are also to be practiced, it makes sense to first carry out all steps of the lithium precipitation before precipitates are analyzed. Thus, the precipitations as well as the extraction of the borate can be carried out sequentially, with resulting precipitates and the borate-containing organic phase being stored first. Ideally, precipitates to be analyzed can be washed once with water to minimize solution impurities before any water remaining on the filter paper in the drying oven is removed. Thus, students should be able to obtain a first Li_2CO_3 precipitate fairly quickly, which should be dried in the drying oven for 60 to 90 min before the first yield determination. During this remaining time, detection reactions can be performed from the precipitates that have dried in the meantime. It is advisable to focus first on borate detection from the extraction, since this should be time-consuming but unambiguous. Subsequently, for example, the flame sample of all precipitates can be considered in order to be able to conclude on any Li impurities in the intermediates. Nevertheless, the flame coloration is not always unambiguous, since sodium is present in almost all steps in the precipitate and usually masks other colorations. The effect can be minimized by using a platinum wire as described above. For comparison, students can test, for example, pure salts of the suspected compounds to get a color impression of the element in question. Detection of potassium in the flame can also be done using a cobalt glass, which filters out typical Na wavelengths. Other classical detection reactions can be performed as indicated in the experimental workup, but are problematic because different alkali and alkaline earth metals often interfere with each other. Consequently, time should not be unnecessarily wasted on repeating the detections if the results are negative.

After analysis of the precipitates, dried Li_2CO_3 can be taken and weighed for yield determination. In most cases, the mass changes only slightly after further drying in the desiccator, which is why the flame test can already be carried out with the substance at this point. Students who work very quickly could also carry out a detection experiment at this point by dissolving the chlorides in amyl alcohol or try to find starting points for optimizing the process. Optimally, all students should be able to put at least one final precipitate in the drying cabinet at the end of the lab day, which will be examined via X-ray powder diffraction until the next week. If some students have not had a result, at least the precipitate in which lithium is suspected based on flame staining could be given for analysis. It is difficult to interrupt during intermediate steps because water evaporates rapidly from the solutions. In this case, therefore, the previous volume must be noted precisely and beakers must be sealed airtight with parafilm or similar.

Ultimately, the process can be continued seamlessly on the next lab day. If it is possible to provide the students with the results of the analyses by then, they can be discussed in detail in the seminar and optimization approaches can be presented. After these, further and further attempts can be made in the following laboratory days to generate a higher yield and product purity. All in all, 4-5 full days in the laboratory could be useful for all experiments and optimizations, since in this time a successful lithium precipitation can probably be achieved and optimization approaches can be carried out without "treading water" after too long a time or only repeating the same experiments over and over again.

5. Summary and outlook

The experimental procedure presented here is intended to ensure the precipitation of lithium carbonate from an optimized salt solution simulating a natural brine over several stages. The solution path presented here (Figure S5) first involves the precipitation of sulfate ions as $CaSO_4$ before borate extraction takes place. From the organic phase, a detection reaction for borate can also be performed in this step. After neutralization, magnesium carbonate can be precipitated from the aqueous phase by adding washing soda. After precipitation of possible magnesium and carbonate residues as hydroxides and lime, respectively, it is possible to isolate poorly soluble Li_2CO_3 as a product in the heat.

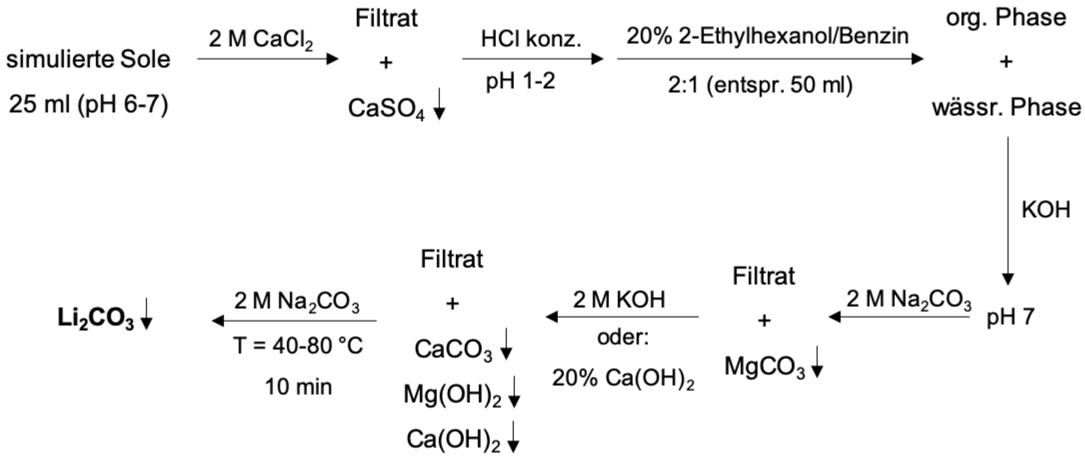

Figure S5. Schematic representation of the experiments on the precipitation of Li_2CO_3 from a salt solution. Poorly soluble components are gradually precipitated from the salt solution (simulated brine). After each filtration step, work continues with the corresponding filtrate until finally the product lithium carbonate is precipitated in as pure a form as possible.

The experimental procedure found represents the end product of an optimization process in which, ideally, a lithium yield of about 45-50% measured in terms of the lithium used in the initial solution can be achieved. In this context, it represents a possible solution path for a laboratory practical course in the concept of problem-based learning, which could also be worked out by the students. The optimization of the process in this work also proved that, based on existing literature, a large number of parameters can be varied, while still achieving success with varying yields between 15% and 40%. This fact shows that the experimental setup can be optimally integrated into the PBL concept, since students can always achieve the precipitation of Li_2CO_3 from the given brine even with very different solution approaches. Consequently, there is a large scope for "research" on the process of lithium extraction.

Initially, one problem seems to be the lack of possibility of combination with analyses, since classical detection reactions are often disturbed by the large number of chemically similar ions present. The possibility of a modern and common analytical method such as X-ray powder diffraction can eventually solve this problem satisfactorily. In addition, the didactic concept is enormously extended by dealing with the new method. A disadvantage remains that X-ray powder diffraction is not actually used for analysis in the course of lithium extraction in industry and therefore lacks a certain parallel to the industrial process. For the future, it may be possible to establish other analytical methods such as atomic emission spectroscopy (AES), which is commonly used in industry, to determine the lithium content in the end product as part of the practical course.

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7.2.2. SI Interview Protocol

Interview Protocol – Intrinsic motivation and implementation

1. Can you summarize what you did during the laboratory course?
2. How did you go about designing the experimental procedure?
3. Where did you get your information?
4. Did you use patent information?
5. If yes: Why did you use it?
6. If no: Why didn’t you?
7. Did you have experimental experience before the laboratory course (e.g. at school)?
8. If yes: Was this laboratory course different?
9. Have there been days when you didn't understand what was being done?
10. Do you feel like you learned something in this laboratory course?
11. What did you enjoy in the laboratory course?
12. What happened on those specific days?
13. Was there specific content that you liked?

7.2.3. SI Deductive Coding Table

Table S1-1. Deductive coding table

Deductive Codes	Code Description	Example
Autonomy	Self-determined, volitional action in accordance with one's own authentic interests and values	Andreas: "It was fun for me to be the master of my own work. I didn't 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's what I enjoyed the most, I really have to say." Andreas: "I had so much fun because no one told us: "Here, listen, you have to do it this way and that way, but do it, look at it, maybe it's right, maybe it's wrong, you don't know"; and that was the cool thing about the whole thing, because in the end we didn't know whether we were in the lab for six hours and precipitated any product or not, that was exciting about the whole thing. I think everyone really liked that, also the others. That was an enrichment to have such an internship, that is very rare."
Competence	Feelings of effectiveness and mastery	Jonas: "We found out something new every day that... I don't want to say surprised us, but for example, with the precipitation of lithium carbonate that was like an aha-effect...It didn't 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 didn't think of before and suddenly found that this is how it works." Max: "On the one hand, we had to do the experiments ourselves, which meant that we were a bit more on our own and had to find out for ourselves how everything worked. And you weren't just told to do this and that, but you had to find your own way around. Because I only had a little bit of that in school and it was still so boring, you just get told what to do. This independent work was definitely a lot of fun."
Relatedness	Feeling socially connected and significant among others	Sven: "When we came out of the lab on Thursday and it didn't 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

Deductive Codes	Code Description	Example
		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." Manuel: "To me the most fun was experimenting with the others, the exchange with the others, that we try out something together that maybe one of us has thought up, so some experiment. For example, with one peer in my group, we saw an experiment with electrolysis that we found on the Internet in the literature, and then we tried to implement it somehow. In retrospect, it didn't work, but I thought it was really cool that we worked it out together and tried to decimate the weaknesses...and yes, I thought it was really cool to work together."

7.2.4. SI Inductive Coding Table

Table S1-2. Inductive coding table

Code	Definition	Example
1. Information sources a. Chemical concepts research	Searching for information to posed problem using chemical concepts	Sven: "Um...I used patent literature for my experimental procedure at the beginning, but when I didn't feel really safe with it and I also had the feeling that I didn't 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 and belief *laughs*."
b. Patent research	Searching for information to posed problem using patent research	Andreas: "Or also generally the patent search as I said, I always come down to the patent search but that is the be-all and end-all. Scientific work is only done by um work of other people who have also thought about it and you orient yourself on that. That doesn't 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."
2. Experimental procedure a. Independent design and application	Central aspect of experimental procedure is independent work	Andreas: "It was fun for me to be the master of my own work. I didn't 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's what I enjoyed the most, I really have to say."

Code	Definition	Example
b. Distinction between school and university work	Distinction between school and university work due to experimental procedure design	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 don't create the experiment instructions yourself, then it's like, uh, like when you stand in the kitchen and prepare noodles, nothing else in my opinion."
c. Apply theory in practice	Apply own learning and preperation in practice	Cem: "I would say that the most fun I had in general was simply experimenting, carrying out experiments, carrying out detection reactions, simply implementing things that I had learned and seeing that they actually worked. That was a cool feeling."
3. Naturally occurring feedback a. XRD and detection reactions	Feedback through experiments and analytics	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."
		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. I thought that was really interesting, that you just really saw what you are doing there."
4. Process optimization a. I would have wanted to continue	Wish to continue work on experimental procedure after end of the course	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 doesn't 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."
b. Trial and error	Experimental strategies and applications to overcome difficulties	Sven: "So, for example, when we came out of the lab on Thursdays and it didn't work out, when we tried something new, everyone went looking for it a bit. That was definitely fun, to see ok now we had a really good sample and what we can do better and that you can also see that it's getting better. I think we learned a lot about how process optimization works."
c. I like a challenge	The process was positively challenging	Jonas: "I thought it was good that you had to do it all yourself. The very first time, of course, it was a bit, I wouldn't say difficult, but you had to sit down and spend a lot of time at home to create such an experimental procedure. Because we have very little basic knowledge of chemistry in the geosciences, it was a very high quality task. I actually thought it was quite good, I liked the fact that you were challenged a bit and didn't just copy things or something."

7.3. Study 2

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Information Is Experimental: A Qualitative Study of Students' Chemical Information Literacy in a Problem-Based Beginner Laboratory

Larissa Wellhöfer* and Arnim Lühken

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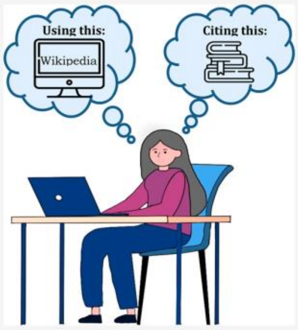
ABSTRACT: The focus in teaching and research is shifting from a traditional perspective of information literacy (IL) as a specific set of general, mostly text-based skills to a more comprehensive understanding of the complex aspects that constitute IL as an ongoing, context-specific process. However, there is a need for further insight into the social and contextual dimension of the information process. The inherent connection between problem-based learning (PBL) and IL holds great potential for a better understanding of students' information experience. The aim of this study was to describe the contextual and social aspects of the information process students engage in during a PBL beginner's lab and how this practical experience can be utilized for teaching. To this end, a wide range of qualitative data were collected over the course of three cohorts, including interviews, on-site audio recordings, and documents. Results suggest that students first evaluate the information they retrieve in terms of experimental safety, feasibility, and usefulness in planning the experimental procedure. Then, the experiment provides the crucial information about whether the previously acquired information was useful for solving the problem. The experiment is at the center of the student information process in a PBL lab. In this work, we discuss how to organize IL instruction from the student perspective and thus place the experiment at the center of IL instruction in a PBL lab. The results of this work contribute to an expanded understanding of IL that is useful for teaching and research in chemistry education.



KEYWORDS: *first year undergraduate/general, problem-solving/decision making, laboratory instruction, inquiry-based/discovery learning, student-centered learning, constructivism*

■ INTRODUCTION

Problem-based learning (PBL) concepts are informed by constructivist teaching and learning theory, focusing on the construction of knowledge through meaning-making.[1−3] PBL laboratory practicals essentially differ from expository concepts by shifting the responsibility for designing the experimental procedure toward the student. The experiment becomes a means of problem-solving. Learners must consider what they wish to achieve through the experiment, why it is necessary, and how they want to do it,[4] instead of following a recipe-like experimental procedure.[5] To design the experimental procedure, the learners require additional information. An essential part of a PBL lab is to determine what type of information is needed, where and how to get it, how to evaluate it, and, finally, how to use it to plan the experimental procedure. These aspects constitute the basic parts of the concept of information literacy (IL).[6] The fundamental connection between PBL and IL became apparent in the first definition of IL by Paul Zurkowski in 1974 (ref 7, p 6); he described information literate people as

> *People trained in the application of information resources to their work can be called information literates. They have learnt techniques and skills for utilizing a wide range of information resources as well as primary sources for molding information solutions to their problems.*

The ACRL (2000) defined the term information literacy as "recognizing when information is needed and knowing how to locate, evaluate, and use it effectively".[8] This definition formed the basis for a set of generic standards, learning objectives, and instructional suggestions that have been highly influential in educational settings.[9,10] Critics claim that the ACRL standards reduce IL to a set of general, text-based skills that are easily measurable, such as searching specific databases or correct citation.[11−13] In response to the changing information ecosystem, the ACRL (ref 14, p 8) published a revised, more

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comprehensive definition of information literacy in 2016 that states:

> *Information literacy is the set of integrated abilities encompassing the reflective discovery of information, the understanding of how information is produced and valued, and the use of information in creating new knowledge and participating ethically in communities of learning.*

The former information literacy standards for higher education were revised into a framework that addresses important developments in IL education research. Instead of a list of standards and skills, it is based on "interconnected core concepts, with flexible options for implementation".[14] The framework is informed by threshold concepts "which are those ideas in any discipline that are passageways or portals to enlarged understanding or ways of thinking and practicing within that discipline".[14] The development of this framework underlines the complexity of IL as a fundamentally contextual and social practice. Especially the idea of threshold concepts highlights the situatedness of IL in "communities of learning".[14]

The benefits of combining PBL and IL in an educational setting have long been a cross-disciplinary research topic.[15−20] Recent research in chemistry education also aims to make use of the inherent connection between PBL and IL to develop critical thinking and to form a better understanding of the underlying processes.[16,21−23] Guidance from community experts aims at teaching students to navigate an increasingly complex information environment and to prepare them for learning beyond university.[23,24]

However, to the best of our knowledge, the previous studies on PBL and IL in chemistry education did not aim at understanding and describing the social and contextual information processes students engage in during PBL. Further research that highlights the contextual and social dimensions of IL practice is needed to advance knowledge in this area. The link between PBL and IL holds great potential for a better understanding and, ultimately, teaching of PBL and IL. Therefore, it is necessary to describe the social and contextual information landscape by shifting the focus from measuring and improving IL to how the information process occurs in practice during a PBL lab.

Information Literacy and Sociocultural Theory

A sociocultural approach to IL research understands IL as a socially shaped and contextualized practice.[25,26] The manner in which information is produced, shared, and valued depends on an intersubjective understanding of the context and the social site.[25,27] This shared understanding constitutes an information landscape. Becoming information literate involves developing a set of abilities and skills (contextual knowledge) to draw meaning from the knowledge base through engagement and experience with information.[27] IL as a practice refers to the knowledge and ways of knowing that are valued and agreed upon in a situated social setting. Lloyd (2021) understands IL as a contextual process of knowing where certain information modalities (e.g., textual versus social) and information skills (e.g., citation) are privileged over others, which is construed by the social community.[28] The sociocultural realities of the social site influence this preference for specific practices over others.[29]

Lloyd (ref 28, p 4) exemplifies it like this:

> *The scientific way of practising information literacy may differ in other settings such as playing soccer, where the practice of information literacy may emerge corporeally and favor knowledges which are developed through physical experiences of playing soccer and therefore embodied.*

Thus, seeing information literacy as generic is problematic, because there will always be the question of, "What/whose view and ways of knowing are being privileged?"[28] The prioritizing of certain information modalities and ways to interact with them are traditionally inherent in the social site and will further be referred to as "privileged ways of knowing".[28]

Privileged ways of knowing are often not research subject themselves but rather the dimension against which IL progress is measured.[28] Focusing on how information literacy emerges in a setting reveals the privileged ways of knowing that shape the information landscape.[30] Lloyd exemplifies the information landscapes by stating: "the larger project of being a librarian draws from previous experiences, histories, social and material practices of librarianship and ways of working as a librarian that are shared among those who engage in this endeavor."[28] The theoretical framework that this understanding of IL is built upon, and that is central for this work, is constructionism. Constructionism states that a practice has its origins "in community settings (workplace, educational settings, home life, sporting, health or other social settings) and are consequently socially shaped."[28] IL research that follows this approach pursues an understanding of how practice is socially and culturally coined. It is a core activity of educational institutions to assess performance. Even so, some aspects of IL may not be easily generalizable and individually measurable.[11,13]

Qualitative perspectives and a sociocultural theoretical frame direct the IL research focus toward the practical experience, thus challenging the traditional notion that information can only be captured, expressed, and researched through textual resources.[28] Sociocultural theory complements the traditional perspective by providing a theoretical frame that points out the importance of social dynamics and context.

The aim is to gain a deeper understanding of the information process and privileged ways of knowing occurring in this PBL beginner lab to advance a description of the information landscape and base instructional suggestions on this understanding.[31]

The following research questions guide this study:

1. How can we describe the in-practice and perceived information process students engage in during a PBL beginner lab?
2. How do privileged ways of knowing in relation to textual source quality shape the information process?

■ METHODS

Data enrichment in qualitative social research implies describing social phenomena in a way that is appropriate to the subject matter, i.e., preserving them in their diversity, ambivalence, and dynamics.[32] The aim was to gain insights into both lived practice and student perceptions. These two aspects complement each other to answer the research questions posed. On the one hand, IL practice is shaped discursively and is often tangible only in the moment it is enacted in a social setting.[28] To this end, on-site recordings were used to describe the in-practice information process of

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students in practice, because many facets occur subconsciously and cannot be explicated retrospectively in interviews. On the other hand, the students' perceptions are often intangible in practice because they are internal processes and considerations. Therefore, the on-site audio recordings were supplemented by an interview study. To describe the actual contextual experience of IL practice, on-site audio recordings were combined with guided interviews over the course of three cohorts; these are described in the following section.

Setting and Participants

This study was conducted at Goethe-University Frankfurt in Germany. Informed consent was received from all participants in the study. Table 1 provides an overview of the different cohorts and participants. All participants were enrolled in a two-semester orientation program, throughout which they attend several courses and practicals of different natural and life science disciplines. During these two semesters, students choose a subject that they wish to continue studying. The chemistry lab practical takes place in the second semester and it was the first lab practical for the students. Due to the many course options in this orientation program, the learning group was highly heterogeneous in terms of their prior knowledge, which was helpful to this work's aim of getting a comprehensive overview of the different information perspectives and needs of students in a beginner's lab.

Table 1. Overview of Cohorts and Participants

	1. cohort	2. cohort	3. cohort
1	Jan	Nils	Laura
2	Jonas	Mareike	Luc
3		Max	Svenja
4		Sophie	Paula
5		Lukas	Lena
6		Sebastian	Sophia
7		Stefanie	Klaus
8		Simon	Lou
9			Jana
10			Julia
11			Lisa

The first cohort consisted of two students who worked together on the posed problems in the PBL laboratory concept for 8 weeks in May and June 2020, with lab sessions once every week for approximately 5 h. In addition to the laboratory sessions, the experimental procedure was also designed by the participants on-site. Five experimental procedure design sessions were audio recorded and a research trainee interviewed the students after completion of the laboratory course. The second cohort consisted of 12 students in August 2020. Lab sessions were now twice a week, shortening the length of the course to one month. The students formed smaller groups of four people to work together on the posed problems. Eight students agreed to participate in the interview study after the laboratory course. The third cohort consisted of 11 students in June 2021. All students participated in an ongoing interview study over the period of the laboratory course. A research trainee interviewed all participants individually once a week during the lab sessions, resulting in five distinct interview sessions. One group agreed, additionally, to audio record three experimental procedure design sessions. Since the course instructor was involved in the research team, two research trainees who were not involved in teaching the course were guided to conduct the interviews. Furthermore, all experimental procedures were gathered from all cohorts. To protect confidentiality, all participants' names were substituted with pseudonyms.

Lab Activity and Problem Design

The laboratory concept is derived from the industrial extraction of lithium from brine and is already published in the Journal of Chemical Education.[33] The aim was to design contextual scientific and economic problems with topical relevance. The industrial extraction of lithium from brine is, despite its importance and timeliness for the world and economy, essentially based on a sequence of precipitation reactions. In order to obtain a broad range of impressions concerning the information process and privileged ways of knowing, the problems were designed with different probable information sources in mind. The first problem was constructed as an introduction to designing the experimental procedure, as well as important concepts such as precipitation and solubility. The anticipated sources to find suitable detection reactions were the Internet (generic search engines) and textbooks of general inorganic chemistry. The second and central problem was the lithium extraction from brine. The anticipated source to find suitable information was patent literature; this was taught to the students as an additional information skill for the second problem during the seminar. A summary of the lab activity and a detailed description of the IL instruction (Table S1) in this course is available in the Supporting Information (lab activity and IL instruction).

Data Collection and Data Analysis

The complexity of the subject required several steps of data collection and refinement of the methodological approach throughout the research process. To answer the research questions, several types of data were collected over the course of three cohorts in a qualitative study design. The data collection and analysis were an iterative process, as shown in Figure 1, whereby data collection and analysis were mutually developed to get closer to the research subject. The gathered material from all three cohorts was eventually utilized and triangulated to answer the research questions.

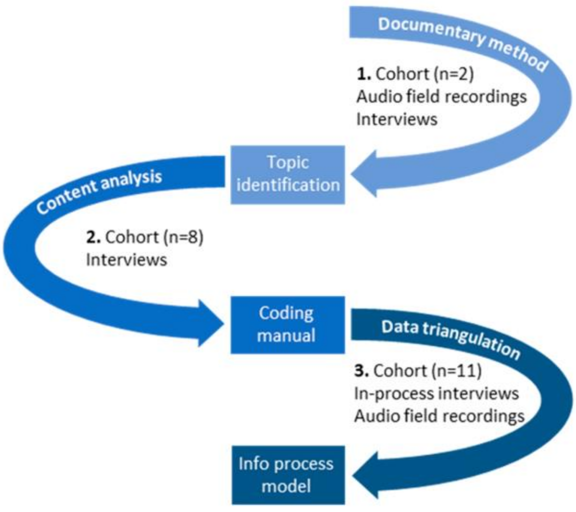

Figure 1. Overview of the data collection and analysis process.

As previously discussed, aspects of the information process are not investigable by only interviewing the individual in isolation from the group. Thus, group discussion methods are suitable here because they consider milieu-typical orientations and experiences cannot be collected and evaluated, representatively, on the basis of individual interviews, i.e., in individual isolation of the study's participants.[34,35]

A pivotal part of this work was based on on-site audio recordings to provide insight into the students' experiences. Approximately 15 h of audio recordings were collected in total. Following the documentary method, thematically relevant parts of the audio data were transcribed and analyzed.[36] Initially, the documentary method was used to discover themes in relation to the information process that may be subconscious to the participants. A table containing central themes emerged from the data (Table S2). At this point, information evaluation established itself as a key topic that directed further adjustments. In addition, semistructured interviews (20−30 min in length) were conducted, which were guided by findings from the audio recordings to include how the students perceived the process and what they deemed important; this enabled a more extensive view of the information landscape. The interview guide is available in the Supporting Information. Themes that emerged from the documentary method were also the starting point to formulate the deductive codes used to analyze the interviews. Inductive codes that originated directly from the data material were formulated and the combination of deductive and inductive codes resulted in an initial coding manual.

During the analysis of the second cohort interviews, the use and understanding of nonscholarly and scholarly sources became particularly interesting in terms of the privileged ways of knowing. The interview data were analyzed using structured content analysis.[37−39] Initially, the previously generated coding manual was applied deductively. Inductive coding of the interview data diversified and specified the coding manual. As the literature suggested,[28] it became apparent during data analysis from the interviews that certain features of the information process were only accessible in the moment of their origin and could not be reconstructed in hindsight. Thus, the interview study left aspects of the information process unanswered and, as a result, the data collection was adjusted correspondingly.

For the third and final cohort, insights from previous data collections were combined and integrated. The interviews were adjusted to an in-process interview study, interviewing the students throughout the lab course concerning the ongoing information process during problem solving (10−15 min in length). The goal was to gain better insight into the development between the different phases of the process. One group voluntarily recorded their three experimental procedure design sessions at home (20−30 min in length); this provided us with deeper insights into the information process in-practice.

The coding system was adjusted over the course of the three cohorts until a system with distinctive code descriptions, anchor examples, and solid coding rules was achieved (Table S3). Apart from the audio recordings, all experimental procedures (n = 25) from the students were collected. Eventually, all data were triangulated and analyzed using structured content analysis and the developed coding manual. Figure 2 shows the data triangulation in this study. The triangulation of various data types, especially the combination of the in-practice audio recordings and interviews, add credibility and conformability to the work.[40,41]

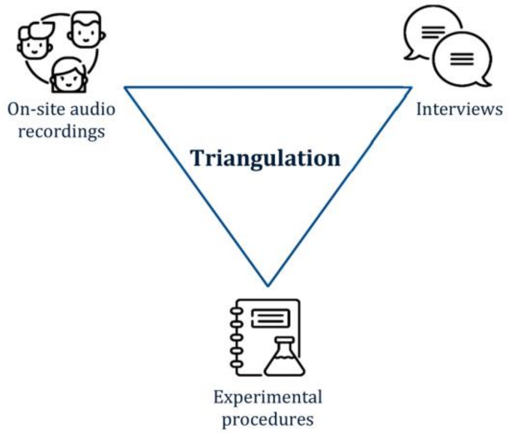

Figure 2. Overview of the data types for triangulation.

To add credibility and dependability to the work, the research team met for several debriefing sessions to discuss any unclear operational definitions, as well as the development of the interview guide over the course of the three cohorts.[40,41] The refinement of the study process over the three cohorts further adds credibility to the work.[41]

The combination of interviews and in-field recordings allowed us to interpret and explicate intuitive aspects of the information process in the field. Thus, a new access to these ways of knowing in the information landscape could be generated, while also verifying and diversifying our findings by taking the explicit perceptions of the students into account. Therefore, the data collection and analysis development fruitfully complemented each other and were continually refined over the course of this three-cohort study.

■ RESULTS AND DISCUSSION

In this study, on-site audio recordings were combined with semistructured interviews to gain deeper insights into the information process in which students are engaged during a PBL lab and the privileged ways of knowing that shape this process. The documentary method and content analysis of the collected data resulted in an information process coding table (Table S3). The connections between the codes were analyzed, resulting in the information process model (Figure 3). Students were prompted in class to pay attention to safety and to perform a mandatory risk assessment for their planned experiment. However, the information process model does not include any direct instructions from the classroom and relies solely on the analysis of the students' statements. The information process model is based on the students' lived experiences, which allowed us to explicate aspects that are practically relevant to students in the field. Information evaluation was the central theme running through all phases of the PBL process, while the criteria students explicitly used to evaluate information were almost exclusively practical. The acquired information was evaluated in relation to the experiment.

The Information Process

The information process (Figure 3) started with the accessible information. If additional information was needed by the

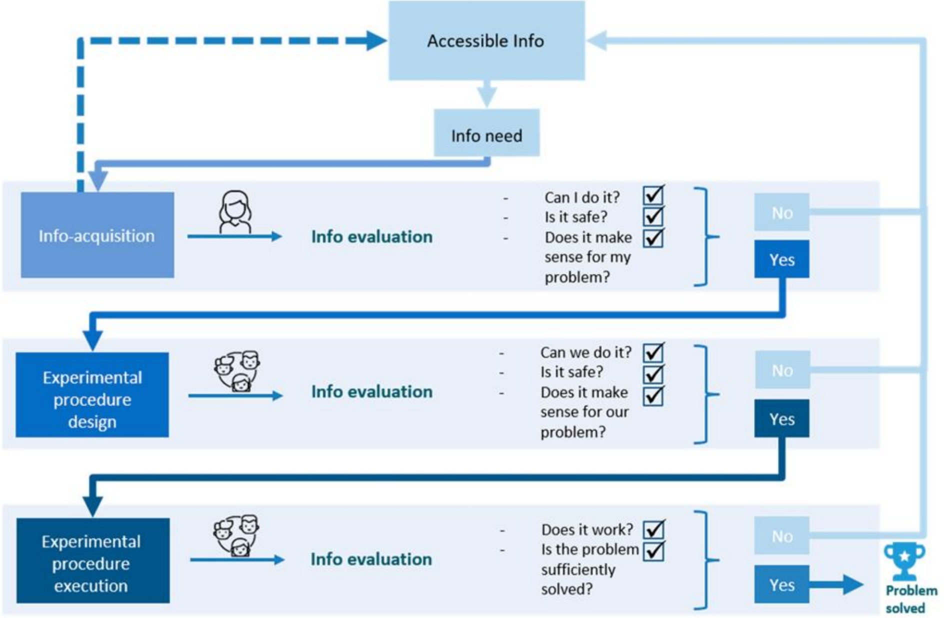

Figure 3. Information process model.

student, an information need was derived which led to the acquisition of the needed information. This process was repeated until a base of information was available to evaluate before the commencement of the experiment. If the criteria for evaluating the information were upheld, the idea for designing the experimental procedure was passed to the group. Again, the information was evaluated, but at the group level where different people examined each other's ideas. If a criterion was negated, the information acquisition process was repeated. If all questions were supported, the information was tested by trial and error in the experiment. If it did not work or if more information was needed, more information had to be obtained and the information process began again from the accessible information. If the experiment provided all the necessary information for problem solving, then the information process and the problem-solving process were successfully completed. The emergence of the model is discussed in detail, including anchor examples, in the next section.

Information Acquisition

The student's process of information acquisition began with the application of their already accessible information to the problem. In this PBL setting, all students required additional information on top of their previous knowledge to approach their problem. From this point, the student derives an information need and then attempts to acquire the needed information. Svenja described this part of the process:

> *Svenja: "[...] And then I just googled in general, as I said. So how can you get lithium carbonate at all? Because at first I thought, there is no lithium carbonate in our solution. So somehow, I have to get it. And then it said that if you have lithium chloride, then you can also get lithium carbonate with sodium carbonate."*

Svenja already knew that she had to precipitate lithium carbonate. She used this knowledge to define her information need ("How can I get lithium carbonate?") and then acquired the needed information.

The initial search strategy from the interviews showed the notion of building a foundation of accessible information that the learners could work with and build upon, as Jan said:

> *Jan: "We basically started by putting everything on Google and seeing what Google tells us."*

The data suggested that a certain foundation of accessible information was necessary, otherwise, the next step of evaluating the information according to usefulness for problem solving was not possible. Svenja explained this notion of having no accessible information at first:

> *Svenja: "So at first, we had no idea at all and we were sitting there thinking: We'll never find out anything."*

In addition, a certain level of accessible information appeared to be a prerequisite for group task distributions, as Paula stated in her group:

> *Paula: "Yes, I'm a bit overwhelmed with the thinking, you just don't know that much of content yet and it's hard to divide it up in the group, because you don't have an overview yet."*

In the search process, the newly acquired information led to newly accessible information and a different and more precise information need.

The process of information acquisition was an iterative process throughout which the newly acquired information led to newly accessible information. This often led to a new and more precise information need and, consequently, new information acquisition, as Jan described:

> *Jan: "If I decided for a certain experiment, then I clicked on the website with the experiment description and we have just looked what the website gives us and if no reaction equation was indicated, which was also relevant for us, we googled again specifically for the experiment or for this detection reaction and then, of course, we got more specific results and then we also looked at the results we got. Then I just looked at which page, which websites give me the knowledge I need."*

The acquired information was scrutinized in terms of applicability and transferability to the problem in the next step.

Information Evaluation (Individual Level)

The necessary information for problem solving was only accessible through experiments and, thus, all information acquisition was oriented to design a useful experimental procedure. The evaluation criteria applied to the acquired information were overarchingly measured in terms of transferability, meaning that the general question students asked themselves was: Can my information (whether from prior knowledge or researched) be applied to my problem and help me to solve it?

This overarching criterion was split up into three key questions that the students asked themselves to scrutinize their acquired information. The first question was: Does it make sense for my problem? In the following example, Jan searched for a detection reaction to help solve the first problem and assumed the detection reaction he found did not make sense for his problem because the precipitate was colored white. He shared his thoughts with his colleague:

> *Jan: "We can't do that. I had found a detection, I think I also know it somehow from school, with silver... but there is a white precipitate and I think if the salt is white in the end, then you wouldn't see anything."*

The second subcriteria that the students asked themselves to evaluate the information at hand was: Can I do it? The question of ability referred to both the skills and the available equipment in order to execute the experiment. Svenja described how the acquired information was often not applicable for them due to the lack of equipment:

> *Svenja: "The problem was that many experiments wanted to be very environmentally friendly and then they used ion sieves. So we just thought that is not available here and it is just industrial and that we just have to look for something else. That was really hard, because most of the new things are based on this technology."*

Alternatively, the question of ability related to the cognitive understanding of the information. Paula spoke about sources not being useful to find the applicable information if the content was not understandable for them:

> *Paula: "So sure, if the source is correct, but you can't understand it somehow because it's too difficult, then that doesn't get us anywhere now. So of course it has to be appropriate. It has to be comprehensible."*

The third subcriteria that the students applied to evaluate their acquired information was: Is it safe? Jonas described how he evaluated safety by looking for chemicals he already knew:

> *Jonas: "Then you just get a feeling when you scroll through your results, how dangerous the chemicals are. Of course it makes a difference if you work with NaOH or with substances you have never heard of."*

The subcriteria that the students applied to scrutinize the acquired information were directed toward the goal of designing a feasible experimental procedure. The criteria were decisive for moving forward with the idea or acquiring further information. This process shows how, in a problem-solving scenario, the in-practice focus switches from applying generic criteria for source evaluation to using sources as collections of information that will be applied and executed in the experiment. Through the use of authentic problems, PBL settings allow for a shift of the learner's focus and a redirection of the IL concept from finding specific sources to using information to learn.[13] The focus is on scrutinizing any information, no matter the source, in relation to feasibility and usefulness for the experimental solving of a problem; this is a key feature of problem-based learning in distinction to recipe-style laboratories.

Experimental Procedure Design: Information Evaluation at the Group Level

After evaluating the acquired information as individuals, the information was discussed and evaluated at the group level. When a group member did not point out experienced difficulties themselves, the member shared the acquired information, and the rest of the group applied the criteria that had been previously applied by the individual. Paula shared her idea of using detection reactions to precipitate certain components with the group. Lisa interjected that only a small amount will precipitate. She evaluated Paula's idea in relation to, "Does it make sense for our problem," which was then accepted by Paula:

> *Paula: "But in the case of a detection reaction, something precipitates. You can simply filter it out and then you have it."*
> *Lisa: "Yes, but I think it is usually the case that only a small amount of sodium reacts."*
> *Paula: "Ok that doesn't work for us."*

The results show that the students used the same criteria, but that these were explicitly discussed and not only applied by the individuals themselves; this led to a broader anticipation of difficulties. The starting point was different, however, because an internal information evaluation by the individual had already taken place.

If the criteria were upheld to the satisfaction of the group members and enough information was gathered, then the experimental procedure was written down and, in the next step, executed.

Experimental Procedure Execution: Information from Experiments

The students had already gone through various difficult thought processes by the time they arrived at the point of experimenting. Up until this point, the students had put a lot of thought into the feasibility and usefulness of their experimental procedure designs, but they could not know if it would work unless they tried it. The information from the experiments is key to evaluating the acquired information and solving the problem. As Lisa pointed out during her group's experimental procedure planning session, they would not know for sure if it would work unless they tried it out:

> *Lisa: "We already have so many approaches, but we won't know if it will work. I think the most important thing would be that we try the precipitation on Monday and then we will see if it works."*

The central information is only available through experiments. As Jan described in the interview, after the experiments, it was obvious if the plan had worked or not:

> *Jan: "...you could always see for yourself after each session that what you did either worked or it didn't work."*

If the experiment did not work as planned, the students would search for solutions and start the information process from the beginning, as Sebastian stated:

> *Sebastian: "The precipitation of lithium carbonate didn't work at first and then we noticed at some point that if we turn the temperature another 4 degrees higher, then something precipitates. And then we found out a few days later, that it also makes a huge difference, how long you keep the whole thing hot."*

Lena pointed out about not knowing for sure if the information was reliable until the information had been tested in the experiment:

> *Lena: "Yes, well, we can't know that for sure, of course. But we notice when the experiment doesn't work, that something, either in our calculations or something else, must have been wrong."*

Lena described how, if the experiment had not worked, either the information was wrong or her team had made a mistake.

This process shows that the information in a PBL lab course is always evaluated starting from and ending with the experiment. Information has to be suitable for the experiment and it has to be critically evaluated and assessed, but, eventually, it will be tried out, which is a basic part of inquiry-based learning.[42] The focus is on using information to experiment.

The role of the privileged ways of knowing and the influence of adding information skills will be discussed in the next section.

Privileged Ways of Knowing: Quality of Sources

The manner in which leaning communities engage with information is socially shaped over time and context-specific. Just as social and embodied information is emphasized in football practice, textual information has traditionally carried more weight in teaching and scholarship.[28] This perspective supports a context-specific exploration of IL. The textual information modality is given a high priority in IL research and teaching, especially information retrieval. These ways of knowing are often not themselves the subject of research, but are used as a benchmark for improving student IL.[28] However, it can also be helpful to examine how privileged ways of knowing shape an information landscape to contribute to a more comprehensive description of the information landscape.

Privileged ways of knowing were examined in relation to the quality of textual sources in this study. No data regarding the general source evaluation criteria were obtained in the on-site audio recordings, as the students did not explicitly discuss them. Thus, the students were asked in their interviews specifically about the role that source quality played for them during the experimental procedure design, in order to gain a deeper insight into the privileged ways of knowing. We refer to the binary source understanding of nonscholarly and scholarly sources; this is a common distinction,[22] also applied by participants in this study. The coding table "Quality of sources" is available in the Supporting Information (Table S4).

Understanding and Use of Textual Sources

The overarching response to questions concerning source quality criteria revealed a binary source understanding that all the students employed. The students clearly stated that scholarly sources are reliable, whereas nonscholarly Internet sources were not; this was exemplified by Paula's statement:

> *Paula: "Well, with patents, you usually know that they are written by scientists who know what they are doing. This is a bit more difficult with Wikipedia, for example, or with the Internet in general. And it's the same with books, of course. So you know or you hope, of course, that the people who wrote this book have written sensible things."*

Nonscholarly sources were used synonymously by students with Internet Web sites, apart from the university library Web site or the patent literature Web site. "The internet" was often used as an expression for nonscholarly sources.

Disadvantages of the nonscholarly sources stated by the students included safety concerns; the students feared that nonscholarly sources might not be as safe as scholarly sources, as Svenja stated:

> *Svenja: "For possibly dangerous things, I would not use Wikipedia. I would rather use for example, a book from a publisher or something. So I think it always depends on what you want to look up."*

Another disadvantage was that the content might be unreliable and would not actually work in the lab, as Jana pointed out:

> *Jana: "For our first problem, we were supposed to detect, I think it was calcium, and on the page it said that you can detect it as sulfate. So if you have the calcium in the sample and just dump sulfate on it, so for example sulfuric acid, then something white should precipitate and that just didn't work for us and that's why I'm not sure if the source is so reliable because we checked it then or I checked it myself in the lab."*

Aside from this, most concerns revolved around the supervisors not being satisfied with the sources. Lena shared her perception of using Internet sources as something she is not supposed to do:

> *Lena: "But with Internet sources, you think about whether it's all going to be true and, of course, whether supervisors will approve or not. You're not supposed to use these sources."*

The frequent use of nonscholarly sources suggests that they have advantages for the students compared to scholarly sources. Besides the previously mentioned use for gaining an overview ("googling around") in the information process, the preference for these sources was also due to comprehensibility. As Klaus stated, forum entries can contain information from people in a similar position who have experienced similar beginner problems, where the information is expressed in more everyday terms and is, thus, more understandable:

> *Klaus: "There are also many forum entries on many, many chemical things. Again, similar to Wikipedia, these are of course not one hundred percent trustworthy, but they are always quite good for rough ideas. Often people have had the same problems before, especially with basics, things like we are doing now."*

The forum entries provided relatable and comprehensible information for the students from people who experienced similar difficulties. The students had the opportunity to ask for and receive specific information from other people around the world, besides asking their classmates. They could participate in a discussion and in turn provide information.

Another advantage of nonscholarly information was the avoidance of using an additional information skill, such as searching for patent literature, which could require a tremendous effort while forming a psychological barrier, as Laura mentioned:

> *Laura: "We didn't use patent literature because we were all overwhelmed and didn't understand how to search for them. I didn't understand it at all. I didn't know how to look for them, where to look, how to proceed, how to narrow them down."*

However, an advantage that the students saw in using scholarly information was the already-mentioned general reliability and security. Indeed, more relevant to practice was the fact that the scholarly sources contained information that was necessary for problem-solving and, otherwise, not acquirable, as Lukas pointed out:

> *Lukas: "Patent literature was necessary for problem-solving. Without patents we wouldn't have been able to do it that way, because it's just... you either really have a lot of specialist knowledge, because the process isn't described in such detail anywhere in the literature, of course, or you have to use patents."*

When asking the students if they felt able to tell if the information was reliable or not, they generally replied with different generic tactics to evaluate the reliability of a Web site, e.g., if there were a lot of advertisements, if it was a university Web site, or how often the same information was found on different Web sites.

Students generally referred to nonscholarly sources as "bad sources" and scholarly sources as "good sources". A common strategy was to search for information content helpful for problem-solving in nonscholarly sources for comprehension and application, and then attempt to find similar information in scholarly sources to be able to quote a "good" source on the experimental procedure.

> *Klaus: "We've also looked at Wikipedia to see what is said there. There are usually also quite good ideas in it, although it is not necessarily usable as a serious source. Often we have summarized a lot of ideas from Wikipedia and then cited a good source in our experimental procedure."*

The notion that both nonscholarly and scholarly information are used in practice was supported when cited sources included in the students' experimental procedures were analyzed. Twenty-five experimental procedures were collected in total: 4 cited only nonscholarly sources, 5 cited only scholarly sources, 15 cited both, and 1 was handed in without the citation of sources. Nonetheless, from the interviews it appears as though there is usually a predominant use, in practice, of content originating from nonscholarly sources that the students find easier to understand.

The results show that there is a remarkable discrepancy between what is done and apparently useful in practice and what is said about the quality of the sources in retrospect, as this seems to have had nearly no influence on what was done in practice. Discrepancies between what students know about source quality and what they do in practice are consistent with other reported findings.[43−45] The students find themselves in a dilemma: they have all used nonscholarly sources to a certain degree, but also consider them unreliable, feel unable to evaluate reliability, and know that the sources are frowned upon by their supervisors. They are looking for generic framework criteria to guide them. In contrast, there is a basic trust in scholarly sources, but these are often incomprehensible and difficult to obtain. The next section will discuss ways to deal with these difficulties and fruitfully use them for instruction in PBL.

■ CONCLUSION AND IMPLICATIONS FOR TEACHING

This qualitative study addressed the information process that students engage in during a PBL lab and how privileged ways of knowing shape this process. A key aim of this study was to contribute to the social and contextual description of the PBL beginner lab information landscape and to develop suggestions for IL instruction based on this description. Thus, the first research question (stated in the introduction) relating to the description of the information process students experience, could be addressed. Reconstructing the information process in a model illustrated the complexity and the effort students put into this process. It is a lengthy process for them to evaluate the information for planning the experimental procedure, at first individually and then at the group level, until the experimental procedure is written down and carried out. The findings show that the experiment is central to the information process students engage in. First, students evaluate the information for the experimental procedure before the experiment, then they evaluate whether the information worked after the experiment.

The second research question related to privileged ways of knowing and how they shape the information process. Different ways of knowing are privileged within the different information landscapes.[28] Our results address textual information, and more specifically textual source quality criteria, as a privileged information modality in this information landscape. The students generally combined scholarly and nonscholarly sources and provided insights into their perceived advantages and disadvantages of these sources.

Findings from both research questions can be combined to derive implications for instruction based on students' experiences with the information process in practice. Traditionally, IL skills in education have often been considered a generic list to be worked off.[13,31] Current developments in IL teaching for higher education highlight the importance of social and contextual aspects.[14] In line with these developments, our research depicts the complex ways in which students know a great deal about their information landscape and how to navigate it. This knowledge can be used as a starting point for supporting their information problem-solving process.

It is challenging to design a problem for a beginner PBL lab that implements the primary chemistry literature because often students either have difficulty understanding the content or lack the experience to assess its usefulness. The students in this study relied on nonscholarly Internet sources in practice, despite knowing about the lack of quality and the disadvantages, which is in line with findings from related work.[43−45] The results of this work can be used to incorporate nonscholarly sources into the classroom in ways that are useful to students while laying the groundwork for their critical evaluation. Students referred to nonscholarly sources, such as forum entries, that they felt contained information from people with similar beginner problems. They did not consider these sources reliable but used them anyway.

Internet sources, such as forums, provide students with information they feel is relevant to their questions. Forums as a source of information are not bad or wrong per se, nor are they evidence of a lack of information literacy. The information has similar advantages and disadvantages to sharing information with classmates; it can be very helpful for learning and understanding, or it can be completely wrong in content, much like information that peers discuss with each other. This illustrates how social and textual modalities of information merge and cannot be easily separated. Information resources reflect the knowledge and credibility of their creators, and evaluation is contextual "in that information needs can help determine the level of authority required".[14] Forum entries can serve as an introduction to understanding information as fundamentally social and questioning resources problem specific. Starting out with nonscholarly sources to exemplify the social and contextual nature of information could help reduce the ambiguity that arises when students think a source is inappropriate and use it anyway.

A common strategy students used was to search for information content helpful for problem solving in nonscholarly sources for comprehension and application, and then attempt to find similar information in scholarly sources to be able to quote a "good" source on the experimental procedure.

Students here demonstrate particular expertise in IL because they know how to navigate the information landscape. They know how to find comprehensible and valuable sources for problem-solving, and they also know which ways of knowing are privileged in this information landscape; meaning in this case how to additionally find sources that meet the expectations of their supervisors. This demonstrates the students' understanding of the historical, ideological, and contextual aspects that form the information landscape. As long as the students are not yet able to find the needed information directly in scholarly sources, e.g., due to comprehensibility, the supervisor can serve as a checkpoint. This can be understood as a deliberate step in the information acquisition and evaluation process for PBL laboratories, because it helps to bridge the gap between scholarly sources that are cognitively difficult for students to access at this point, while nonscholarly sources are not as reliable.

These two examples demonstrate the opportunity to incorporate nonscholarly sources into PBL and IL education in a meaningful way. Moving from nonscholarly sources to more advanced professional information is a practical part of the students' learning experience to navigate the information landscape and draw meaning from the knowledge base. To acknowledge and support students' reality may create new opportunities.

The PBL cycle and targeted problem design provide an instructional advantage in helping students move from using nonscholarly sources to increased incorporation of scholarly sources or specific IL skills. Students can gradually expand their repertoire of sources as they continue to refine their problem-solving process. Deliberate problem design can be used for more advanced students to design problems that target specific information skills and are otherwise unsolvable. Then students can learn in a meaningful way that certain sources are more useful or even necessary for certain problems; this was evident in the students' common need for patent literature in relation to the second problem in this course.

Our results have shown that first all the information is evaluated to design the experiment, and then the decisive information whether the experiment works is obtained through the experiment. The results of the experiment show students whether the information was useful in solving the problem. Thus, the experiment provides information, but it is also the crucial means to test the information used to design the experimental procedure. These findings suggest placing the experiment at the center of IL instruction: teaching students how to acquire, use, and evaluate information for and from the experiment, and connecting other modalities (textual, social) to it. The students' primary concern is to find safe, feasible, and useful information and to begin IL instruction at this starting point practically supports them. It is an important contextual difference and advantage over other nonexperimental disciplines or learning contexts that information is tested in the experiment. If a problem can be solved using Wikipedia and the experimental procedure is tested for safety, feasibility, and usefulness to the problem, there should be room for discussion of why it is not a contextually appropriate source.

PBL laboratories holds great potential for students to learn how to use and examine multiple sources in a contextually meaningful way. As the results show, one team used nonscientific sources to design the experiment. After the experiment did not produce the desired result, the group concluded that it had not worked because the sources used were unreliable.

This illustrates that while nonscholarly sources may be students' first strategy for solving information problems, they are fundamentally skeptical of them and, in this case, attribute difficulties that arise to the source rather than to their own execution. Two important aspects for teaching can be derived from this example: First, students are willing to adjust their information behavior when problem solving with low-threshold, nonscholarly sources does not work as expected. This opens the possibility of discussing with students why certain sources need to be questioned more than others when designing the experimental procedure. Most importantly, students can learn for themselves which sources should be examined more critically.

Second, students weigh the information gleaned from the experiment to determine whether they made mistakes in conducting the experiment or whether the source was unreliable. This can be a starting point for teaching them to evaluate information in a way that is often shortchanged in expository formats. In an expository format, students do not question the given experimental procedure; they repeat the same experimental procedure until the desired result is achieved. PBL instruction can prepare them to gather information from experiments and, when difficulties arise, to consider that they may have done something wrong in performing them, but also to understand the experimental procedure as information created by someone and, finally, to question any information as fundamentally social.

This work offers a new perspective on IL instruction in conjunction with PBL by understanding the experiment as the contextual center for IL, and deriving from this, integrating textual and social modalities into instruction. In this approach, IL instruction is centered on students' experiences and difficulties while directly supporting students in their problem-solving process. This holds great potential for teaching and further research.

■ LIMITATIONS

This study is a first attempt to describe the student's information process in a PBL beginner lab using a qualitative study with a sociocultural frame. This perspective is greatly underrepresented in chemical IL research. This work provides comprehensive insight into the occurring information process by incorporating different types of data and by continually refining the research process across cohorts. However, this study can only provide a starting point to improve our understanding of the complex social and contextual dimensions that form the information landscape. An information landscape includes many social and contextual factors that could not be considered in this study, such as supervisor behavior, the influence of problem design and its implementation in the IL process, and the role of the group as a social source of information. Furthermore, this study took place in one PBL setting and, thus, our findings may not be transferrable to other PBL settings. According to our data, the information process model includes aspects of IL that are central for problem-solving. Further studies are necessary to test this model in different PBL settings. Even though this study opened many additional questions, it does present a good starting point and reveals opportunities for chemical education research in this field.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.2c00305.

Interview protocol (PDF) (DOCX)

Lab activity and Table S1: IL instruction (PDF) (DOCX)

Table S2: Documentary method coding table (PDF) (DOCX)

Table S3: Information process coding table (PDF) (DOCX)

Table S4: Quality of sources coding table (PDF) (DOCX)

■ AUTHOR INFORMATION

Corresponding Author

Larissa Wellhöfer – *Department 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 – *Department 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.2c00305

Notes

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7.4. Supporting Information Study 2

7.4.1. SI Interview Protocol

Interview protocol – Information process and sources

1. How did you go about designing the experimental procedure?
2. Where did you get your information?
3. Did you use patent information?
4. If yes: Why did you use it?
5. If no: Why didn't you?
6. Describe the process of researching information to solve the problem. How did you go about it step by step?
7. Can you name a specific source that you used?
8. Do you have a basic strategy for getting information?
9. Did you think about the quality of the sources?
10. Is source quality important to you?
11. Were you able to do something with your first search results? What were they?
12. Which factors are relevant for you to consider a source as reliable?
13. Did you subsequently research and acquire further information during the lab work?

7.4.2. SI Table Central Themes

Table S2-1: Documentary method theme table

Topic	Formulating interpretation	Reflective interpretation
Main topic/Information need (use prior knowledge, anticipate problems)	12-26: Jonas tries as a first strategy to limit the problem logically by proceeding according to the exclusion principle: CO_3 is only in sample A and by establishing its presence or excluding it, one has directly an information whether it is sample A or not. From this idea, Jonas derives a need for information ""How we can do that would be...let's do some research"", because he has already concretized his plan. Following this principle, he goes through the remaining ions and comes to the conclusion that calcium, magnesium and "CO_3" must be detected, which Jan confirms.	12-26: Identify information gap: Jonas approaches problem solving through logical narrowing, much like a puzzle. In doing so, Jonas attempts to limit the amount of work and be efficient. It is also possible that due to lack of expertise and experience, such an approach is the only possible one for Jonas. No concrete approach is mentioned yet in this proposal (see if it this ion or rule it out; do some research). The identified, explicit information gap is "look if it is this ion". Identifying info needs is also info use: Jonas uses the info from the problem statement to narrow down the problem and determine info needs. Identify info needs: Jonas continues to pursue the idea of logically narrowing down the problem and figuring out what they need to prove, and now seeks confirmation from Jan ("look at what that is" now is called detection). Jan basically confirms the idea. Jonas explicates the ions to detect: Calcium, Magnesium and CO_3. (CO_3 is not titled as carbonate by Jonas.)
	69-77: Jonas addresses that they should look for the boiling temperature (need for info) in order not to accidentally precipitate out the substance to be detected. He refers to his previous knowledge of volatile compounds and thinks that the salts in the sample could be part of it. The need for information arises here because Jan uses his prior knowledge to anticipate difficulties. Jan replies that they only know that it "works" with NaCl, which is based on his prior knowledge from everyday life about salt in a cooking pot and cannot be automatically transferred to the other components (transferability). But it doesn't have to be proven anyway, because a) according to the exclusion procedure it is in everything and b) according to Jonas "it is salt" and therefore in all	69-77: Info need is determined by using accessible information (prior knowledge). Difficulties are anticipated and the added info need supplements the research strategy. Apparently there are two strategies running in parallel: On one hand "just search" (probably because of lack of previous knowledge) and on the other hand concrete ideas are suggested and concrete problems are anticipated by previous knowledge, leading to more specific info need. 188-192: Match info needs, research strategy. The students again formulate a more specific information gap: Characteristics of $CaCO_3$ that one would have to

Topic	Formulating interpretation	Reflective interpretation
	samples. (It seems as if the students think that if you have a salt sample, NaCl is automatically in it). The info requirement still results from the exclusion procedure, supplemented with the problem anticipation. 188-192: Calcium carbonate is to be detected, but the students do not know much about the properties that are to be researched and that are recorded here as info requirements. Jan notes that he actually learned this in a lecture and says that he should know this, but doesn't remember. 197-207: The students discuss if calcium is a metal or not. Jan convinces Jonas that it is in fact a metal and agrees to research the idea of flame staining.	"just research." ST1 notes that he ""actually had"" that in the exam/lecture. Establish knowledge hierarchy: Who has what knowledge. Jonas clarifies that his chemistry exam is significantly harder than Jan's. Perhaps also: how credible is this person as a source? Which social source can claim more credibility in this dynamic? 197-207: Info use and negotiation: Jan shares info that metals have different flame colors. Jonas questions whether calcium is a metal (negotiate). Jan seemingly implicitly disagrees by stating the main group, which Jonas finds convincing and concedes that calcium may be a metal after all. Detecting calcium with flame staining, however, is met with three question marks.
Main topic/Info use: ideas for problem solving, reference to everyday life	41-44: Jan proposes a solution from everyday life: It involves evaporating salt water, with the salt then remaining as a solid. "where...where...for example if you, if you mix salt in water and the water evaporates, then you only have the salt at the end. That settles at the bottom...And that would also be, there you have NaCl in any case...that's what I would have said now. Jonas: Right, sodium chloride is also contained." Jan knows this from everyday life and transfers it to the effect that you then have "salt", which for him means NaCl. Jonas confirms that NaCl is also contained (note: and not simply formed). 131-138: Jonas has an idea to add other chemicals to the sample and thereby color it, which is implicitly supported by BT3 ("Why not"). Jan also supports the idea and adds that carbonate "in chemistry" (presumably school) has always been easy to detect."	41-44: Jan probably refers to the previous question-answer-situation about the "type of sample", because now the idea with evaporation makes sense for Jan. He knows this from everyday life with a cooking pot full of salt water. As in everyday life, for Jan NaCl and salt are to be used synonymously. It seems as if he thinks that automatically NaCl "is formed" because NaCl "is salt". Jonas accepts the suggestion, but explicitly relates the idea to the fact that NaCl is also present in the sample (it does not necessarily arise as NaCl as "salt"). Information use in discourse is information exchange: Information that a person has is made explicit, applied in conversation and thus shared, and is now the subject of negotiation. 131-138: Info use and info negotiation with BT: Jonas formulates very defensively but for the first time explicitly the procedure of a proof reaction, apparently hoping for a reaction from BT3. He also gets the confirmation

Topic	Formulating interpretation	Reflective interpretation
		implicitly and both laugh again. Seems very uncertain again from both sides and a bit agitated. Jan picks up on Jonas' idea of using detection reactions and refers to his prior knowledge with carbonate, even though he doesn't remember exactly how that was done.
Main topic/Research strategy "just search"	65-68: "Jan: That means you would then just look for how to detect CO_3 in a mixture when you do your research? Jonas: For example. Jan: ...And the same with the other ions...ok. Jonas: Yes." The info need is established and manifested in the research strategy	65-68: Jan summarizes the research strategy with "simply search." This seems to be an unambiguous endeavor for Jan. Jan refers again to the idea about Jonas' approach to research the detection reactions. Jonas apparently takes the expert role. The answer of Jonas "for example" seems to be a "backpedaling", there are also other possibilities. Jonas is not yet fully satisfied.
	90-96: BT1 asks the students what they are thinking about. Jonas answers for both of them: He thinks about how to solve the problem and how to proceed with the research strategy. He adds that it would probably be best to just Google it and see what he finds.	90-96: Jonas answers for both here. The info need seems to be completed here. Search strategy: "just search". The info from their own prior knowledge seems too uncertain for the Students to pursue it further seriously.
	135-148: Jan:"Maybe with the CO3, I can imagine that too. That is carbonate...I think you can do something with it. I think it's easy to detect, but I don't know how...(laughs)...But, in chemistry, carbonate was easy to detect. BT3 (laughs). BT3 How could...you could research that, couldn't you? Jan: Yes clearly. BT3 Yeah, you say, you say clearly...but?	135-148: Negotiate info search/research strategy: Here, it seems that "just search" is questioned by the students as a research strategy. It's "already clear"(ironic!) that you can research it, but is that a sufficient plan? "You can research anything" seems to express a bit of overwhelm with the information available and the ""just search"" strategy.

Topic	Formulating interpretation	Reflective interpretation
	Jonas: We can research everything BT3 Yes. BT3 picks up on the "just search" Strategy. This seems to be insufficient to the ST "You can research anything". They would apparently like it to be more concrete.	
	188-192: Jonas does not know the characteristics of calcium carbonate, which "one would just have to research". Jan again refers to his prior knowledge that they "actually had it in material chemistry" but does not get more specific.	188-192: Match info needs, research strategy. The Students again formulate a more specific information gap: "Just search" characteristics of $CaCO_3$ that they would need.
Main topic/Information evaluation: Shared ideas are evaluated for transferability	74-77: Jan refers to his idea that they don't have to detect NaCl, because it is in every sample to which Jonas adds that they don't have to detect it because "that's salt."	74-77: The shared idea is narrowed down and questioned here in terms of applicability. Prior knowledge is questioned in terms of transferability to this problem. It is unclear here whether the students agree that NaCl does not need to be detected because it occurs in all samples (logically narrowing the problem) or because it "occurs anyway" because "it's salt".
	101-118: Jonas talks to BT3 about his concern regarding sublimation of solid sample during crystallization. BT3 ignores this for the moment and asks for other ideas. BT3 repeats the idea of evaporation of water and uses technical terms. BT3 then asks again for other ideas. There is a misunderstanding with Jan what concentration means. BT3 repeatedly asks which phase would be best to work with. There are technical difficulties in understanding (technical language).	101-118: BT3 encourages the ST to summarize and explicate their negotiated ideas again: Here BT3 refers to both research strategy and solution strategies from prior knowledge. Information use: Jan refers to the video in which the evaporation of the brine is shown. Thereby Jan presumably combines the info from the video and from his prior knowledge, which was addressed before, with the salt in the boiling pot. Jan cannot yet recognize that this is not a proof (he cannot evaluate the information regarding its transferability). When BT3 asks whether ST1 can work better with this, this uncertainty becomes clear and the idea is apparently discarded. Whether it makes sense is questioned by BT3, but it is not clarified whether it makes sense and why/why not.

Topic	Formulating interpretation	Reflective interpretation
		Both just laugh at the end (uncertainty?). Jonas picks up Jan's idea and anticipates a problem regarding the usability of this idea for the problem: he evaluates the information in terms of its applicability to the task, using his own prior knowledge, namely regarding volatile substances. BT3 also passes over this suggestion. She apparently does not want to reject the students' ideas, but because they do not make sense, she still wants to steer them in a different direction. The massive lack of expertise relative to the problem is evident here. BT3 clears this up a bit by referring to the aggregate state, but is still less in the role of "teacher" and more in the role of "inquirer." Still, it is clear that she rejects the idea.
	516-549: The students discuss how to detect natrium using flame coloration. Jan wants to figure out how much background knowledge he needs to be able to do the experiment and know what to do with the information from the experiment. Jan refers to the difficulty of having different flame colorations in one sample. Jonas responds that they could see that the flame coloration changes.	516-549: Information evaluation: Does this make sense for my problem: The problem creates a need for the students to understand the theory enough to assess whether the info is transferable to their problem (how much do I need to understand to solve my problem?). Match problem understanding with BT: Here the hierarchy and uncertainty becomes clear again ("Jan: Is this relevant for us?"). The students want BT3 to narrow down more precisely what is actually required, because in the end the BT decide whether this is sufficient. The students must always compare their “problem-solving level” with the BTs' understanding of the problem, because the BTs evaluate it eventually.

7.4.3. SI Information Process Coding Table

Table S2-2. Information process coding table

Code	Description	Anchor example
1. Info search for experimental procedure		
Accessible Info	Starting point of the information process is prior knowledge or newly acquired information	Laura: I think the data was from an old lab. What Jana did at the university in Mainz, where she got the data from. So the experiment came from that. Sophia: For example, the patent said that you have to pay attention to the solubility, because different substances have different solubilities, and you can get them out that way. But it didn't say exactly how to do it and what temperatures you have to pay attention to or something.
Info need	The information need that results from the detected information gap	Klaus: Everyone tried in their own way to find search terms that lead to a good result. So things like lithium carbonate. We basically picked out: What are the properties of that? Lithium carbonate precipitation, lithium chloride reactions with sodium carbonate. We searched for exactly how magnesium chloride and potassium chloride react with sodium carbonate and how magnesium carbonate and potassium carbonate would react and how they would behave in an experiment.
"Google around" for overview	Search for key words in a search engine as a initial strategy to gain an overview	Laura: I first got a rough overview on Wikipedia, on the Internet and then, when I had a rough overview, I looked through various pages and saw if the reactions that were there were also on other pages and how often they occurred. That's how I put my stuff together at first.
Info acquisition causes new info need	Acquiring information during the search reveals additional information needs.	Lena: I found a process in these patent things, but it was somehow not explained specifically. It just said yes there is a filtration step, then this step and that step and something like that and what is precipitated in the process. So I still had to find out how to do that.
2. Search strategy		
Group task distribution a) Divided into tasks b) Divided into sources	Group members distribute individual member responsibilities into different roles or sources.	Lukas: Then we divided the whole thing up a bit. Who researches a bit in the patents, who looks into the classical literature, who writes the protocol together. I, for example, was the one who looked at the patents.

Code	**Description**	**Anchor example**
Info search evaluation (individual) a) Can I do it? b) Is it safe? c) Does it make sense for my problem?	Acquired information is evaluated considering specific criteria with regard to the experimental procedure design.	a) Svenja: We have found, for example, experimental designs for student experiments from the University of Göttingen website or something, which people have already prepared. We then looked at how it is done, because we thought student experiments are a good info source. It is probably not so difficult, that is, we can probably do it and secondly, it is probably not so dangerous that we somehow blow something up or so. b) Jonas: Then you just get a feeling when you scroll through your results, how dangerous the chemicals are. Of course it makes a difference if you work with NaOH or with substances you have never heard of. c) Jonas: We can't do that. I had found a detection reaction, I think I also know it somehow from school, with silver...but there is a white precipitate and I think if the salt is then white in the end. Then you wouldn't see anything.
3. Experimental procedure design		
Info evaluation (group) a) Can we do it b) Does it make sense for our problem	Information is evaluated on a group level. The focus is either on the individual pointing out difficulties or other group members applying the criteria to the individual's idea.	a) Lena: I found a process in these patent things, but it was somehow not explained specifically. It just said yes there is a filtration step, then this step and that step and something like that and what is precipitated in the process. So I still had to find out how to do that. I think we can't do it as an experiment on the scale that was described there. b) Paula: But in the case of a detection reaction, something precipitates. You can simply filter it out and then you have it. Lisa: Yes, but I think it is usually the case that only a small amount of sodium reacts. Paula: Ok that doesn't work for us.

Code	**Description**	**Anchor example**
4. Experimental procedure execution		
Experimental info evaluation a) Did it work? b) What is left to improve for problem-solving?	The experimental procedure is tested and the results are evaluated applying practical criteria.	a) Paula: or how we can now check again whether that has worked, now for example with this borate.... Borate detection with the flame, which didn't work out so well. But we don't know such things in advance. And that is of course also interesting to see how you can adapt it in the whole process that you have in the laboratory. Yes, in any case, the experiments give you additional information. b) Sophia: I wanted to see if there is another experiment to get sodium chloride out. Because we had tried that last time by heating it first and then putting it in the refrigerator. So heating it to reduce the volume and then that precipitates when you cool it. But we got relatively little out of that and we didn't have the result from the XRD yet, didn't know if it was really a lot of sodium chloride that we got out. Therefore, I had to search for more information on that.
Information is experimental	Results from the experiment show if the information was useful or not.	Lena: Yes, well, we can't know that for sure, of course. But we notice when the experiment doesn't work, that something, either in our calculations or something else, must have been wrong. Max: So, for example, when we came out of the lab on Thursdays and it didn't work out, when we tried something new, everyone went looking for it a bit.That was definitely fun, to see ok now we had a really good sample and what we can do better and that you can also see that it's getting better.

7.4.4. SI Quality of Sources Coding Table

Table S2-3. Quality of sources coding table

Code	Definition	Example
1. Binary source understanding	Sources are categorized into reliable sources (scholarly sources) or unreliable sources (non-scholarly sources)	Paula: Well, with patents, you usually know that they are written by scientists who know what they are doing. This is a bit more difficult with Wikipedia, for example, or with the Internet in general. And it's the same with books, of course. So you know or you hope, of course, that the people who wrote this book have written sensible things.
2. Non-scholarly sources disadvantages		
a. Internet sources are unwanted by supervisors	Source decisions are influenced by anticipated supervisor preferences or aversions	Lena: But with Internet sources, you think about whether it's all going to be true and, of course, whether supervisors will approve or not. You're not supposed to use these sources.
b. Non-scholarly information is unhelpful	The information found in non-scholarly sources doesn't work in practice	Jana: For our first problem, we were supposed to detect, I think it was calcium, and on the page it said that you can detect it as sulfate. So if you have the calcium in the sample and just dump sulfate on it, so e.g. sulfuric acid, then something white should precipitate and that just didn't work for us and that's why I'm not sure if the source is so reliable because we checked it then or I checked it myself in the lab.
c. Non-scholarly sources can be a safety concern	When potentially dangerous experiments are planned, the sources should not be non-scholarly for safety reasons	Svenja: For possibly dangerous things, I would not use Wikipedia. I would rather use for example, a book from a publisher or something. So I think it always depends on what you want to look up.
d. Quality difference between non-scholarly sources	Additional criteria can be applied to non-scholarly internet pages to figure out their quality	Klaus: The question is always: How are the sources editable? Who has access to them? Things like: Who runs the site? I mean in Wikipedia everyone can change something. In other sites it's only the operators who can change it. Sometimes there are things like the website of Chemiebund-Deutschland, I think it's called something like that. I simply put a lot of trust in the fact that they write the truth and that the Chemikerbund Deutschlands operates it. They won't write any nonsense in there.

Code	Definition	Example
3. Non-scholarly sources advantages a. Comprehensibility of content/level of understanding	Forum entries can contain information from people in a similar position with similar beginner problems	Klaus: There are also many forum entries on many, many chemical things. Again, similar to Wikipedia, these are of course not one hundred percent trustworthy, but they are always quite good for rough ideas. Often people have had the same problems before, especially with basics, things like we are doing now.
4. Scholarly sources disadvantages a. Quality doesn't matter if I don't understand the information	Quality of sources doesn't matter if the content is not understandable	Paula: So sure, if the source is correct, but you can't understand it somehow because it's too complicated, then that doesn't help us. So of course it has to be appropriate. It has to be comprehensible.
5. Scholarly source advantages a. General notion of secure information	Working with scholarly source information generally appeared secure to students.	Jan: Patents are in any case a safer information than if search for it on Google. Patents are developed because people find something that might be even better, and prevent someone else from copying it because it works so well. That is why patents are secure and it was of course sensible to work with patents, and that's why we also worked with patents, simply because just the source of information was just much much safer.
b. Patent literature opens up possibility to acquire specific content necessary for problem-solving	The content to design the experimental procedure necessary for problem-solving was only available by patent literature	Lukas: Patent literature was necessary for problem-solving. Without patents we wouldn't have been able to do it that way, because it's just... you either really have a lot of specialist knowledge, because the process isn't described in such detail anywhere in the literature, of course, or you have to use patents.
6. Further strategies concerning source quality a. Info from "bad" source verfied in "good" source	Information stems from a source deemed qualitatively low by students and is verified by looking up the same information in a "good" source.	Klaus: I had to cite Wikipedia as a source because I have found nothing better. But later I got a tip on how to get a similar result using a different website. I have then been able to replace Wikipedia as the source because Wikipedia just.... It's not an incredibly bad source, but it's just not a hundred percent trustworthy source, just like forums, because everyone can effectively change what they want.
b. Success of an experiment confirms source credibility	If information from a certain source is repeatedly tried out in an experiment and yields positive results, the source gains credibility	Klaus: On chemie.de I have found so much, which is also confirmed several times and has already proven itself in the laboratory, that I used it very often and believe that it's correct.

7.5. Study 3

Reprinted with permission from Wellhöfer, L.; Machleid, M.; Lühken, A. "I don't know, ask the chemists -. I think it's kind of a consensus among them" – Information practice in a problem-based beginner lab. *Chemistry Teacher International.* 2023 (Accepted for publication).

Introduction

Research unveiling educational shortcomings of expository laboratory practicals has given way to the increasing implementation of nontraditional laboratory concepts (Di Fuccia, Witteck, Markic, & Eilks, 2012; Eilks & Byers, 2010) such as problem-based learning (PBL) (Raker, Dood, Srinivasan, & Murphy, 2021; Sandi-Urena, Cooper, Gatlin, & Bhattacharyya, 2011). PBL "empowers learners to conduct research, integrate theory and practice, and apply knowledge and skills to develop a viable solution to a defined problem" (Savery, 2006). In a chemistry PBL lab, students are responsible for designing the experimental procedure, and the experiment becomes a means for problem-solving (Eilks & Byers, 2010; McDonnell, O'Connor, & Seery, 2007). However, non-traditional lab formats, such as PBL labs, also present new challenges that are yet to be understood by research (Keen & Sevian, 2022).

In a beginner laboratory, students experience a new, complex learning environment (Seery, Agustian, & Zhang, 2019). Unfamiliarity with non-traditional lab concepts and the addition of implicit expectations can cause "a general state of confusion" (Chopra, O'Connor, Pancho, Chrzanowski, & Sandi-Urena, 2017). The learning scenario in the laboratory is "complex, collaborative, and context dependent" (Keen & Sevian, 2022) and is determined mainly by human interaction (Jobér, 2017). Thus, Keen and Sevian (2022) adopted a sociocultural framework to examine students' struggles in the undergraduate chemistry laboratory. The authors suggested characterizing the students' struggles in the laboratory into four domains – cognitive, psychomotor, epistemological and socioemotional - comprising a domains-of-struggle framework.

However, more research is needed to gain a better understanding of the beginner PBL laboratory as a complex learning environment. As students enter the lab, they learn to engage with textual, social, and physical information in specific ways that are sanctioned by experienced group members. It is worth noting that the physical experience in the laboratory is linked to learning beyond isolated "psychomotor" or "practical skills" (DeKorver & Towns, 2015; Flaherty, O'Dwyer, Mannix-McNamara, & Leahy, 2017; Hofstein, 2004; Keen & Sevian, 2022)Carnduff et al., 2003).

To complement the aforementioned findings on laboratory learning, this article analyzes students' experience of entering the laboratory as a new community of practice by examining it through an information literacy practice lens. By exploring their engagement with information, we can gain insights into how beginner students learn and how we can best support them. This approach addresses one of the "important questions" identified by Hofstein and Lunetta (1982) namely "What is the student really doing in the laboratory?" (Hofstein & Lunetta, 1982).

Information literacy in this work is defined after Lloyd (2010) "as a sociocultural practice that facilitates knowledge of information sources within an environment and an understanding of how these sources and the activities used to access them is constructed through discourse. Information literacy is constituted through the connections that exist between people, artifacts, texts and bodily experiences that enable individuals to develop both subjective and intersubjective positions" (Lloyd, 2010b). Figure 1 shows the information modalities relevant for information literacy based on a model by Lloyd (2007) that is adjusted to chemistry practice (Lloyd, 2007).

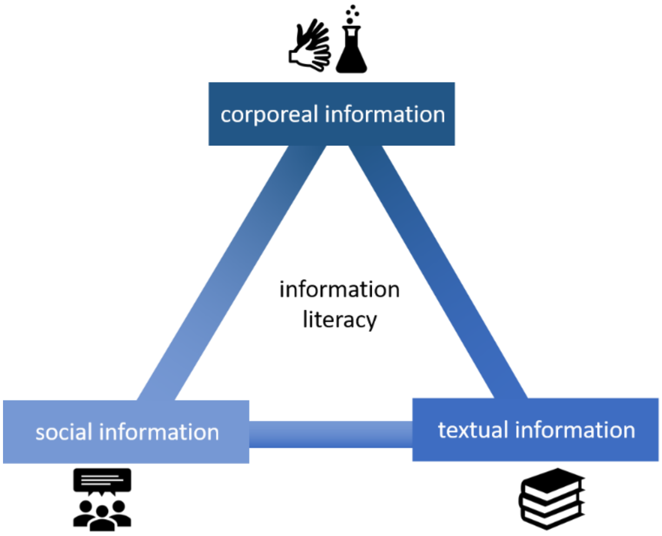

Figure 1. Information modalities relevant to chemistry practice based on the information literacy model from Lloyd (2007)

The particular ways of engaging with social, textual and corporeal information in a PBL beginner lab are examined in this work by adapting a documentary methodology (Bohnsack, 2010). The intent is to explore in detail students' experiences when they first enter the lab. To this end, the student and teaching assistant (TA) discourse of the first laboratory session serves as a discourse between a new member and an experienced practice member.

Information literacy as a social practice

Information literacy has been theoretically framed as a social practice for almost 30 years (Hjørland & Albrechtsen, 1995; Rath, 2022). How information is acquired, shared, valued and transmitted to newcomers depends on the particular community and its participants (e.g., nurses, librarians, firefighters) (Lloyd, 2021). Despite extensive discussion of these developments in the scholarly literature (Cox, 2012; Head, van Hoeck, Eschler, & Fullerton, 2013; Lloyd, 2010a; Ross Todd, 2017; Tuominen, Savolainen, & Talja, 2005), there is still a lack of understanding of how information literacy functions as a social practice in the context of chemistry education. However, exploring information literacy as a social practice could lead to a better understanding of laboratory learning.

Lloyd (2010) draws on Schatzki's site ontology (2002) to explain the theoretical framing of information literacy as information practice (Lloyd, 2010a). This framing views practice as the central feature of social life, where knowledge is situated locally and is the result of collective, embodied, and informed work within a specific space, such as a workplace, school, or chemistry laboratory (Ibid.). To make sense of information in a given context, one needs the experience of authentic practice (Lloyd, 2007). Therefore, Lloyd suggests that researchers should focus on the sociocultural affordances of practice as the unit of analysis for studying information literacy, rather than information skills. This is because these affordances lead to the development of information skills (Lloyd, 2010b), which is a widely acknowledged attribute in the literature (Association of College and Research Libraries, 2015; Hosier, 2019; Rath, 2022).

The framework of workplace-related information practice is particularly relevant to the chemistry laboratory, given the many similarities between laboratory practice and workplace practice: "In workplaces where there is an emphasis on practical and embodied understandings and more value placed on experiential knowledge and know-how, information literacy will reflect the informal nature of learning within site" (Lloyd, 2010a). Professional practice requires more than the application of theoretical knowledge, and involves "knowing-in-practice," which is characterized by developing knowledge collectively and in an ongoing way in response to specific situations (Price, Gherardi, & Manidis, 2020). The literature also emphasizes the importance of social sharing of information between experienced and novice practitioners, which provides a useful theoretical frame for this study's intent (Brown & Duguid, 1991; Wenger-Trayner, 2008). As beginners interact with community members, they decode the "sayings of practice" and eventually become equal members by establishing a shared understanding (Lloyd, 2010a).

Novice practitioners encounter both explicit and tacit knowledge in the chemistry laboratory. Explicit knowledge is expressed through codified rules, lab manuals, textbooks, and written and verbalized guidelines (Lloyd, 2010a). In contrast, tacit knowledge refers to knowledge that cannot be fully expressed by the subject, such as flexible processes of perceiving, evaluating, expecting, thinking, deciding, or acting (Porschen, 2008).

Kirschner (1992) argued that one central aim of laboratory practicals in education is to accumulate tacit knowledge through experiencing scientific phenomena. This involves obtaining an implicit, often indescribable, feeling for what is happening or what is supposed to happen, rather than explicit knowledge of how something works or why it works (Kirschner, 1992). Keen and Sevian (2022) also highlighted the importance of rules and routines in the laboratory, as they are how the community and participants implicitly and explicitly negotiate their beliefs about the structure, content, and process of learning chemistry " (Keen & Sevian, 2022) This work aims to explore how the experience of scientific phenomena and the experience of rules and routines contribute to the information practice of students in the laboratory. It highlights the importance of both explicit and tacit knowledge, as well as the embodied aspects of information practice, for effective learning.

The following research question guides the study:

- **How is information practice represented and developed in a problem-based beginner laboratory?**

Methods

In this study, the documentary method was the method of choice to explore the different characteristics of information practice in the chemistry beginner lab because it enables empirical access to group practice (Bohnsack, 2013). The documentary method is an approach of reconstructive social research that explores how social reality is constructed (Bohnsack, 1999) and is based on the epistemological and methodological foundation of Karl Mannheim's sociology of knowledge (Bohnsack, 2017). Mannheim provides a framework of conjunctive spaces of experience that are characterized by their members sharing common structures of experience and knowledge (Mannheim, 2003). Conjunctive spaces of experience describe how people are connected by common existential backgrounds, i.e., that they understand each other directly due to a common background, and can, thus, articulate themselves as if they were attuned to each other (Bohnsack, Nentwig-Gesemann, & Nohl, 2013). The conjunctive nature of language in specific experiential spaces constructs a shared understanding of meaning and a way of handling things that is specific to the group (Mannheim, 2003).

The social science interpreters, in the sense of Karl Mannheim's sociology of knowledge, do not assume that they know more than the study subjects, but rather the latter, themselves, do not know what they actually know, and, thus, have implicit knowledge that is not readily accessible to them (Bohnsack, Nentwig-Gesemann, & Nohl, 2013). This implicit knowledge emerges in conjunctive experiential spaces and is documented in the "how" of social actions and discourse (Ibid.). It is the task of the researcher to explicate this implicit knowledge to understand practice: "It is the change from the question *what* social reality is in the perspective of the actors, to the question *how* this reality is produced or accomplished in these actors' everyday practice. By practice, I mean the practice of action as well as of talk, of presentation and of argumentation" (Bohnsack, 2010).

By asking *how* the practice is constructed yields the reconstruction of the organizational principles of the conjunctive spaces of experience (orientations) that are the implicit action-guiding nature. The distinct steps of data analysis in the documentary method will be further elaborated in the section "Data collection and analysis."

Usually, the documentary method uses group discussions for data collection. However, the aim is to keep the discourse situation as authentic as possible (Meyer & Verl, 2019). In this study, the information practice in the laboratory was of interest, therefore, there was no need to create an artificial interview setting. Instead, the first lab session of two groups of students was recorded on-site. The approach is described in the following section.

Setting and participants

This study was conducted in a problem-based learning lab at Goethe-University Frankfurt, Germany. Due to the focus of the study is the information practice of beginners, we chose the first lab session of two groups of non-major chemistry students for data collection.

The students participated in the problem-based lab course in line with a general inorganic chemistry module for non-majors. The participants' names were substituted with pseudonyms to protect confidentiality. All the students majored in earth sciences, between 19-22 years old, and had a mandatory general inorganic chemistry module in their bachelor studies. They worked together in groups on the problems posed in the PBL laboratory concept for four weeks in August 2020, with lab sessions once every week for approximately 5 hours. The division of the groups was left to the students. In total, 12 students participated in the laboratory course, resulting in three different groups. The two groups selected for this study were chosen because they were not taught by one of the authors. The third group, however, was instructed by one of the authors and it was therefore excluded from the analysis. The two groups consisting of seven students and their teaching assistants gave informed consent to have their first lab session audio recorded. Table 1 gives an overview of the participants.

Table 1. Overview of participants

	Group A		Group B
1	Johannes		Florian
2	Jakob		Frederik
3	Arne		Marie
4			Philipp
TA	Jana + Ben		Carina + Ben

In group A, Johannes and Arne were in the second semester when attending the lab course, while Jakob was in the sixth semester. All the students that participated in group B were in the second semester. This was the first chemistry lab practical for all students. The teaching assistant, Jana, had studied chemistry to become a teacher and had already completed her first state exam. The second teaching assistant, Carina, was a postgraduate chemistry major thus, both Jana and Carina had extensive laboratory experience, however, they did not have any previous laboratory teaching experience as TAs. Ben was an additional supervisor working for the institute who alternated between both groups and who had long-standing teaching experience in supervising different laboratory practicals.

On the one hand, the undergraduate students were all newcomers to the chemistry lab, while, on the other hand, according to their education and experience, Jana, Carina and Ben were considered experienced members of the chemistry community. Therefore, the sampling was deemed suitable for the current study in further comprehending the representation and development of an information practice as well as the role of tacit knowledge in the chemistry lab.

Lab activity

The lab activity focused on industrial lithium extraction from brine, providing an authentic problem for introductory chemistry students to address basic chemical concepts and laboratory techniques. The experiments involved classic detection reactions and current analytical methods, and students are instructed as if they were employees of an industrial company. Details about the problem-based laboratory concept, the problem design and implementation have already been published (Wellhöfer & Lühken, 2022b). The problems are small-step extensions of known material.

The study was set up around the first problem: "Analysis of an unknown salt mixture". For the first problem, the students analyze an unknown salt mixture and determine which ions their sample included. The problem concerned a qualitative sample analysis that included a possible limited number of ions. It was designed as an introduction to the problem-based concept and is, thus, suitable for the current study in understanding the students' first-time practical experiences in the laboratory.

Data collection and analysis

The data for this study stems from the audio recordings of the first lab session of groups A and B. Both lab sessions yielded around 4 hours of group discourse and were transcribed verbatim. Initially, following the documentary method, the transcribed dialogs were thematically structured according to their relevance to the research question (Bohnsack, Nentwig-Gesemann, & Nohl, 2013). Subsequently, sections relevant to the information practice were identified.

Selected for the interpretation were certain text sections that had a particular narrative or interactive density (Bohnsack, Nentwig-Gesemann, & Nohl, 2013). These sections were identified by looking for linguistic patterns, such as the group's interaction patterns, including the frequency of two-person exchanges, simultaneous speaking, and extended periods of silence. Additionally, sections were selected with a notably high number of questions asked. It can be assumed that these sections contained important aspects related to the participants own experiences as well their information practice (Kleemann, Krähnke, & Matuschek, 2009). Based on these criteria, linguistically significant passages were identified and analyzed, seeking out thematically similar passages for comparison. The analysis was started with Group A's transcript, identifying themes related to acidification, disposal, and safety, and then comparable themes in Group B's transcript were identified. As this interactive density was predominantly found in the transcript of group A, this group yielded more passages which were selected for interpretation.

The interpretation of the identified sections involves two steps: formulating interpretation and reflective interpretation. The formulating interpretation is concerned with the immanent, literal meaning, which asks the question, "what?" It considers the literal content of what the study's subjects expressed and is rephrased by the researcher. In the second step, the researcher provides reflective interpretations about the implicit knowledge of the study's participants (Nohl, 2005). This marks the switch from "what" to "how." In this study, the reflective interpretation was used to uncover the conjunctive knowledge of the group. It consisted of interpreting how the study participants dealt with situations and problems around the topics of acidification, safety, and disposal. The specific way of dealing with a problem is made visible by contrasting how, in other situations or groups, the course is set differently in the treatment of a comparable topic (Bohnsack, 2013). Orientation patterns are carved out by comparative analysis through different cases inside thematically similar topics (Ibid.). Tables that include the selected passages, formulating interpretation, and reflective interpretation for the named topics can be found in the supporting information Table S1: Safety, Table S2: Disposal, Table S3: Acidification.

The authors first worked individually on the formulating interpretation and the reflective interpretation. Afterward, they gathered for several debriefing sessions to discuss the resulting tables and develop a shared analysis. The debriefing sessions and the collaborative work add credibility and dependability to the analysis (Hadi & José Closs, 2016; Shenton, 2004).

Results and discussion

This study examines the information practice in a chemistry beginner laboratory using the documentary method; this provides “access to the structure of action and orientation.” (Bohnsack, 2010) The representation of the information practice in the case of explicit information is depicted in the next sections, using the topics of safety and disposal. The role of tacit and corporeal information is illustrated in the subsequent section using the topic of acidification.

Drawing on the topics of safety, disposal and acidification, key aspects of the representation and development of the information literacy practice were analyzed. All these topics have a common feature namely, that they exemplify group-specific knowledge (Kleemann et al., 2009). The themes are discussed using anchor examples presented according to the original chronological course of the conversation. All selected passages incorporated into the analysis are presented in the supporting information as tables, including the formulating and reflective interpretations (see Table S1: Safety, Table S2: Disposal, Table S3: Acidification).

The results show that the students need action-guiding social information from an experienced member in addition to textual information. Similar results were reported by Keen and Sevian (2022) who stated a common example in their study in which "students could not move forward without information from the TA or without the TA checking their work" (Keen & Sevian, 2022).

Practice requires the students to develop situational agency in different scenarios, it requires of them to" know-in-practice" (Reich, Hager, Tara Fenwick, & John Field, 2014). In order to develop "knowing-in-practice" concerning safety and disposal, students need to physically experience different lived scenarios. We illustrated the critical results in a model of the students' information practice in the PBL beginner laboratory (Figure 2). The model displays the main results of this study and does not aim at representing the total of students' information practices, which would be too complex to be displayed in a procedural model. However, the model is helpful to support understanding of the main results of this study and the importance of social and physical information for chemistry laboratory learning. All the data that were used to develop this model are available in Table S1 and Table S2. The following section gives a brief description of the model with examples from the data. It will be further elaborated, in detail, in the upcoming sections.

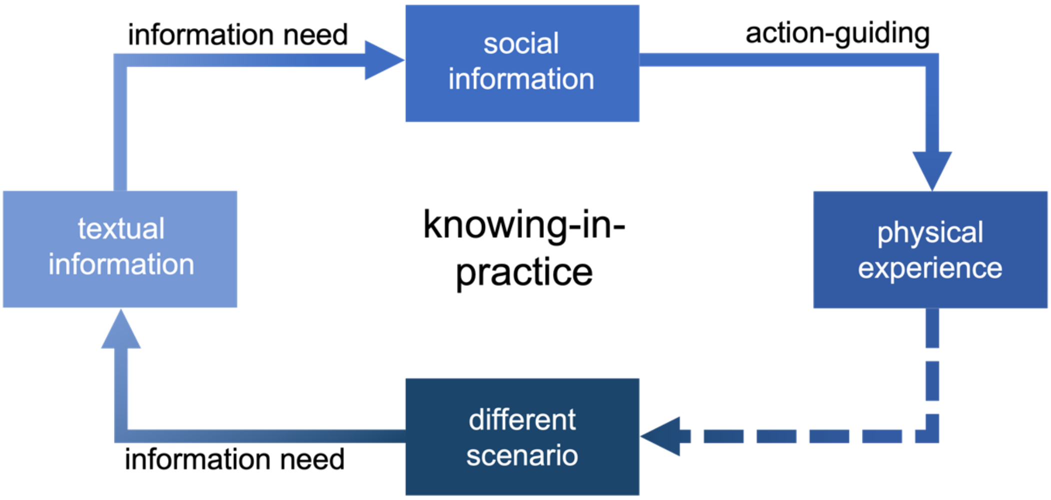

Figure 2. Illustration of the students' information practice in a problem-based beginner lab.

The model begins with a scenario in a problem-based beginner laboratory that triggers an information need (as indicated in the "different scenario" box at the bottom). In this study, when students encountered a scenario related to disposal or safety, the laboratory guidelines and teaching assistants expected them to have prior knowledge of the procedures. To meet this requirement, students initially researched the necessary information in textual sources to design their experimental procedures prior to the laboratory sessions. In the following case where a disposal strategy was missing, Jakob conducted further research in textual sources to address the information need:

> Jakob: “And the titan yellow and the Magneson I have to take a quick look at now.”

This starting point, where the students need to research textual information for their problems, is due to the problem-based learning approach. Since they do not receive an experimental procedure, they have to look it up, initially by using textual resources (Wellhöfer & Lühken, 2022a).

In practice, the textual information was frequently not sufficient. In the following example in a conversation between Jakob and Jana, the information need is not met in the textual information:

> Jakob: “That's strange.”
> Johannes: “What's strange?”
> Jakob: “It says here: Notes on disposal. Under waste treatment methods it says no further information available. Does that mean it's not dangerous or-?”
> Jana: “At Magneson or what?”
> Jakob: “Yes.”
> Jana: “That no further-.”
> Jakob: “It just says that there is no information.”
> Jana: “Then you can put it down the drain.”

Jakob cannot find textual information for his attempt to dispose of his sample. An information need arises that is met by Jana who provides action-guiding social information (Jana: “Then you can put it down the drain.”)

The next example shows again how the lived scenarios can be so versatile, that in practice, an information need arises that requires social information. Johannes explains to Jana the amount of barium contained in his sample. Jana explains to him that he does not have to dispose of this sample separately in the heavy metal waste container:

> Johannes: “That's six drops of barium and that was 0.5 mol per liter.”
> Jana: “Then you don't have to pour it in there (note: the heavy metal waste) again.”

Despite the clear disposal guidelines for heavy metals, Jana instructs Johannes to not dispose of the solution as heavy metal waste. This example shows how Jana, as a source of action-guiding, social information, is needed to decide how, exactly, one must dispose of the waste in each situation.

This social guidance was also necessary for reassurance in the next example. Arne expresses that he cannot dispose of barium hydroxide solution down the drain because barium has to be disposed of separately. Jana confirms Arne's assessment of the situation:

> Arne: "If now for example, - if I now have barium hydroxide solution, I can't dilute it with this acid and then tip it down the drain. That doesn't work because barium is a heavy metal."
> Jana: "With barium, exactly, that doesn't fit. That's right."

After receiving the action-guiding social information, the students act; in this case, they dispose of the waste (physical experience). Following the physical experience, a new scenario occurs. By repeating this cycle, according to the model, the students will continue to develop their ability to make decisions on their own, they develop "knowing-in-practice" (Reich et al., 2014). The dotted line in the model in Figure 2 indicates that it is an ongoing process for the students to develop knowing-in-practice. The following sections clarify the model further, specifically underlining how the information practice materializes through the action structure.

“So is it OK to tip it away after neutralization or what?” – Reconstructing the materialization of information practice

The following section will draw on the topic of disposal to reconstruct how the information practice materializes. Practice is dependent on the situation and is required to adapt previously acquired knowledge to a variety of situations that are not anticipated by the students in advance through theoretical preparation. In the following example, Johannes asks about specific ways to dispose of pH paper.

> Johannes: “These pH samples, do you have to dispose of them in a certain way?”
> Jana: “Do you mean the acid solutions or what?”
> Johannes: “No, I mean the paper samples.”
> Jana: “The snippets?”
> Johannes: “Yes.”
> Jana: “You can-, you can do that in a way that you-. Do you have paper towels with you, or?”
> Jakob: “There's toilet paper up there.”
> Jana: “Okay. Then you just take toilet paper like that, lay it out and then you can always let the pH strips dry. Okay. And then when they're dry, you can just throw them in the solid waste trash can and that's it.”

Johannes asks if there is a "certain way" to dispose of the pH paper scraps. He does not formulate an idea of how to dispose of the pH paper scraps and asks directly. Nevertheless, his formulation shows that he has already learned that there are certain ways of disposal, certain "doings of practice" (Lloyd, 2010a). While the students have prepared for the disposal of chemical and material waste, the procedure in practice, which Jana demonstrates to them by letting the pH strips dry "like that" on the toilet paper, is not something that they have prepared for theoretically. Jana provides instructions on how to dispose of the paper snippets without explaining why it is necessary to dry them and dispose of them in solid waste. This example again highlights the need for social information in practice. When learning in practice, there are situations in which the TA guides procedures that the students in the theoretical preparation would not have anticipated. Becoming an equal member and making self-sufficient decisions in the laboratory means learning the ways of practice that the other members of the practice legitimize.

This situation of pH sample disposal is exemplary for disposal practice in chemistry because, although one would like to think so, it is not always possible to deduce from theory how to handle disposal in practice situationally. Instead, disposal situations are handled by responding to the situation at hand and considering guiding principles, depending on the subject's own socialization into the community of practice.

The following scenario further exemplifies the disposal in practice when Johannes asks Jana how he should dispose of the remains of silver nitrate in his pipette:

> Johannes: “So I have a pipette here with silver nitrate.”
> Jana: “The other way around.”
> Johannes: “I see. Yes, I have ... I assume that has to be disposed of in heavy metal, right?”
> Jana: “Silver nitrate. Do you have anything else in there or what?”
> Johannes: “There is no more liquid in it. But there are remnants of silver.”
> Jana: “Just rinse it out. That's-, well, it's minimal only. You can rinse it once, there is no liquid left.”

Johannes has a suggestion for making a situational decision based on his theoretical knowledge of heavy metal disposal. He assesses the situation but still needs validation by an experienced member of the practice community. Jana tells Johannes how to “just rinse it out” and explains why ("there is no more liquid"). Johannes does not question her suggestion.

Keen (2022) describes a similar situation in which the students experience epistemological struggles “when the lab procedure asked students to go against a lab norm,” e.g., throwing waste into the sink instead of in the chemical waste garbage can (Keen & Sevian, 2022). Again, this is an example of the student’s socialization into practice; they learn to handle these situations through social guidance and physically lived experiences.

In the further course of the session, the students proceed to discuss among themselves how they should proceed with the disposal:

> Johannes: “Where do you keep the heavy metal stuff?”
> Arne: “Here, with me.”
> Johannes: “Should I throw it in there? Yes, right.”
> Arne: “What if something emerges. *laughs* It will end up exploding, who knows.”

At this point, the students know about the disposal procedure in theory and from previous situations in the lab and linked conversations. During the lab session, Johannes's knowledge about his waste belonging to heavy metal waste becomes repeatedly evident (see Table S2: Disposal). Nevertheless, he now looks to Arne for action-guiding social information who answers, "It will end up exploding, who knows," meaning he does not actually know. Despite the remaining uncertainty, the students can act without their supervisor and dispose of their waste. Keen and Sevian (2022) described socioemotional struggles in their study of students' struggles in a beginner lab and found that “often times, students moved forward as long as their emotional struggle was acknowledged” (Keen & Sevian, 2022). In our example, the social interaction was needed for reassurance and sharing the responsibility of making a decision. Even though the students did not ask the TA, they did ask each other. Thus, the students gain experience through action and negotiation, and eventually learn to make situational decisions independently.

These examples reveal different manifestations of the development of the students' information practice. They develop from, initially, asking the supervisor directly without actionable suggestions to then asking for feedback on suggestions and to group discussions between peers resulting in action.

The results exemplify how information practice is represented and developed in a chemistry beginner laboratory and the different characteristics it can exhibit in experienced community members and complete novices who are entering a new community of practice. The following section will discuss the structure of action in a beginner lab with regard to the group-specific importance of general guidelines in the case of safety measures, looking at the instruction in more depth.

"Always go into the fume hood with sulfuric acid."- Situational decisions and general guidelines for safety

The following section discusses the application of general guidelines to information practice exemplified by safety measures. The situational application of general guidelines can provide indications of the group-specific socialization in the laboratory environment. The cases of situational hazard assessments referring to guiding principles illustrate how information practice is both subjective and intersubjective (Lloyd, 2007). In the following example, Jakob and Jana discuss whether Jakob should use one drop of one molar sulfuric acid in the fume hood.

> Jakob: "With 1 mole per liter sulfuric acid, I don't have to go into fume hood, right? *laughs* Or even then?"
> Jana: "Now, if you take a drop of-."
> Jakob: "One drop ..."
> Jana: "You could maybe take a fume hood once or something."
> Jakob: "Okay. That is, put the thing in the fume hood, then?"
> Jana: "If something tips over there by accident, then you have the fume hood, then you're safe. With sulfuric acid always go into the fume hood."
> Jakob: "Okay. Good."
> Jana: "Just take that over here in fume hood."

Jakob finds the idea of going into the fume hood with one molar sulfuric acid amusing and absurd, therefore, he laughs and asks the question in a manner that shows he expected a "no" as an answer. However, even though Jakob feels competent to propose this situational assessment for the practice, he does not act independently. Here, Jakob's participation in the practice community is documented; he applies and adapts his theoretical knowledge to practice, which, however, still needs corroboration (social guidance). Nevertheless, his formulation clarifies that he has assessed the application of safety measurements and is not "just" asking (Jakob: "With 1 mole per liter sulfuric acid, I don't have to go into fume hood, right?"*)*. In theory, Johannes knows to use the fume hood when working with sulfuric acid, but his knowledge becomes meaningful only when he learns to adapt it to practice, where one nuanced situation always differs from another (Elmborg, 2006; Reich et al., 2014). He needs social information, that is action-guiding from Jana.

Jana cautiously disagrees, suggesting that Jakob "could maybe take the fume hood or something." Even though Jakob does not question the proposal, Jana explains: "If something tips over. Always go into the fume hood with sulfuric acid." She refers to a guiding principle she knows to support her instruction. The initially cautious suggestion to go into the fume hood becomes a general statement. Jana's formulation, "With sulfuric acid, always go into the fume hood," suggests that she bases her instruction on a guiding principle that she, herself, learnt in practice. Jana's guiding principle of to always use sulfuric acid in the fume hood is explained by her because the acid could tip over; the fact that other acids could also tip over and cause severe damage is not of consideration at this point. The guiding principle from Jana stands in contrast to Jakob's initial situational hazard evaluation and idea for action. Jakob accepts the suggestion without questioning it.

Safety is of crucial importance in a chemistry laboratory. The use of guiding principles in a variety of situations highlights different characteristics of chemistry information practice. Considering safety, the supervisor might act out of their responsibility according to the motto "safety first" and refers to higher-order rules that they learnt in practice. The supervisor applies general conventions which correspond to a higher safety standard.

In the following example, the supervisor intervenes and advises Arne against using gloves. They contradict the student's theoretical preparation and their subsequent safety concept.

> Jana: "Why do you need gloves for this?"
> Arne: "Because of barium hydroxide solution?"
> Jana: "Well…"
> Arne: "No, fuck it, I don't care. I was just-."
> Jana: "You have to-, I wanted to ask again anyway, why, for what you need gloves, in general, when you-."
> Arne: "For acids in any case?"
> Jana: "If you take the instructions very seriously. But a little bit of acid, in such a small amount, should also-. Just work concentrated. On your bases anyway, that you don't spill anything, okay? If something should get on your hand, rinse off directly. And with sulfuric acid generally in the fume hood....It's very - okay."

The conversation shows how Arne interprets Jana's question and her answer "Well..." as a rejection of the gloves he uses. His response to her rejection of the gloves, "No, fuck it, I don't care," depicts how keen he is to follow Jana's suggestions, again, without an explanation. Jana's instruction is a general rejection of gloves in this laboratory context. This is evident from the way she phrases the question, "What do you need gloves for in general," and her subsequent comment, "Just work concentrated (…) If something should get on your hand, rinse off directly." She is not just referring to this situation, but to a guiding principle about when or when not to use gloves. Although the dialog is only between her and Arne, she uses the German plural "you" and addresses all the students which emphasizes the generality of her statement. A similar situation occurred in the other lab where Ben also advised students not to use gloves (see Table S1: Safety). However, Ben explained that his suggestion was for safety reasons; the students might accidentally touch their faces or other vessels with dirty gloves. Jana makes no such explanation. An explanation was not a requirement for the students to accept these guiding principles.

Differences in the instruction by the TAs and subsequent differences in the meaningful use of learning situations have been reported in the literature (Huffmyer & Lemus, 2019; O'Neal, Wright, Ewing Cook, Perorazio, & Purkiss, 2007). In this study, the difference in instruction by TAs was particularly evident in relation to "the sayings and doings of practice" (Lloyd, 2010a), and how they were sometimes passed on without explanation and unquestioned. The findings suggest that this may be related to the information practice in the laboratory. The way students accept all social information from the TA, with or without explanation, could indicate the socialization in this setting. Some of these students will become TAs, thus, the present TAs were once students. The sharing of these guiding principles could indicate how Jana herself learned about them when she was a newcomer in the laboratory practice.

In the case of both Ben and Jana, the students accepted their suggestion not to use gloves without question. The use of general guidelines contributes to the socialization of students in this community of practice and provides a specific framework. This framework allows situations and action decisions to be clustered (no gloves, always go into the fume hood with sulfuric acid). The unquestioned transmission of rules of conduct illustrates the socialization of members into the community of practice, their transmission, and the likely transmission by students in the future.

In the following section, the need for physical experience and the role of tacit information are considered in more detail.

"Acidified is usually,- a few drops are enough" – tacit knowledge and corporeal information exemplified by acidification

The topic "What does acidification actually mean?" runs through the lab session in this study. Based on the discourse around acidification, core aspects of information practice can be highlighted, described as "getting a feel for phenomena" (Kirschner, 1992). The examples around the topic of acidification show how tacit and nuanced aspects of information practice need physical experience (corporeal information) and social guidance for a practical understanding. While physical or psychomotor struggles are included in lab activity research, they are often depicted in isolation, e.g., relating to issues with tools or non-functioning equipment (DeKorver & Towns, 2015; Keen & Sevian, 2022). What is missing in the research literature is the connection between the corporeal information modality and other information modalities that contribute to learning; this is important because the corporeal information modality is a necessity for practical understanding.

The results are illustrated in a model, Figure 3, which describes the students' development of tacit knowledge, referring to the concept of acidification for practice. Again, this model is not a representation of the complex information practice in this laboratory but a tool to display the central results concerning tacit information needs in this study.

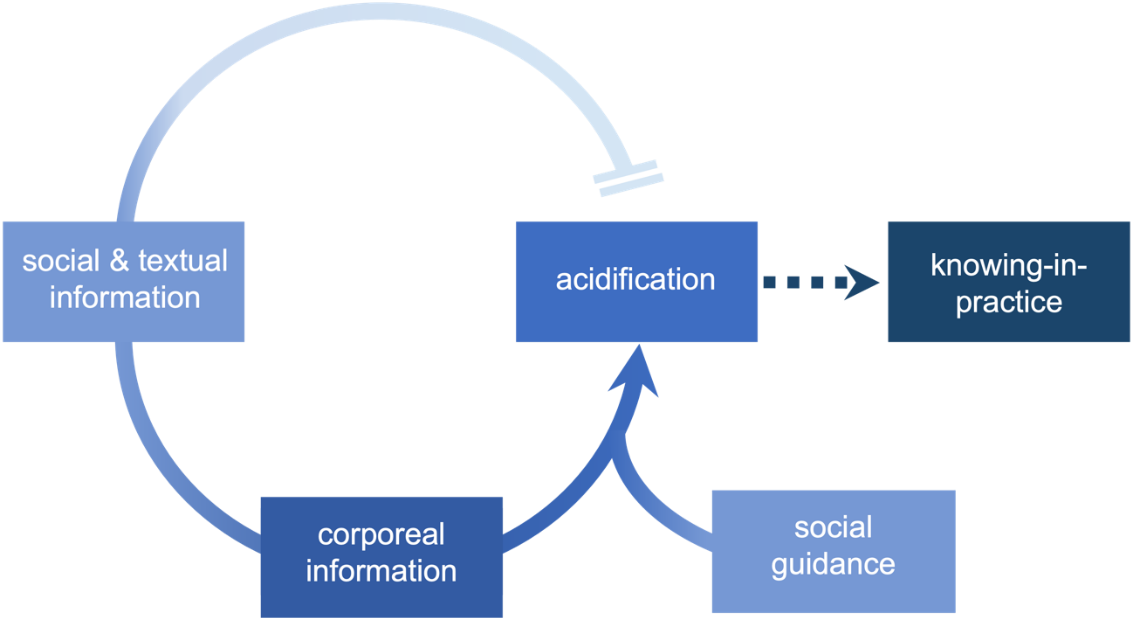

Figure 3. Illustration of students' information practice in the case of tacit information needs, exemplified by acidification.

In this study, both textual and social information modalities alone did not lead to a practical understanding of the group-specific concept of acidification for novices. The students needed the physical experience (corporeal information) in different scenarios, classified through social instruction by an experienced member of the community of practice to give practical meaning to the concept of acidification, the "interweaving of cognitive and physical sources" that gives meaning to the knowledge (Lloyd, 2010a). The dotted lines in the model depict the necessity to repeat this process in different scenarios for the students to develop knowing-in-practice. The following section depicts how the model was derived from the data and discusses the results.

In the following example, students Johannes and Jakob begin by discussing the practical meaning of acidification:

> Johannes: "Now the question, what does acidifying mean? So how much should I add to it?"
> Jakob: "That's why I just wrote acidify and not somehow a specification because I have no idea. Ask the chemists somehow-. I think that's such a consensus among them that they all know what that means. And everybody else doesn't know. And that's why they always write acidified or acidifying."
> Johannes: "Yes, then I have to ask because I don't know either."
> Jakob: "Yes, I don't know either. Otherwise just measure the pH and add a little bit."

Jakob reflects that there is group-specific knowledge ("consensus") in the circle of "chemists" to which he has no access because he does not belong to it. He tells Johannes that if one belongs to that circle, then one knows it, and that there is no need to manifest that knowledge explicitly. During his research for the experimental procedure, he was not able to find anything explicit in writing on the subject of acidification. The textual information he found was not sufficient for him to make sense of the topic in practice.

Johannes does not know either about this topic, however, he shows no uncertainty about who he might ask. He has access to "chemists", i.e., access to the circle of those in the know (Johannes: "Yes, then I have to ask because I don't know either."). Jakob also suggests a further possibility for action, how information can be obtained alternatively - without asking anyone - or how they could act without additional information ("Otherwise just measure the pH and add a little bit."). This example documents the students' information need in the form of a social resource when textual information is insufficient.

In the following situation, Jakob asks Jana, the supervisor, about the procedure of acidification:

> Jana: “Well, in the lab practical it is very important that you simply try out a bit. There is no right or wrong here. Sure, you have your literature, you are well read, but-.”
> Jakob: “Yes, but we are still a bit helpless, I think. What I've heard, in the literature, much is kind of already assumed. Basic things for chemists, for example: Acidify the solution. How much acid goes into it until it is acidified?”
> Jana: “Acidified is usually-, a few drops are enough. Then you look with the pH paper.”
> Jakob: “Diluted by what, how much? Sometimes it says 2 moles, sometimes it says 5 moles. Then it says it in percent.”
> Jana: “You usually take a hydrochloric acid, a diluted one. You add a few drops, check whether it's acidic or not, with the pH paper, and then it's usually ok. Otherwise, it will say strongly acidic or something like that.”

Learning the ways of a community of practice takes place when people participate: "They learn not only about the actual performance of practice (e.g., the doing of practice), but they also engage with nuanced and tacit information (e.g., the saying of practice)" (Lloyd, 2010b). This excerpt shows how the newcomers to the practice question the "sayings of the practice." Jakob is frustrated by the unclear textual instructions and changing formulations. New members with a fresh look can challenge circumstances that the long-time community members take for granted. This example illustrates the difficult process of the students' experience with understanding "the saying of practice" and translating it into action.

The supervisor encourages the students to use "trial and error" methods independently of textual information. Nevertheless, they experience a need for information that they feel is fundamental to be able to act and, thus, they demand the information that is missing from the supervisor. They need access to the missing information through an experienced member of the chemistry laboratory practice who is privy to this kind of tacit knowledge, in this case, Jana. However, Jakob has previously suggested a possible course of action ("just add a little and measure the pH") which is also offered repeatedly by the supervisor during the discourse ("Acidified is usually also-, a few drops are enough. Then you look with the pH paper"). Although Jakob has verbalized the same information as Jana, content-wise, he cannot act without further input, i.e., he cannot start experimenting in order to try something out. Although Jakob does not lack theoretical knowledge, he is still unable to take action.

Even though the content of the verbalized information on acidification is similar between the students and Jana, they have different practical experiences to give meaning to the information. The difference with these "basic things" is documented in the binary meaning of the word "basic": The term "basic" carries the connotation of being both fundamental and necessary for taking action, as well as the connotation of being primary or easy. For the students, on the one hand, the basics are fundamental prerequisites for action which is why Jakob reacts to the suggestion for trial and error with "We are helpless." They are at the beginning of their socialization in this community of practice. On the other hand, the supervisor's basics are self-evident and straightforward, however, she cannot elaborate on her instruction rooted in tacit knowledge. This can be seen in the example when Jana attempts to explain acidification: Jana: "Acidified is usually-, a few drops are enough." She cannot explicitly state what the concept of acidification is. Jakob responds with another request for her to clarify what acidification means, to make it explicit: Jakob: "Diluted by what, how much?" Jana, again, cannot clarify what acidification means, she can only explain how it "usually" goes and delimits acidified from "strongly acidic or something like that."

During the lab practical the supervisor draws on memories of situations she has experienced that she cannot express clearly and looks for procedures to verbalize to the students. These procedures are, for example, expressed by Jana when she attempts to explain acidification. She does not give a clear, explicit answer but she thinks about how “it is usually done.” We interpret this as her drawing on her memory and how she “usually” experienced acidification. This can also be seen by her stating, “You usually take a hydrochloric acid, a diluted one. You add a few drops (…),” which clearly depends on the situation, but in her memory, this is how it usually happened. To explain a practical endeavor, she draws on her experience in practice.

The notion that Jana’s understanding of acidification is rooted in tacit knowledge becomes clearer when she provides a definition of what acidification means in the next example, and then repeatedly contradicts it in the latter course of action. Johannes asks her what “acidify” practically means:

> Johannes: “Yes, I have another question.”
> Jana: “Yes, sure.”
> Johannes: “It says acidify. So I understand that I add an acid. But the question is how much. Because I can't estimate that now.”
> Jana: “Yes. Acidifying means that it should be in the acidic range, yes. pH value below seven. And then you just add a few drops and then you can check with the pH paper whether it is acidic or not and test it first.”

Jana clarifies that acidifying means “pH value below seven.” The next examples will show that this, however, is not what she considers acidified in practice. During the discourse around the acidification of a solution, Jana suggested that Jakob should test the pH value of his sample first because it might already be acidic and not need further acidification, which he did. He negotiates the results with her in the following example:

> Jakob: “That is, I have about six to five now. So it's acidified.”
> Jana: “Exactly. I would still- a little bit because that's really-, so that's not so clear. That's...even a little bit more-, yeah, it's still very neutral. I would add a little bit more.”

Although the case that Jana proposed has occurred, she previously defined acidified - the solution is already in the acidic range - she is now dissatisfied with her previous definition of acidified. In her practical understanding, it is not acidified, "it's still very neutral." Jana has no explicit explanation for what acidified means, she just has a “feel” for the phenomenon (Kirschner, 1992). Ultimately, the students learn to acidify by experience and exclusion criteria, namely by practical examples classified by Jana as acidified or not acidified. The students attempt to acidify their samples by taking physical action and Jana classifies the experiences for the students.

This can also be seen when the contrary example occurs. The sample was supposed to be acidified but is now classified by Jana as "strongly acidic," which Jana points out to the students could be a disturbing factor for the test.

> Jana: "Okay. Is there anything in it maybe? Because it is in the strongly acidic range."
> Jakob: "What does strongly acidic mean?"
> Jana: "Well, it said acidify."
> Johannes: "Yes, I have-, pH value one I have."

When Jakob asks, "What does strongly acidic mean?" Jana answers with "Well, it said acidify," thus avoiding the question that requires an explicit answer. Again, the students learn about acidification by experience (corporeal information) that is classified by Jana (social guidance). She contradicts her former definition of "Acidifying means that it should be in the acidic range, yes. pH value below seven." What counts as acidified and what does not in practice clearly diverges from her theoretical explanation. There is "strongly acidic" and there is "too neutral," both of which occur in the range of pH <7. Jana has passed her tacit knowledge on by categorizing the students' experiences. The students try "to acidify" and only then can she give them an estimation if they succeeded or not. To Jana, acidification is self-evident and intuitive. What is necessary for the students to learn about acidification is the physical experience of doing it, combined with the classification and guidance by Jana as an experienced member of the community of practice; the "entwining of cognitive and corporeal sources" that gives meaning to knowledge (Lloyd, 2010b).

These examples document how both the textual and social information modalities alone do not lead to a practical understanding of the group-specific concept of acidification for the beginner chemists (Ibid.). The students need the physical experience (corporeal information) classified through social guidance to give practical meaning to the concept of acidification. A common reference frame develops in a specific group through people engaging in practice together. Newcomers to a community of practice learn the sayings and doings of the practice and eventually become information-literate members who can act independently and decide situationally (Ibid.).

The acquired information, the sayings of practice, can have tacit aspects, as in the case of acidification, or clear and explicit aspects, as in the cases of disposal and safety. Both incidents require the physical experience of practice for the students to develop situational agency. However, in the case of acidification, the students need Jana to classify their findings in order to understand the concept of acidification for practice. In both cases, the students require experiencing multiple situations, which eventually leads to the shared conceptions between people belonging to the chemistry community of practice.

The following section will discuss ways to implement these insights into information practice for information literacy instruction.

Implications for teaching

Reconstructing aspects of the information practice in a beginner laboratory provides insights into students entering the laboratory practice as newcomers and the TAs guiding the students as experienced members. The results of this study have shed light on group-specific explicit and tacit aspects of chemistry laboratory practice and can be helpful for laboratory teaching and learning.

The results show that the TA plays a vital role in the students' learning experience in the laboratory, which aligns with findings from the literature (Good, Colthorpe, Zimbardi, & Kafer, 2015; Huffmyer & Lemus, 2019). The students unquestioningly accepted the social guidance provided by the TAs in this study. However, the results also show that many of the "doings of practice" instructed by the TAs sometimes lacked explanations altogether, or the reasoning was incomprehensible, for example, Jana advised the students against using gloves, explaining that "a little bit of acid" would not be too bad. A lack of an reasonable explanation can be problematic because the students might need help understanding why the procedures and doings in the laboratory are performed in a certain way. The students' need for appropriate explanations concerning standard procedures is in line with existing literature on what students deemed one of the most important types of knowledge that TAs need: ”knowledge specific to the laboratory experiment (procedures, techniques, and safety concerns.)” (Herrington & Nakhleh, 2003) However, a prerequisite for TAs to provide explanations is an awareness of these group-specific aspects of practice that, in this study, frequently appear self-evident to the actors. Clarifying the sayings and doings of practice in the beginner laboratory can be helpful for TAs to reflect on their practice and how they pass it on.

Even though the TAs in this study were experienced in the laboratory, they did not have previous laboratory teaching experience. New TAs are often eager to be perceived as capable of answering questions. (Robinson, 2000), and, therefore, they might not clarify when unsure of the rationale for a procedure to maintain their authority. It could be helpful to include discourse excerpts from practice in TA training to create an awareness of potential difficulties in practice. For example, the acidification discourse excerpts from this study could be presented to the TAs with the question of how they would have dealt with it. In training, disposal and safety could be introduced as explicit group-specific aspects of information practice, and acidification could be introduced as an example of tacit aspects in the laboratory. Using these examples, TAs could reflect on their practice, how they learned things, and how and why they passed them on in a particular way. Further research is needed to uncover other group-specific aspects of information practices in the novice lab. TA training, including the "sayings and doings of practice," in order to ensure that they understand why they do what they do.

In addition to improving the explanations of doings in practice, the TAs could also check for the student’s understanding. Huffmyer and Lemus (2019) suggest that TAs "should increase surveying for understanding to increase student achievement" Aside from checking the student’s understanding (Fisher, Erdelez, & McKechnie, 2005) concerning subject content about the experiments, it could also be helpful also for the TAs to check for understanding concerning the group-specific doings of practice focused on in this study, especially in the beginner laboratory.

However, the idea is not to "transform" tacit information into explicit information or to generalize the rules of conduct. Nevertheless, reconstructing information practice shows how demanding this experience is for students. The difficulty of a beginner lab as a confusing and possibly overwhelming place is broadly discussed in the literature (Chopra et al., 2017; Kirschner, Sweller, & Clark, 2006). The students in a problem-based laboratory do not receive detailed instructions and are required to solve problems by looking for information largely independently. Similarly, the idea is to have TAs "respond with questions that help students make progress without making decisions for them." (Clark, Ricciardo, & Weaver, 2016) However, having specific areas of direct instruction in problem-based laboratory teaching could be helpful to lighten the cognitive burden on the students (Kirschner et al., 2006). For example, the scenario around acidification that we discussed in this study could have taken the form of a demonstration by Jana, showing the students what she means by acidification. More research is necessary on how the chemistry community's group-specific knowledge is represented in practice and, thus, this article can only act as a starting point. With more thorough research, we could then determine more precisely when a situation can be understood as a "productive struggle" (Keen & Sevian, 2022). When we wish the students to engage in this struggle, or when we make it unnecessarily harder for them. Instead, we could aim to instruct them more clearly and remove some of the cognitive load and "general confusion" (Chopra et al., 2017).

Similarly, the findings of this study suggest that the students did not seek explanations for unclear information. For example, Jakob scrutinized the alternative modes of expression used in chemistry literature and was frustrated when the formulations changed between percent and mole. The importance of supporting students in critically evaluating textual information is discussed in the information literacy research literature (Li & Liu, 2022; Wellhöfer & Lühken, 2022a; Yevelson-Shorsher & Bronstein, 2018). However, no student questioned the information provided by their supervisor, regardless of whether an explanation was given or not. The study's excerpts demonstrate how internalized principles were passed on from teaching assistants to new members, increasing the risk that social information would be accepted without question. While current information literacy research focuses on improving the critical evaluation of written sources, the authors suggest a holistic approach. Students should be taught to understand that all textual information is fundamentally social and that they should apply a critical mindset to all information, including social sources.

One way to start this process is by teaching students to scrutinize all textual information as fundamentally social. A helpful example for this is forum information from the internet. The usage of Internet forum information for textual research is a popular way of gathering information for students because oftentimes, the information is easily accessible and easier to understand. This information can be used to exemplify and highlight its similarities to information acquired from peers (Wellhöfer & Lühken, 2022a). Ultimately, students should understand that the authority of sources is constructed and it is up to them to evaluate the required authority in a specific context (Association of College and Research Libraries, 2015).

From the students' perspective, their lack of awareness of the need for corporeal information and physical experience for their conceptual understanding could contribute to their insecurity. There are instances when the required information is not available in writing, and even when a supervisor is consulted, there may not be a precise answer as the required information may be rooted in tacit knowledge. The students may know that something is missing, but they cannot identify what it is. This is because the information must be enacted to become meaningful. Raising awareness of the necessity of physical experience for understanding could help students gain a better understanding of their learning process. One way to achieve this is by making this part of the learning experience transparent to the students. The Transparency in Learning and Teaching (TILT) approach (Winkelmes, 2014) encourages educators to discuss with students how and why they learn in a certain way. This approach could be applied to help students understand that laboratory practice requires physical experience for their knowledge to be meaningful in practice. By making these parts of learning more transparent to students, their feelings of insecurity in a beginner laboratory may be addressed.

This way, instruction includes the corporeal, social, and textual information modalities and how they are connected in practice. This understanding could lay the groundwork for the students to challenge and evaluate the "sayings and doings of practice". By acknowledging and incorporating the importance of physical experience and tacit knowledge, students can develop a more holistic understanding of their field of study, which can ultimately enhance their learning outcomes and reduce feelings of insecurity.

Limitations

This study refers to understanding information literacy through a practice theory lens. This approach understands information practice to be complex, contextual and fundamentally social. Thus, the aim is also to draw attention to the usefulness of practice theory for understanding and teaching information literacy and, ultimately, learning. The physical learning experience has so far been neglected in the educational and scientific discourse concerning chemical information literacy. However, this study can only provide the first indications of the usefulness of this approach; further studies are necessary to gain a broader picture of the information practice in the field. The main limitation of this study, however, is that it relies mostly on one group and, thus, needs further comparisons in terms of other groups of students. The study presents an in-depth qualitative analysis with no claim to generalization. The models we suggested are intended to help to understand the information practice in this study, referring to the different information modalities. However, they are limited in terms of their representation of the complex information practice in the laboratory also due to their sole reference to safety, disposal, and acidification. Nevertheless, further studies with regard to different scenarios in the laboratory are required to gain a broader picture of how social and physical experiences coin the information practice. Information literacy's contextual and social aspects are being increasingly acknowledged in educational research and practice. We believe that this work forms a good starting point and we hope that future research can emerge from this.

Supplementary information

Table S3-1:	Formulating and reflective interpretation “Safety”
Table S3-2:	Formulating and reflective interpretation “Disposal”
Table S3-3:	Formulating and reflective interpretation “Acidification”

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7.6. Supporting Information Study 3

7.6.1. SI Table Safety

Table S3-1. Anchor examples and data analysis for the topic of "safety"

Quote	Formulating Interpretation	Reflective Interpretation
Jakob: With 1 mole per litre of sulphuric acid I don't need to use the fume hood, do I? *laughs* Or also with this? Jana: If you now a drop of-. Jakob: One drop ... ##. Jana: Could you maybe use a fume hood or so. Jakob: Okay. That is, put the thing in the fume hood then. Jana: If something tips over by accident, then you have a fume hood, then you're safe. With sulphuric acid always go into the fume hood. Jakob: Okay. Good. Jana: Just take it over here in the fume hood.	OT: With 1 molar sulphuric acid in the fume hood? Jakob jokingly asks if he should go into the fume hood with 1 molar sulphuric acid. Jana and Jakob communicate that it is a drop. Jana then says he can " maybe use a fume hood or so." Jakob accepts the suggestion and asks how he should handle it ("Put the thing in the fume hood"). Jana explains why Jakob should go into the fume hood with the sulphuric acid: If something tips over. With sulphuric acid you should always go into the fume hood for safety reasons. Jakob accepts without comment and is sent into the fume hood by Jana with the sulphuric acid bottle.	Jakob finds the idea of going into the fume hood with 1 molar sulphuric acid funny and absurd, so he laughs and asks the question in such a way that he does not have to go into the fume hood, "does he?" This documents that Jakob feels competent to make a suggestion for assessing the danger situation that contradicts the theory (but still wants to reassure himself.) Jakob sees himself in a position to assess the danger potential for practice, for the concrete situation (cf. otherwise only Jana "can" this), although the theory says something different (Where did he get the idea to do this in the fume hood? It was not discussed beforehand in the course of the conversation). Here Jakob's participation in the information landscape is documented, his contextual tacit knowledge, which, however, still needs reassurance. By the way he phrases it, he makes it clear that he has assessed this for himself and is not "just" asking. He tries to weigh up and adapt theoretical knowledge in practice ("how precisely" do you have to take rules for safety situationally?). Jana keeps in mind what quantities are involved ("If you now a drop-."), she does not go into the concentration. So both have agreed that the quantities are extremely small. Jana cautiously suggests that Jakob could "maybe use a fume hood or so". Jakob accepts this directly without question and only asks how he should handle it ("Put the thing in the fume hood "). Despite the fact that Jakob doesn't question it at all, Jana now makes it explicit why: If something tips

Quote	Formulating Interpretation	Reflective Interpretation
		over. Always go into the fume hood with sulphuric acid. Jakob is safe in the fume hood. The extent to which other acids are less problematic if they tip over and what exactly constitutes safety in the fume hood is not made explicit. At the beginning, Jakob proposes a situational assessment of the danger and thus becomes an active part of the information landscape (contradicts the theoretical rule and assesses situationally for practice), but as soon as Jana makes a counter-proposal, it is accepted unquestioningly. The authority of Jana's information (as a source) is not doubted. On the other hand, it is documented how Jana falls back on a generally valid rule for the situation ("always in the fume board"). Quasi the opposite of Jakob in this situation.
Jana: (13 sec.) Be careful with your shorts. Ben: Yes. Especially when you carry around a pipette where nobody knows what's in it. Jana: But also remember, boys, that you really have long trousers too, that everything ... ##. That's important. Because actually-, here are actually shorts-. I don't know how it's regulated here now. But actually-, we were never allowed to wear shorts.... Johannes: Actually it was also called long trousers. Jana: Yes. You actually get into trouble and are not allowed to experiment at all. That's why I also ask myself why you're actually allowed to do that. Because it's dangerous. Ben: No, you're not allowed to. Jana: It's-, yes.	OT: You are "actually" not allowed to wear shorts in the lab. UT: Jana tells a student (unclear who) to be careful with his shorts. Ben confirms this and adds "especially if you carry a pipette around where nobody knows what's in it." Jana tells the students to wear long trousers. However, she does not know exactly how it is regulated in this lab. Johannes confirms that the instruction came that long trousers must be worn. Jana says that Johannes "actually gets in trouble" and is not allowed to experiment. She wonders why they are allowed to do this even though it is dangerous.	From the wording, it is unclear to outsiders what she means by what exactly he is supposed to watch out for. In the following sentence, it becomes clear that Jana and Ben are clear about what is meant. Context-specific knowledge and belonging to the same group that has it are documented here. Ben does not know what is in the pipette (the student probably knows). The following orientation pattern is documented in this: the hierarchy is clarified by the fact that Johannes (?) is not an equal because he did not know about the danger of the shorts and the pipette. This clarification is further consolidated by the fact that he is then also denied knowledge of the liquid in the pipette he carries "nobody knows what is in it". (Johannes is denied independent agency.) Johannes is thus made to understand that he does not know what he is doing and how to work safely. Jana begins with a "friendly admonition" that long trousers should be worn. Here it is documented that Jana sees herself in a parental ("boys") function, in which she is responsible for the safety of her protégés. Then she is no longer quite sure of her authority. She knows that "actually" shorts are not allowed, but is not sure how it is regulated in this lab and fears overstepping her jurisdiction. She has never been allowed to do so, but she is not sure if

Quote	Formulating Interpretation	Reflective Interpretation
Ben: That's not allowed at all. Jana: They know that too, but-. It's just no fun when acid gets on it somehow in proper quantities.	Ben confirms that one is not allowed to experiment with short trousers and emphasizes again that it is not allowed at all. Jana answers that the students actually know that they are not allowed to experiment with shorts and explains again with an example that it is dangerous to experiment with shorts because then acid can get onto the skin in large quantities.	she is competent to forbid the wearing of short trousers right now. So she comes into conflict between her own responsibility for safety (authority, competence) and the applicable rules in this room "from above", which are hierarchically above her again. She tries to define her own role and responsibility. Johannes confirms to Jana that "her rule" is in line with the "general rules from above". The general validity, which goes beyond the authority of individual persons, is documented in the formulation "it was also called long trousers", in which no specific persons are named. Here it is documented that she does not see herself in authority (even after confirmation from Johannes that the same rules apply) because instead of scolding herself, she passively refers to "others" from whom Johannes actually gets in trouble. She is still in conflict with her safety responsibility and the role as executive of generally applicable rules. Ben clearly confirms the rules that apply in the lab, but also does not see himself in a position to enforce them. Jana defends the students that they actually know this. Here the parental role is documented again. The protégés are now no longer protected from potential dangers, but from consequences (being seen as ignorant or incompetent). She makes the potential danger clearer again and figuratively states that "it's no fun when acid gets on it in decent quantities". However, the topic of conversation then changes and no verbalized consequences follow (all participants are still present afterwards). Here it becomes clear again that although Jana and Ben communicate the danger very explicitly, neither of them see themselves as responsible for preventing this potential.
Jana: Why do you need gloves for that? Arne: Because of barium hydroxide solution?	OT: Gloves are not needed	Jana asks a question that is supposed to indicate a mistake on Arne's part (she wants the answer to be that the gloves are not needed).

Quote	Formulating Interpretation	Reflective Interpretation
Jana: Yaaa. Arne: No, fuck it, I don't care. I was just- .Jana: You have to eh-, I wanted to ask again why, what you need gloves for, in general, when you ... ## (cross-talk). Arne: ... ## For acids in any case. Jana: If you take it exactly. But a little acid, in such a small amount, should also-. Work concentrated. On your alkaline solutions anyway, that you don't spill anything, okay. If something gets on your hand, rinse it off. And with sulphuric acid, generally in the fume hood.... ##. It's very-. Okay.	UT: Arne uses gloves and Jana asks why they are needed. Arne answers questioningly: "Because of barium hydroxide solution?" and Jana responds with "Yaaaa". Jana now asks again what they generally need gloves for. Arne answers "for acids in any case". Jana confirms this: If they are very precise, then gloves for acids would be the right thing. But according to Jana, a little acid is not so bad. She asks the students to work in a concentrated manner, to be particularly focused on the alkaline solutions and not to spill anything. If something gets on their hands, they should rinse it off. And sulphuric acid is generally only used in the fume hood.	Arne responds very effusively and wants to make it clear that he thinks it's over the top anyway and that he doesn't care (about his safety?) and that he's not afraid. Jana now asks again why they generally need gloves, Arne again takes this as a serious knowledge question and answers "for acids in any case". He thinks acids are in a different hazard category than barium hydroxide solution, so he doesn't care. Jana does not question this assessment. If they take it very seriously, then it would already be right with gloves for acids. In the second sentence, she now thinks that a little acid is not so bad. She advises the students not to spill anything, but does not think much of gloves for protection. Her recommendations are situational and contradict the students' literature. Alkaline solutions should be worked with particularly carefully now. "And sulphuric acid anyway in the fume hood, it's very-. Okay." Jana actually wants the answer to this question: we don't need it. The way she asks the questions and reacts to the answers makes it clear that she doesn't think much of the gloves. Arne wants to satisfy her and hopes to hit on the right answer. When Jana "slightly disagrees" he immediately goes along with it fully. Here it is documented: Jana contradicts (without having been asked) the students' literature and the "safety concept" based on it. Arne accepts this "effusively" (authority is constructed). The textual sources do not stand a chance against Jana as a source here. Jana's decision, however, does not seem so situational, but rather a general rejection of gloves in this context. (as with sulphuric acid and fume hood). Formal level: (Jana addresses the whole group again ("you") but only Arne is actively involved in the conversation, so she has presumably seen it with the others as well).

Quote	Formulating Interpretation	Reflective Interpretation
Carina: Drip it in with a pipette or something similar (it's about disposal). But I don't think it has to be much. Depending. Maybe it's best to put it under the fume hood, because I'm not sure at the moment. I don't want anything to happen. You still had some of the ammonium nitrate, so you also had the waste at the fume hood. Marie: Yes.	Carina tells Marie that she had better go into the fume hood for the planned disposal so that nothing happens. She expresses her own uncertainty.	Carina thinks about how to dispose of it herself. She is not sure and expresses this ("I think", "because I am not sure right now"). It becomes clear that she is aware of making situational decisions ("Depending") and that she has mastered this. Carina pursues the strategy that it is better to use the fume hood as a protective device, because she is not sure and cannot assess the situation comprehensively. The fume hood gives her a feeling of security.
Ben: Hey, hey, hey. Florian: What? Ben: Very badly. You have to be careful with the gloves. Honestly, you don't really need gloves. I just mean it. Because the problem with gloves is, now for example, if you wipe your mouth like this, purely theoretically you wouldn't notice if you had something sticking to your gloves. If you had it on your hands, you would notice it relatively quickly. Yes, because if you feel it, okay, I have a drop on my hand, I go to the sink, wash it clean and that's it. You don't have to be afraid of that when we work with these acids and so on. If you notice something, you put something on your hands, everything easy, stand up, go to the sink, wash your hands, and that's it. It's not like	Ben observes Florian and urges him to be careful when experimenting with gloves. He explains that they are not absolutely necessary either. Ben explains the problem with gloves using the example just observed. He points out that you don't notice when you get acid on your glove and therefore spread it around the lab. He contrasts this with working with bare hands and the frequent washing of hands, which is less dangerous.	Ben expresses that he doesn't like something without formulating it first ("hey hey hey"). Florian, however, understands this and asks about it. Ben evaluates what he has seen as "really bad". Before explaining what is really bad, Ben reminds Florian to be careful with gloves. Ben follows this admonition directly with a hint, namely that gloves are not needed at all. It seems as if Ben had been thinking about this hint for a long time and has now finally said it ("honestly"). He puts both statements into perspective immediately afterwards ("I just mean it."). He doesn't want to offend the students or grumble. However, Ben wants the students to understand his concern and explains it to them using the example he has just observed. He contrasts working with gloves with working with bare hands and explains the differences in detail. He anticipates that the students are probably afraid of the acid and therefore reassures them that the acid is not dangerous at first. He tries to lighten the situation with the help of an exaggeration, which is meant to be funny, and to underline the fear of acid as unfounded ("It's not like your hand will fall off immediately or something."). In his explanation, Ben distinguishes between dangerous substances, toxic substances and the acids used. It becomes clear that he has some experience with chemicals and also makes an assessment of the danger that differs from that of the students. However, he only explains why a little acid on the fingers is not

Quote	Formulating Interpretation	Reflective Interpretation
your hand will fall off immediately or something. It takes time for it to take effect. It's a bit more dangerous, you put something in, let's say here in a hydrochloric acid or something, you touch something somewhere and the next person takes the beaker, for example, and something sticks to your hand. Because you don't notice when something sticks to your glove, yes. But if you work with something dangerous, poisonous or something like that, then ... But for that kind of thing it's not really necessary. It's more dangerous that you touch something or touch someone else, because you don't notice it.		dangerous by saying that the acid has to act for some time before it becomes dangerous.

7.6.2. SI Table Disposal

Table S3-2. Anchor examples and data analysis for the topic of "disposal"

Quote	Formulating Interpretation	Reflective Interpretation
Johannes: These pH samples, do you have to dispose of them in a special way? Jana: You mean the acid solutions or what? Johannes: No, I mean the paper samples. Jana: The snippets? (Johannes: Yes.) You can-, make it so that you-. Did you bring kitchen paper, or-? Jakob: There is toilet paper up there. Jana: Okay. Then you just take a piece of toilet paper, lay it out and then you can always let the pH strips dry. Okay? And when they are dry, you can just put them in the chemical solids garbage can and that's it.	Johannes asks whether the pH paper strips need to be disposed of in a special way. Jana answers that the students should dry them and dispose of them in the chemical solids garbage can.	Johannes asks whether the paper strips have to be disposed of "specially" and he is right, because he is then told the exact procedure by Jana. Johannes anticipates that there is a special way of disposal. The students cannot yet assess how something is "specially" disposed of. Jana's instruction is very specific (special) and is not questioned. The way Jana gives the instruction shows that she wants to "defuse" the detailed procedure ("simple", "and that's it"). She wants to say: it's not that complicated. The following orientation patterns are documented here: In practice, there are always situations in which decisions are given by the supervisor that were not/could not have been anticipated by the students beforehand with theoretical preparation.
Johannes: So I have a pipette here with silver nitrate. Jana: The other way round. Johannes: I see. Yes, I have ... I suppose that has to be disposed of in heavy metal, right? Jana: Silver nitrate. Do you still have something in there or what? Or ... (over speaking). Johannes: There is no more liquid in it. But there are remnants of silver ... Jana: Just rinse it out. That's-, it's only minimal. You can rinse it once, there is no more liquid.	Johannes has silver nitrate in his pipette and asks whether he should dispose of the remains in the heavy metal waste. Jana instructs him to simply flush the pipette down the drain because of the small amount.	This shows that Johannes wants to make a proposal in order to make a situational decision himself. He gives an assessment of the situation, but still needs to be reassured. Jana tells Johannes how to do it, gives an explanation and assessment ("there is no more liquid") and it is not questioned. (Is this how students learn to assess situations?). Note (comparative analysis): Also interesting compared to the pH snippet situation: situational decision whether to "just rinse it out" or "dry it in the fume cupboard and put it in the chemical solid garbage can". The way it was learned it is passed on and then that

Quote	Formulating Interpretation	Reflective Interpretation
		is just the way it is. Social information is questioned less than textual information (?) because of immediate hierarchy? → Only what has been understood can be questioned.
Arne: If now for example-. If I now have barium hydroxide solution, I can't dilute it with this acid and then tip it down the drain. That doesn't work because barium is a heavy metal... Jana: With barium, exactly, that doesn't fit. That's right. Barium yes-, but you could also neutralize it with the acid and then put the jointly neutralized into the heavy metal waste, for example. That's okay, because chloride or something is in here, so it doesn't matter ... Yes, but as soon as there is barium in it, you put it into the heavy metal...	Arne expresses that he cannot dispose of barium hydroxide solution down the drain because barium has to be disposed of separately. Jana agrees with him and shows a possible way of disposal.	Arne also makes a suggestion for disposal in the form of an example. He first plays through a disposal scenario in his mind and shares this process with "thinking out loud". He does not ask a direct question, but this is also a situation where Arne wants to have his assessment of the situation approved by Jana. Development: From "purely asking" to giving an assessment of action and having it verified/falsified. He gets confirmation. Jana also explains how neutralization still plays a role here, heavy metal or not. This shows that she does not yet trust Arne to have really understood the many "nuances" of disposal (she wants to teach him this?).
Johannes: Where do you keep the heavy metal stuff? Arne: Here, with me. Johannes: Shall I put it in there? Yes, isn´t it. Arne: Something is created. *laughs* In the end it explodes, who knows.	Johannes wants to dispose of something in the heavy metal waste. He asks Arne again whether he should dump "that" in there. Arne answers with "In the end it explodes, who knows."	Johannes and Arne are still very uncertain about disposal. When you combine the chemicals they use with those in the waste "something is created". (They know that when different chemicals are brought together a reaction can take place, but they do not know which chemicals are already in the waste). Here it becomes clear that it is not a lack of theoretical knowledge, (but a lack of certainty through experience). Johannes knows that his leftovers belong in the heavy metal waste, but still seeks confirmation from Arne. Arne feels overwhelmed with this position (authority): "In the end it explodes, who knows.” The students ask each other and look for confirmation here with each other instead of with Jana. Disposal is a possible source of danger and brings uncertainty.

Quote	Formulating Interpretation	Reflective Interpretation
Johannes: That's six drops of barium and that was 0.5 mol per litre. Jana: Then you don't have to pour it in again. Johannes: It's expensive to dispose of it. Jana: Exactly. ...	Johannes summarizes what is contained in his sample. Jana explains to him that he therefore does not have to dispose of this separately. Johannes explains that the high costs of disposal also argue against it. Jana agrees with him.	Here it is a question of how exactly one has to dispose of the waste in a given situation, and this is assessed by Jana. This also shows that Johannes wants to participate actively, because he can estimate that it is expensive to dispose of it. He wants to show himself as part of the community of practice (similar to Jakob with the expensive graduated pipettes) and Jana also confirms this to him. Orientation framework: This is then exactly this situation-specific implementation that is not reflected in the theory. No matter how it is written somewhere in theory, in practice it is situationally different.
Arne: Why are you fooling around here so long now? I want to go home, man. *laughs* Jakob: We still have to go to the seminar, boy. Johannes: Wait, where does that have to go now? Jakob: Nothing home. It has to go into a special container anyway, right? Johannes: Yes, I think so too. What kind of stuff did you have in there before? Heavy metal? Jakob: No, there is nothing in there that is dangerous. Except the alkaline solution. Arne: The alkaline solution was neutralized. Jakob: So you can throw it away after neutralization or what?... Johannes: But it is neutralized now. It is neutralized. Jakob: Yes, then you can tip it out or what? I think, isn't it?	The students try to make a decision together about disposal. Johannes asks Jakob where they should dispose of it. Jakob answers that it has to go into a special container, "right?" and Johannes confirms this, but now asks again if there were heavy metals in it. Jakob denies this and says that there is nothing dangerous in it. Jakob asks Arne and Johannes again whether it is allowed to put it down the drain. Jakob reports that in another part of the university you are not allowed to throw it away. Now Jana comes in and asks what is in the sample. Jakob describes what is contained and that he still has to look up a substance.	Here, the students try to deal with the question of disposal on their own. First, Johannes and Jakob agree that this cannot simply be dumped away. Then Johannes brings in his knowledge of when something is not allowed to just go down the drain (heavy metal). Jakob says that there is nothing dangerous in there, except the alkaline solution. Arne brings in his knowledge that the alkaline solution has now been neutralized. The question of whether it can go down the drain is raised again and Johannes does not answer the question (uncertainty): Jakob: So after neutralization you are allowed to tip it away or what?... Johannes: But that is neutralized now. It is neutralized. Jakob has now, after checking for indications that it must be disposed of elsewhere, changed his mind and says "I think so, don't you?" Jacob has a conflict with his other community of practice and the rules that apply there. Here again the context specificity

Quote	Formulating Interpretation	Reflective Interpretation
Arne: Yes, of course. It's only water. Johannes: Well, it's not just water. Jakob: Over here you are allowed to dump it anyway-, in the geology centre you are not allowed to dump it, even if you neutralize it. It's not allowed to go down the drain, for whatever reason. Johannes: It's neutralized now and apparently there's nothing dangerous in it. Jana: What is it then? Is it titan yellow or what? Johannes: Yes. There is among other things ... ## (over speaking). Jakob: Wait a moment, until Magneson has-. Johannes: Or what else did you have in there with your stuff? Jakob: There's nothing else. That's just the sample, alkaline solution, a little acid. But it was all neutralized. And the titan yellow and the Magneson I have to take a quick look at now. Jana: Yes, exactly. Check whether Magneson is something organic. Then you have to use organic solvents. Otherwise pour it down the drain if there is nothing else in it. There's no heavy metal in it. Arne: But titan yellow is an organic compound. Jakob: Yes, but that's not-, you can dump it out, titan yellow. Only Magneson, I still have to look it up.	Jana again describes the criteria for disposal and how organic solvent waste is dealt with. Jana encourages Jakob to look it up and that it can be disposed of down the drain.	is evident. Johannes comes closest to an actual proposal for action: "That's neutralized now and there doesn't seem to be anything dangerous in there." Now Jana intervenes. Jakob argues for the implicit proposal developed by the group to tip it away: Jakob: "There's nothing else. That's just the sample, alkaline solution, a bit of acid. But that has all been neutralized. And the titan yellow and the Magneson I have to take a quick look at now." Jakob does not ask Jana how Magneson is disposed of, but wants to look in textual information sources himself. Jana doesn't seem to know either and confirms to him to look it up. However, she makes it clear that she knows possible options for disposal. She now gives the suggestion for action that the students have worked out herself: "Otherwise, pour it down the drain if there is nothing else in it. There's no heavy metal in it." Here it is documented: Jakob is confused and comes into conflict with his experiential knowledge from the geosciences (other community of practice). Also: The way the students get closer to agency by talking to each other (what does this say?).

Quote	Formulating Interpretation	Reflective Interpretation
Jana: You can ...Look again at the disposal, like this. Otherwise drain.		
Jakob: That's strange. Johannes: What's strange? Jakob: It says here: Notes on disposal. Under waste treatment methods it says no further information available. Does that mean it's not dangerous or-? Jana: At Magneson or what? Jakob: Yes. Jana: That no further-. Jakob: It just says that there is no information. Jana: Then you can put it down the drain. Ben: I think so, too. Would otherwise be on the label, I think. Jana: So titan yellow, Magneson, that's also drain.... ##.	Jakob is unsure about a disposal notice. He considers whether the indication that there is no information means that it is not dangerous. Jana confirms that he can therefore put it down the drain.	Jakob researches (as announced above) the disposal of Magneson. He finds no information on this in his textual source. He concludes himself that this could mean that it is harmless "right?" Jakob: It simply says that there is no information. Jana: Then you can put it down the drain. Ben then confirms that again. No further textual info is equated here with: You can put it down the drain. Jana compensates for the lack of textual information and gives Jakob an instruction for action. She can translate the lack of information and turns it into information that enables her to make a decision.
Ben: So, what do you guys do? Neutralize, I heard. (10 sec.) Look, you're doing it far too hard. You don't need to put the pH paper in tongs, you can just use a great glass rod like this. That is, so ... Pick out a glass rod there, yeah, perfect. Dip the glass rod into the sample solution and then go onto the strip with it. You'll find it much easier, that's it. And now you go there with the syringe, voila. So, what do we have here? Basic, I would say. Frederik: Yes. Ben: Very good, that means?	Ben watches the students neutralize. He gives them tips on how to neutralize more easily and explains an alternative course of action. Ben tells the students that their sample is basic and asks them what the consequence is. Frederik says he needs to add more acid. Ben explains that this is possible, but again shows a (in his eyes) simpler way. He asks the students what possibilities there are to avoid a sudden rise in pH value. Philipp	Comparative analysis: Lab Jana: Ben explains simply. The students do not ask questions, but are given instructions by Ben. In this lab, there is much less asking, more giving and explaining (Ben explains a lot, Carina explains little). A distinction can be made: Learning through demonstrations or learning through question/answer. Here, theoretical knowledge (buffer) is combined with practical application.

Quote	Formulating Interpretation	Reflective Interpretation
Frederik: More hydrochloric acid. Ben: More hydrochloric acid in, exactly. What else could you do? Because somehow it's a bit strange, if you think about it, what's the approximate pH value, you can't see it? Put that aside and you can have a look. Exactly, that's where we are. (18 sec.) You are also neutralizing? Okay, what's your solution? Daniel: I first had the sample with HCl. Ben: Okay, watch out, that's basic too, yeah? You can also, if you want, so we have it super simple over there, if you start from acidic solutions, that is, if you have any acidic waste, how can I prevent that the case occurs that I am too quickly in the basic and then have to acidify again? What can I do to counteract this sudden difference in pH value? Do you happen to know? Philipp: Buffers or something? Ben: Aha, buffer, very good, very good, yes, super. Buffer. What is a buffer for? Philipp: To keep the pH value stable. Ben: In principle, correct, exactly. So, do you know a buffer? You don't. Well, it doesn't have to be. So we have a hydrogen carbonate barrel over there. That's our buffer we use in that case.	answers that a buffer avoids this. Ben explains which buffer the students can use and where they can find it in the lab.	

7.6.3. SI Table Acidification

Table S3-3. Anchor examples and data analysis for the topic of "acidification"

Quote	Formulating Interpretation	Reflective Interpretation
Johannes: I do the SO_4^{2-} proof once. I think I have forgotten that again. What was that? Acidify with hydrochloric acid, right here it says-. *reads aloud* The whole thing is put into a test tube and then acidified with dilute hydrochloric acid. Jakob: That was barium chloride, yes. Johannes: Add barium chloride ... ##. Now the question, what does acidify mean? So how much should I add? Jakob: That's why I just wrote acidify and not any kind of indication, because I have no idea. Ask the chemists somehow-. I think it's kind of a consensus among them that they all know what that means. And everybody else doesn't know. And that's why they always write acidified or acidifying. Johannes: Yes, then I have to ask, because I don't know either. Jakob: Yes, I don't know either. If necessary, just measure the pH and add a little bit.	OT: Discussion of sulphate detection Johannes wants to do the sulphate test, but does not remember exactly and reads up again. Jakob clarifies that he knows which experiment it is ("That was barium chloride, yes"). OT What does acidify mean? Johannes raises the question of what acidifying means. He then becomes more specific and asks how much acid he should add (he is concerned with the quantity). Jakob makes it clear that he has written the preliminary protocol and also explains why he has not added any quantities: Because he does not know how much. Jakob assumes that "the chemists" all know what this means and "they" should ask Johannes, everyone else doesn't know. That is why it is never explained in writing anywhere. Johannes replies that he has to ask then, he doesn't know either. Jakob confirms again that he doesn't know either. When Johannes wants to ask, he responds with an alternative solution in case of emergency: Johannes should measure the pH and add a bit of water. The answer to Johannes's difficulty with the quantities is "a little something" from Jakob.	Johannes is clear that "acidification" is the addition of an acid to a test solution. However, the exact procedure (the detail of the amount of acid) is unclear to him. Jakob reflects that there is common-sense knowledge ("consensus") in the circle of "chemists" to which he does not have access because he does not belong to it himself. If you belong to this circle, you just know it and no one has to make it explicit. Johannes apparently doesn't feel he belongs to "the chemists" either, accordingly he doesn't know that either. However, he shows no uncertainty about it if he could ask. He has access to "chemists", i.e. access to the circle of those in the know. He knows directly whom to ask, he has access to this circle of knowers. Jakob confirms again that he also does not belong to the "initiated" circle of those in the know (the chemists). Jakob suggests an alternative way of acting, how information can be obtained alternatively (without asking) or how work can be continued without information. This suggestion contains the most "natural" course of action: Trying. But "a little bit of something" how much? Which acid with which conc.? These two questions keep him from the practical trial and error.

Quote	**Formulating Interpretation**	**Reflective Interpretation**
Arne: I need a test tube holder. I really need a plan where everything is. Jana: The rough things that are actually always used are all in there. Jakob: I also have all the books with me. So if you want to look up something again, you can do that at any time. Jana: Well, in the lab practical it is very important that you simply try out a bit. There is no right or wrong here. Sure, you have your literature, you are well read, but-. Jakob: Yes, but we are still a bit helpless, I think. What I've heard, in the literature, much is kind of already assumed. Basic things for chemists, for example: Acidify the solution. How much acid goes into it until it is acidified? Jana: Acidified is usually-, a few drops are enough. Then you look with the pH paper. Jakob: Diluted by what, how much? Sometimes it says 2 moles, sometimes it says 5 moles. Then it says it in percent. Jana: You usually take a hydrochloric acid, a diluted one. You add a few drops, check whether it's acidic or not, with the pH paper, and then it's usually ok. Otherwise, it will say strongly acidic or something like that.	OT: Finding needed equipment in the lab Arne is looking for a test tube holder and wants a plan of where the materials are. Jana tells him that the basic equipment and utensils "that are actually always used like this" are all in his place. OT: Jakob provides literature (theory knowledge). Jakob has many books with him ("all of the books") and makes them available to the others. He makes it clear that colleagues can access the literature provided at any time. OT: trial and error vs. literature and: There is no right or wrong Jana steps in and stresses that it is important that they students try out There is no right or wrong. She contrasts this with the literature that Jakob has just offered to help the group. "Sure, you have your literature, you are literate, but-". OT: Problem of translating theory knowledge into practice. Jakob interrupts Jana. Jakob agrees with Jana, but objects that the group is nevertheless helpless. Jakob notes that a lot of knowledge is assumed in the literature, including chemical basics like acidification. He asks how much acid has to be used for acidification. The topic of acidification is taken up again in terms of quantity. OT: What is acidifying?	Arne is unhappy that he does not yet have an overview of the laboratory, because he wants a plan of "where everything is". Jana wants to reassure Arne. Jakob offers to help the others. The books are for Jakob at this moment the cornerstone for research/for information gathering. Formulation: They should not try something out, but find out for themselves their own strengths and weaknesses etc.? Jana wants to say: The literature only helps the students here to a certain extent, they just have to do it. The fact that they are well-read and Jakob has literature with them is "clear", i.e. to be taken for granted and rather pejorative. Jakob agrees with Jana that they are well-read. However, he has a direct objection, since being well-read/reading in itself causes problems. He is unhappy with this statement because it disregards the difficulties of the group ("we are helpless"). "What I have heard" vs. in the literature He has apparently already heard incomprehensible things (from other students? From assistants, lecturers?) and has read in the literature. Although he has just offered the literature as help, he now expresses his frustration about it, because the terms are incomprehensible to him and therefore cannot be implemented practically. Jakob thinks that the suggestion to "just try it out" misses the difficulty he feels because he has no basis from which to try something out. The conceptual difficulties are in fact "basics", i.e. simple basics

Quote	Formulating Interpretation	Reflective Interpretation
	Jana answers the question very vaguely: "Acidified is usually-", then she breaks off the sentence and gives a quantitative answer, still vague, a few drops, to answer Jakob's question. In the second part of the interrupted sentence she answers the question about quantities: a few drops. In the next sentence she gives a hint on how to check the acidification. You check whether the acidification was successful with the help of a pH paper. Jakob now also asks again. He wants more concrete answers regarding the acid to be selected and its concentration. Jakob notes that in the literature the specification changes from mole to percent. Jana again does not answer parts of the question at all. She answered which acid to use with "you usually take a hydrochloric acid". She does not answer the question about dilution, only that the acid should be diluted. Otherwise she repeats the answer from before.	that are, however, fundamental in order to work practically. He does not feel he belongs to the group of "chemists" because he does not understand the language. Jana answers as if she were recalling past situations she has been through ("most of the time") in which she got angry and thinking about how it was most of the time then tries to derive a regularity from it. For her, there is no universal answer here, but a situational one based on memory. She therefore confirms Jakob's assumption: Only "the chemists" know that. In terms of content, Jana gives the same answer that Jakob had previously given to Johannes. Jakob therefore already knew this himself. Jakob notices further ambiguities. He first complains about the incongruent concentration information in the literature regarding acidifying. Jakob makes it clear here how incomprehensible he finds this "language", which he does not understand and accordingly cannot apply practically and cannot "simply try it out". Jana answers vaguely and from her memory ("mostly"). This "that's just the way it's done" speaks for Jakob's assessment that it is a matter of simple basics that "chemists" somehow simply know. It becomes clear that she considers this to be a "no brainer" and not worth mentioning, so to speak, that one should just do it. The concept of "acidifying" appears to be a simple one in Jana's explanation: add hydrochloric acid of whatever dilution and check with pH paper whether it is acidic (no matter how). An obviousness

Quote	Formulating Interpretation	Reflective Interpretation
		and simplicity is conveyed. At the same time, Jana throws in other conceptual differences: "strongly acidic or so". Jana has also understood when it is explained in more detail in the experiment instructions and thus the more precise procedure is also "more important" ("Otherwise it says..."). She has experience with nuances of formulation.
Johannes: Yes, I have another question. Jana: Yes, sure. Johannes: It says acidify. So I understand that I add an acid. But the question is how much. Because I can't estimate that now. Jana: Yes. Acidifying means that it should be in the acidic range, yes. pH value below seven. And then you just add a few drops and then you can check with the pH paper whether it is acidic or not and test it first. And as soon as it's above seven, it's acidic... ## (cross-talk). Johannes: It doesn't matter how far above seven ... ## (crosstalk). Jana: Exactly. So it doesn't have to be strong now. It's enough if it's a bit acidic.	OT: What is acidification in practice? Johannes turns to Jana with a question. He has read the term acidification in the instructions. He describes his idea of it to Jana. He does not know exactly how much acid to add. Jana confirms to Johannes that acidifying, means that the solution should be acidic. acidic range means a pH value below seven. She again gives the vague answer (cf. lines 24-25) about how exactly Johannes should proceed. Finally, she again gives a precise indication of when the acidification was successful (her definition of acidification: pH above 7 Attention: Here is a mental twist that continues in the conversation). Johannes does not find the statement in the sense of "greater than" to be accurate and asks for a Jana confirms Johannes's assumption that it does not matter how far above seven. However, she directly inserts a qualification (it does matter). She relativizes the "it doesn't matter" statement and gives Johannes "a bit annoyed" as a limit.	Derived from the term, Johannes would now add an acid to the sample. However, for putting his idea into practice, he experiences a lack of information that prevents him from proceeding further in practice. He reflects that he lacks knowledge to estimate the quantity. Jana also derives her definition from the term. However, she makes this more precise below with a quantitative value. This is the theoretical framework that Jana finds important for the further practical procedure ("And then you just give..."). Jana's statement that the pH should be below 7 and that one simply adds a few drops of acid is misleading because it makes a difference whether acidifying means adding an acid or whether acidifying means that the solution is in the acidic pH range.

Quote	Formulating Interpretation	Reflective Interpretation
Jakob: I have to get my samples now, if there is room. And then I have to acidify them first and then-. Jakob: How do I do that if I only take a few drops of the sample and then want to acidify it? Because three drops of sample, if I add one drop of hydrochloric acid, even diluted, that's already a lot, isn't it? Jana: You have to add one drop of sample solution and one drop of sulphuric acid. Jakob: But I have to acidify the solution first, with hydrochloric acid. Jana: ... Show me the proof ... Jana: Exactly, then you just put a little bit into your test tube. And you can test it first, maybe the solution is already acidic, that's possible. First test it with the pH paper. See, OK, what pH value do I have? And then you can always acidify. But first of all, get your solutions, both of them, and test what kind of pH value you have. Maybe it is already acidic, yes. Jakob: Yes. Do I just put a drop on the pH paper with the pipette or how? Or do I dip it then? Jana: Um. You can do it however you want, it doesn't matter. You are really free. So feel free to do a little bit of ... (over speaking).	OT: How can I acidify with a few drops if I only have a few drops of sample? UT: Jakob asks how he should acidify if he only has 3 drops of sample solution, even one drop of diluted hydrochloric acid is then "extremely much". OT: First test the pH value of the solution, maybe the solution is already acidic. UT: To Jakob's concern that the pH of the sample ends up strongly acidic rather than acidic, Jana responds by saying that perhaps the solution is already in the acidic range without having to acidify (as Johannes said: add an acid). If the pH value is already acidic, Jakob does not need to acidify and that's it. OT: How do I use pH paper? Just do it. Jakob accepts the offer and doesn't ask further about acidifying. Instead, he now asks how to complete the testing with the pH paper and suggests two courses of action on his own. Jana says that he can do it however he wants and that they are "really free". She encourages him, but also tells him that he should just do it now. Jakob says that it's not so bad if something goes wrong. Jana confirms it again and adds that it is not so dangerous yet.	Jakob is worried that it will be "too acidic" and he will miss the unclear area "acidified". It seems like this is a big risk for him. He does not verbalize the option (as suggested by Jana) to "just try it and then measure the pH". Jakob feels that the reduced sample size puts him in a completely new situation. The concept of "acidification" now unsettles him again, now that it is becoming concrete for the first time and has to be implemented. He knows that he can add just one drop, but that this will still make up a quarter of the total solution ("already a lot"). Here it becomes clear that the process of acidification itself is clear to Jakob, but the goal of acidification or its effects on an experiment remain unclear (compulsion to add acid in combination with the fear of doing something wrong). Jana thus virtually avoids the whole issue at this moment. Jana reassures Jakob that the solution might already be acidic all by itself. This would eliminate the stressful process of acidification (possible relief for Jakob). Overall, there seems to be an ambiguity here as to whether "the act of acidifying" (adding a specific acid, like hydrochloric acid) is the task, or whether reaching an acidic pH range in the solution is the task. Jana says that the Studies are "really free" to act: free in the sense that no matter what you do, there will be no disaster She can assess whether the accuracy required by Jakob is necessary for the final result. She focuses on the experimental result, Jakob focuses on the execution. Jana has a far-sightedness (assessment of the reaction conditions, the effects of individual steps, quantities etc.) while Jakob is

Quote	Formulating Interpretation	Reflective Interpretation
Jakob: If something goes wrong, it doesn't matter ... Jana: Exactly, we are not working with such dangerous things yet. Now first of all we ...		still very short-sighted). On the one hand, she wants to encourage Jakob, on the other hand she refuses to give more concrete instructions. (Does she want to or can she not give more concrete guidelines?) Jakob once again gives himself encouragement. He obviously has a very clear feeling that there is right and wrong here. Jana tells Jakob that he should really dare and try it out, now it is still easy, but later it will become more serious, Jana encourages Jakob by saying that it is "just not yet" dangerous, that in principle there is a right and wrong and there is a limit (which is crossed with other chemicals) and then it becomes really "bad" when something goes wrong.
Jakob: That is, I have about six to five now. So it's acidic. Jana: Exactly. I would still a little bit, because that's really-, so that's not so clear. That's ... ## even a bit more-, yes, it's still very neutral. I would add a little bit more. That it's already-. Jakob: Okay. On the amount then maybe a drop of the 2 mol hydrochloric-. Jana: Which acid did you use for the acidification? Jakob: I haven't acidified anything yet. That's just the solution now. Jana: That's still the solution, okay. So I would definitely acidify again so that you are in the	OT: pH below 7 is not acidic after all. Jakob announces that the pH is five to six and it is therefore acidic. Jana answers that it is not quite clear. Jakob should add a bit more. Jakob has not yet acidified (as previously suggested by Jana), but has determined the pH of the sample. Now Jana is more certain than ever: the sample must be acidified again so that it is "clearly acidic, because it is still very neutral".	Jana therefore has a clear idea of "acidified" and it is not yet, "it is still very neutral". Since Jakob has not yet added any acid, Jana is sure that it is still "very neutral". Presumably, this assessment would have been different if Jakob had already added acid. According to the motto: It is better to follow the instructions for the experiment (if it says that acidification is necessary). Jana can only ever answer situationally; Jakob is thus unsettled. While Jakob is very sure in line 64 that it is acidic and thus the acidification can be omitted, Jana is a bit more uncertain and rethinks the procedure ("not so clear"), loses a bit of foresight or the focus on the "Why is acidified=so that it is acidic". Jana says what Jakob says before. The conversation ends as it began, only with exchanged speaker roles.

Quote	Formulating Interpretation	Reflective Interpretation
clearly acidic range, yes. Because that is still-, right now it is still very neutral. Jakob: Hydrochloric acid. Jana: It shouldn't be red. So you don't have to be strongly acidic, but-. Jakob: Okay. But does one drop already make a difference? Jana: You have such a small amount here, one drop already makes a difference. In any case.		
Johannes: So you said what else can interfere with that. But we don't have all that inside. Jakob: Exactly, we don't have all the interfering ions inside. So-. Jana: Okay. Is there anything in it maybe? Because it is in the strongly acidic range. Jakob: What does strongly acidic mean? Jana: Well, it said acidify. Johannes: Yes, I have-, pH value one I have. Jana: Not that anything else dissolves as a complex or-. I just want to show you ... ## also take others. Jakob: It doesn't say anything about that, I don't think. Only Cl is here. You can take here ... Jana: Maybe check it once for a moment. And otherwise you can be sure already then.	OT: Too much acidification can be problematic/ There is a big difference between "acidified" and "strongly acidic". Johannes and Jakob talk about interfering factors of the reaction. Johannes picks up on something Jakob has said before (what disturbs everything). He notes that none of this applies and is sure of it. Jakob agrees here and is also sure. Jakob wants to draw a conclusion from this observation, but is interrupted. Jana points out an instruction to Johannes and Jakob and asks them to read it again. Jana deliberates with Johannes and Jakob together. Jana also moves away from interfering ions and brings the conversation back to the acidic environment of the sample. Jana describes that a sample is in the highly acidic range. Johannes confirms this with an exact value (pH=1). Jana now addresses the fact that something can also dissolve in the sample. She emphasizes that she only wants	Is Jana sure that there must be something there and only points it out to Johannes and Jakob or is Jana not sure himself? Jana does not say "it" (the sample) is in the strongly acidic range, but "he". It points thereby quite clearly to a person, who adjusted a "wrong" range. This also becomes clear again when Jakob asks what strongly acidic actually means. This term is still unclear and has always been used undefined. However, Jana does not answer this directly, but emphasizes that acidifying is something different from strongly acidifying. And since "it is in the strongly acidic range", something has gone wrong. Johannes (which is presumably what this is all about) confirms with an exact reading that he has pH=1 (again, this is talking about "I have" and not "the sample has"). The responsibility for the pH is seen by both Jana and Johannes to be with the (own) person. Jana pivots attention to the consequences of "wrong" acidifying (NOT right acidifying!). Before she can name more

Quote	Formulating Interpretation	Reflective Interpretation
	to help by pointing out what has not been considered so far. Jakob rejects this and emphasizes that none of this is in the instructions. However, she is not quite sure of this or relativizes by saying "I think". Jana cautiously recommends ("maybe") to just check it briefly (!).	than one consequence negatively perceived for this situation, she interrupts herself and appeases her statement. Jakob believes the instructions more than Jana's statement. Jana now tries another strategy to draw attention to this (rows back again, does not want to stir up fear and also does not want to contradict the instruction, wants to let Jakob do it). Jana signals that a check does not take long, is not a big effort, but can still give a feeling of security once it has been tested.

8. Deutsche Zusammenfassung

Einleitung

Diese Dissertation behandelt das Thema des Lernens in Chemielaboren, insbesondere die Herausforderungen und Vorteile des problembasierten Lernens (PBL) für Anfänger im Labor. Obwohl das Lernen im Labor als entscheidend für die Ausbildung der Studierenden angesehen wird, gibt es kein einheitliches Verständnis darüber, was im Labor gelernt werden sollte und warum es wichtig ist. Daher versucht die chemiedidaktische Forschung zu verstehen, was Studierende im Labor lernen, wie sie lernen und wie das Lernen im Labor verbessert werden kann.

PBL-Labore unterscheiden sich von traditionellen Laborkonzepten, da sie Forschungsprozesse in den Vordergrund stellen und das Experiment als Forschungsinstrument nutzen, um lernendenzentrierte Bildung zu fördern. Statt vorgegebene Versuchsanweisungen zu befolgen, wird von den Lernenden erwartet, dass sie ihre eigenen Versuchsplanungen entwerfen, was das Sammeln von Informationen aus verschiedenen Quellen erfordert. Dies kann jedoch für Studierende, insbesondere für Anfänger im Chemielabor, eine Herausforderung darstellen, da sie mit ungewohnten, nicht traditionellen Laborkonzepten und impliziten Erwartungen konfrontiert werden.

Information literacy ist im Kontext von PBL-Laboren ein zentrales Konzept, da Studierende Informationen aus verschiedenen Quellen sammeln müssen, um ihre eigenen experimentellen Verfahren zu entwerfen. Information literacy wird als soziokulturelle Praxis definiert, die es den Lernenden ermöglicht, Informationsquellen in einem bestimmten Umfeld zu identifizieren und so zu nutzen, wie es durch die Praxisgemeinschaft legitimiert ist. Diese Dissertation verfolgt einen soziokulturellen Ansatz für das Lernen und Lehren im Labor, da das Lernen im Labor kontextabhängig ist und weitgehend durch menschliche Interaktion bestimmt wird. Die Definition von Information Literacy als soziokulturelle Praxis ermöglicht es, die Verbindungen zwischen textlichen, sozialen und körperlichen Informationsmodalitäten zu untersuchen, die während der ersten PBL-Laborerfahrung der Studierenden entstehen und diese prägen.

Die übergreifende Forschungsfrage, die dieser kumulativen Dissertation zugrunde liegt, lautet: "Wie wird die Informationspraxis von den Teilnehmern eines problembasierten Anfängerlabors dargestellt und entwickelt?" Durch die Beantwortung dieser Frage soll ein Einblick in die Schwierigkeiten, Vorteile und Möglichkeiten des Lernens im Labor gegeben werden. Ein qualitativer Ansatz wird verwendet, um die Wahrnehmungen und Erfahrungen der Studierenden zu verstehen. Die Ergebnisse zweier Inhaltsanalysen und eines dokumentarischen methodischen Ansatzes, einschließlich Audioaufzeichnungen der Praxis und Interviewtranskripte, dienen als Grundlage für die Untersuchungen.

Theoretischer Hintergrund

Problembasiertes Lernen und Information Literacy

In den vorliegenden Artikeln wird die Beziehung zwischen PBL und Information Literacy im Rahmen der konstruktivistischen Lehr- und Lerntheorie untersucht. PBL-Laborpraktika übertragen die Verantwortung der Gestaltung der Versuchsplanung auf die Studierenden, was zur Förderung der Problemlösungskompetenz und Motivation beitragen kann. Im Rahmen von PBL sind die Studierenden aufgefordert, herauszufinden, welche Art von Informationen benötigt werden, wo und wie sie zu beschaffen sind, wie sie zu bewerten sind und wie sie für die Planung experimenteller Verfahren zu verwenden sind, was die grundlegenden Bestandteile von Information Literacy darstellt. Die Association of College and Research Libraries (ACRL) hat 2015 eine überarbeitete Definition von information literacy veröffentlicht, die die komplexe, kontextbezogene und sozial geprägte Natur der information literacy betont: *„Information literacy is the set of integrated abilities encompassing the reflective discovery of information, the understanding of how information is produced and valued, and the use of information in creating new knowledge and participating ethically in communities of learning.”*

Ein soziokultureller Ansatz von information literacy versteht diese als eine sozial geprägte und kontextualisierte Praxis, in der bestimmte Informationsmodalitäten und Wissensformen je nach sozialem Umfeld gegenüber anderen privilegiert werden. In diesem Zusammenhang bedarf es einer tieferen Untersuchung der Informationspraxis und der "privilegierten Wissensformen" im PBL-Anfängerlabor, um ein besseres Verständnis der zugrundeliegenden Prozesse zu erlangen und Unterrichtsempfehlungen zu entwickeln.

Kumulativer Teil der Arbeit

In diesem Abschnitt der Dissertation werden die drei Publikationen vorgestellt, die die Grundlage für die kumulative Dissertation bilden.

1. Studie: Wellhöfer, L.; Lühken, A. Problem-Based Learning in an Introductory Inorganic Laboratory: Identifying Connections between Learner Motivation and Implementation. *J. Chem. Educ.* 2022, *99 (2)*, 864−873.

Die erste Publikation, Wellhöfer und Lühken (2022a), untersucht den Zusammenhang zwischen problembasiertem Lernen (PBL) und Lernermotivation im Kontext eines Anfängerlabors. Die Studie zielt darauf ab, die zentralen Implementierungsfaktoren zu identifizieren, die die intrinsische Motivation der Lernenden in einem PBL-Kontext erhöhen. Die Forschungsfrage lautet: Welche zentralen Umsetzungsfaktoren förderten die intrinsische Motivation der Lernenden in diesem PBL-Konzept?

Studierenden, die an ihrem ersten Chemie-Laborpraktikum teilgenommen hatten. Die Interviews wurden wortwörtlich transkribiert, und die Daten wurden mithilfe einer strukturierten Inhaltsanalyse analysiert. In einem ersten Schritt der Datenanalyse wurde ein deduktives Suchraster verwendet, um alle Aussagen zu sammeln, die sich auf die theoretischen Definitionen von Autonomie, Kompetenz und Verbundenheit gemäß der Selbstbestimmungstheorie (SDT) bezogen. Ein induktiver Ansatz wurde verwendet, um Themen in Bezug auf die Umsetzung zu identifizieren, die dann in einer systematischen Reihenfolge zu theoretischen Codes verbunden wurden. Diese theoretischen Codes wurden verwendet, um das Modell des autonomen wissenschaftlichen Prozesses zu erstellen.

Die Studie ergab, dass Autonomie, definiert als selbstbestimmtes, willentliches Handeln in Übereinstimmung mit den eigenen authentischen Interessen und Werten, ein gemeinsamer Faktor zur Steigerung der intrinsischen Motivation der Studierenden ist. In der Studie wurden verschiedene Umsetzungsfaktoren identifiziert, die die intrinsische Motivation von Studierenden in einem PBL-Labor fördern, und diese Faktoren wurden zu einem Modell des autonomen wissenschaftlichen Prozesses verbunden. Das Modell besteht aus vier Schritten: Informationsbeschaffung, Entwurf und Anwendung des experimentellen Verfahrens, experimentelles Feedback und autonome Optimierung des Prozesses. Die Ergebnisse deuten darauf hin, dass es die intrinsische Motivation in PBL-Laboren erhöhen kann, wenn die Studierenden diese vier Schritte eigenständig durchführen können.

Die Methodik der Studie umfasste halbstrukturierte Interviews mit zehn Insgesamt legt diese Publikation das empirisch-analytische Fundament für den zentralen Zusammenhang zwischen PBL und information literacy, der für alle weiteren Arbeiten grundlegend ist. Sie gibt Aufschluss darüber, wie man sich der Komplexität der Umsetzung nähern kann, indem man die motivationalen Effekte von PBL inhaltsanalytisch untersucht. Das in dieser Studie entwickelte autonome wissenschaftliche Prozessmodell ist ein nützliches Instrument für Lehrende, um die intrinsische Motivation in PBL-Laboren zu erhöhen.

2. Studie: Wellhöfer, L.; Lühken, A. Information Is Experimental: A Qualitative Study of Students' Chemical Information Literacy in a Problem-Based Beginner Laboratory. *J. Chem. Educ.* 2022, *99 (12)*, 4057-4067.

Die zweite Publikation, Wellhöfer und Lühken (2022b), zielt darauf ab den Informationsprozess zu verstehen, den die Studierenden während ihres ersten PBL-Laborpraktikum durchlaufen. Der soziokulturelle Rahmen der Studie bietet die Grundlage für die Erforschung von information literacy, um Einblicke in die Art und Weise zu gewinnen, wie Studierende mit Informationen in der Praxis umgehen, und um ihre Wahrnehmungen des Informationsprozesses zu untersuchen. Die Forschungsfragen dieser Studie lauten:

1. Wie können wir den praktischen und wahrgenommenen Informationsprozess beschreiben, den Studierende während eines PBL-Anfängerlabors durchführen?
2. Wie prägen privilegierte Wissensformen in Bezug auf die Qualität von Textquellen den Informationsprozess?

Zur Beantwortung der Forschungsfragen wurden im Laufe von drei Kohorten mehrere Datensorten in einem qualitativen Studiendesign erhoben. Die Datenerhebung und -analyse war ein iterativer Prozess, bei dem Datenerhebung und -analyse gemeinsam weiterentwickelt wurden, um dem Forschungsgegenstand näher zu kommen. Das gesammelte Material aus allen drei Kohorten wurde schließlich verwendet und trianguliert, um die Forschungsfragen zu beantworten.

Die Ergebnisse zeigen, dass im PBL-Labor der Entwurf eines anwendbaren, problemorientierten Versuchsablaufs entscheidend für die Lösung des Problems ist und den gesamten Prozess der Informationsbeschaffung bestimmt. Der Informationsprozess ist ein iterativer Prozess, bei dem neu erworbene Informationen zu neu zugänglichen Informationen führen, die wiederum zu einem genaueren Informationsbedarf führen. Die Studierenden bewerten die erhaltenen Informationen, indem sie sich drei Hauptfragen stellen: "Ist es für mein Problem nützlich?", "Kann ich es tun?" (in Bezug auf das kognitive Verständnis, die verfügbare Ausrüstung und die psychomotorischen Fähigkeiten) und "Ist es sicher?".

Die zweite Forschungsfrage untersucht die Rolle privilegierter Wissensformen in Bezug auf die Qualität von Textquellen bei der Gestaltung des Informationsprozesses. Die Studierenden der Studie bezeichneten nichtwissenschaftliche Quellen als "schlechte Quellen" und wissenschaftliche Quellen als "gute Quellen", wobei sie im Allgemeinen trotzdem beide zur Informationssuche verwendeten. Die Studie zeigt, dass die Wahrnehmung der Quellenqualität durch die Studierenden nicht unbedingt ihre praktischen Entscheidungen beeinflusst, und dass es Diskrepanzen zwischen ihren Bewertungen der Quellenqualität und ihrer tatsächlichen Nutzung von Quellen gibt.

Insgesamt bietet die Studie Einblicke in die komplexe Art und Weise, wie Studierende Informationen in der Informationspraxis der Chemie in einem PBL-Setting navigieren. Die Ergebnisse können als Ausgangspunkt für die Unterstützung ihres Informationsproblemlösungsprozesses dienen.

Studie 3: Wellhöfer, L.; Machleid, M.; Lühken, A.: "I don't know, ask the chemists -. I think it's kind of a consensus among them" – Information practice in a problem-based beginner lab. *Chemistry Teacher International 2023.* (accepted)

Die dritte Publikation, Wellhöfer, Machleid und Lühken (2023), untersucht die Informationspraxis von Studierenden in der Laborpraxis. Die Studie konzentriert sich auf den Diskurs zwischen Lernanfängern und erfahrenen Assistenten in ihrer ersten Laborsitzung an der Universität. Ziel ist es zu verstehen, wie Lernende Wissen durch soziale, textliche und körperliche Modalitäten innerhalb der Praxisgemeinschaft erwerben. Die Forschungsfrage dieser Studie lautet: Wie wird die Informationspraxis in einem problembasierten Anfängerlabor dargestellt und entwickelt?

Die Studie zeigt, dass theoretisches Wissen allein nicht ausreicht, damit Studierende in der Praxis selbständig handeln können, und dass sie handlungsleitende soziale Informationen von erfahrenen Mitgliedern der Praxisgemeinschaft benötigen. Die Ergebnisse zeigen, dass die Informationspraxis im Labor für Neulinge, die einer neuen Community of Practice beitreten, verschiedene Merkmale aufweist. Die Verwendung von allgemeinen Leitlinien fördert die Sozialisierung der Studierenden in der Praxisgemeinschaft und bietet einen Rahmen für die Handhabung von Situationen und Entscheidungen. Die körperliche Erfahrung und das *tacit knowledge* sind entscheidend für das Erlernen der Methoden der Praxisgemeinschaft und von gruppenspezifiischem Wissen. Der gemeinsame Bezugsrahmen wird durch die aktive Teilhabe von Individuen geschaffen. Neulinge lernen die *sayings and doings of practice*, um informationskundige Mitglieder zu werden, die unabhängig handeln und situativ entscheiden können (knowing-in-practice). Insgesamt zeigt der Artikel, inwiefern das Erlernen der Informationspraxis in der Praxisgemeinschaft eine soziale und körperliche Erfahrung erfordert und gibt Hinweise, wie Lehrende diesen Prozess unterstützen können.