Inquiry-Based Learning in the Life Sciences

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16.1 Trends in the Life Sciences as Determining Factors for Teaching and Research

The life sciences comprise numerous disciplines; these study physiology, anatomy, behavior, development, evolution, ecology and disorders of living organisms as well as the use of organisms in natural or technical procedures. Life sciences include biology, biomedical research and pharmaceutics, biochemistry, biophysics, bioinformatics, agricultural and nutritional science as well as food technologies, bio-based economy and the use of biogenic resources. The life sciences contribute not only to our understanding of basic

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The term research-based learning is used here throughout to describe what is subsumed under undergraduate research experience (URE) in English speaking countries. In the German academic culture, research-based learning aims at a high level of self-dependence on the part of the student.

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mechanisms of living organisms and ecological systems; new research opens up novel possibilities to elucidate and treat human diseases as well as securing food for a growing world population.

A high degree of empiricism is intrinsic to the life sciences. The state of scientific knowledge in the life sciences is based on observations and experiments with which researchers describe, measure and analyze the conditions and behavior of nature. Methods are chosen to ensure the reproducibility of results. Many studies require sophisticated methodologies, e.g. advanced imaging, "omics" approaches and the like. Thus, the ability to acquire knowledge in these disciplines very much depends on development and availability of methods. Methodological advances and improvements may yield data of higher quality, allow novel conclusions and open up new areas of research (e.g. brain research, gene therapy, stem cell technologies, etc.). In recent years, rapid technological advances in many fields, including information technology, data processing, genetic engineering, or molecular biology, have led to a rapidly increasing complexity of methods. As a result, life sciences are characterized by an exponentially growing volume of knowledge and fragmentation into numerous sub-disciplines.

This development impacts on university teaching and higher education. New challenges arise with respect to the volume of knowledge that is taught, or the discrepancy between traditional text book knowledge and the results of modern research. Combining highly specialized subject areas with practical and methodical approaches in a meaningful way presents additional challenges for teaching in higher education. In addition to a sound knowledge base and understanding of biological relationships, which are increasingly explored more broadly, students ought to develop competencies in terms of research methodology such as purposeful planning, executing and evaluating experiments as well as analytical and critical thinking. With a possible career in research in mind, students have to learn how to work collaboratively in a group, on campus and in an international context.

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In the light of limited human and spatial resources, imparting the described wealth of knowledge and developing the required competencies place high demands on lecturers that will be barely accomplished via the traditional curricula. Given the high numbers of students in present-day study programs, life sciences are often taught in large classes of 100 participants and more. Such courses make it difficult to establish a close link to state-of-the-art research, especially in terms of the necessary use of modern devices and techniques. This development is all the more problematic if one considers the close connection between the life sciences and the current state of research. This may not only lead to demotivated students, it also reduces personal contact between students and lecturers. Consequently, it is difficult for the latter to assess the level of knowledge of an increasingly heterogeneous student body and to adequately address knowledge gaps.

It is essential to strengthen the students abilities to accumulate knowledge and research competence in a self-dependent manner. This ability is of particular importance, given the rapid increase in knowledge that we face, as well as the associated shorter half-life of the current state of knowledge in life sciences. Life scientists working in academia and industry must continuously have a critical look at current research findings, technical developments and modern experimental approaches, as well as the resulting new insights and hypotheses. However, it is by no means sufficient to enable future life scientists to (self-dependently) acquire and reproduce already existing knowledge. They will be the ones in charge of ensuring future insights and innovations, and to deal with new technological opportunities in a responsible way, for the benefit of society in the midst of global competition and in the face of global challenges. For this reason, academic teaching should focus more on key competencies such as analytical, creative and reflective thinking, on acquiring specific scientific skills and on furthering the capacity for teamwork.

How can the acquisition of these competencies be fostered in the life sciences, given the high numbers of students and limited resources? How can the concept of “research-based learning”, put forth in German-speaking countries under the formative influence of Ludwig Huber (2009), be integrated into curricula of the life sciences? In the tradition of the “Humboldtian model of higher education”, teaching is essentially derived from the research process. Students develop competencies in a dynamic and unbiased process in order to self-dependently gather new insights. In the following, we will outline specific characteristics of the life sciences that have beneficial or inhibiting effects in terms of an increased use of research-based learning in academic teaching. Moreover, strategies to counteract inhibitory effects as well as advantages of research-based learning will be discussed.

16.2 Research-Based Learning: Advantages and Facilitating Conditions

The implementation of research-based learning in the life sciences is favored by the concept of research itself, as well as by the sequential structure of the research process. The experimental nature of research allows an easy understanding of the concept of research.

However, beginners often have a biased understanding of the research process in which data collection is overrated, while the proportion of literature review, statistical planning, data analysis and publication is underestimated. Research is often perceived as a linear process, while in practical terms it consists of small steps, setbacks, discarding and reformulating of hypotheses and the like.

Many research topics in the life sciences are extremely complex. However, in many cases, they can be separated into sets of specific research questions, which individually require less background knowledge. Such questions can be addressed in the setting of research-based learning, with limited efforts and a small subset of required methods. For example, most students will not be able to elucidate the complex processes of neural circuits in the central nervous system. Within the context of research-based learning, however, they could study neurotransmitters used by cells of the brain or spinal cord and how they communicate with other cells. Dividing complex research topics into small, easy-to-address research questions thus facilitates the participation of students in the research process. Students get introduced to the research process by carrying out experiments, collecting and evaluating their own data. This process is supported by the fact that the complexity of research-based learning can easily be adapted to the students' respective knowledge and skills. Students can perform simple experiments under the guidance of a supervisor, for example during a course, and they can perform independent (and less guided) research during an internship (i.e. research-based learning in the classical meaning). This transition from receptive to self-guided learning supports the students in their developing self-awareness as scientists.

The structure of the study program reflects the importance of experimental data collection and methodological development in the life sciences. The curricula contain a wide range of courses and tutorials, in which students apply modern research methods. It would be relatively easy to apply the concept of research-based learning within such courses. The format of research-based learning is variable; it may consist of courses held in regular intervals during the semester, of whole-day courses that last for a few weeks, of internships during summer break and seminars or student projects. Moreover, the scope of research-based learning can vary, i.e. it can cover the entire research process related to a research question (Fig. 16.1) or it focusses on specific aspects such as scientific writing, statistical data analysis or literature review. The latter may include the elaboration of the research topic as well as the identification of the current state of research, the drafting of hypotheses and the design of statistically sound experimental set-ups. Depending on the research question, appropriate methods must be acquired, developed or validated before collecting data in the experimental part of the work. The data are (statistically) evaluated and discussed in relation to the research question. An essential part is the documentation of the research process in a comprehensible and reproducible manner, and making the results available to the research community. Several authors published examples of how research-based learning could be implemented in the curricula of life-science curricula (e.g. Brewer and Smith 2011; Ott and Carson 2014; Resendes 2015; Ward et al. 2014).

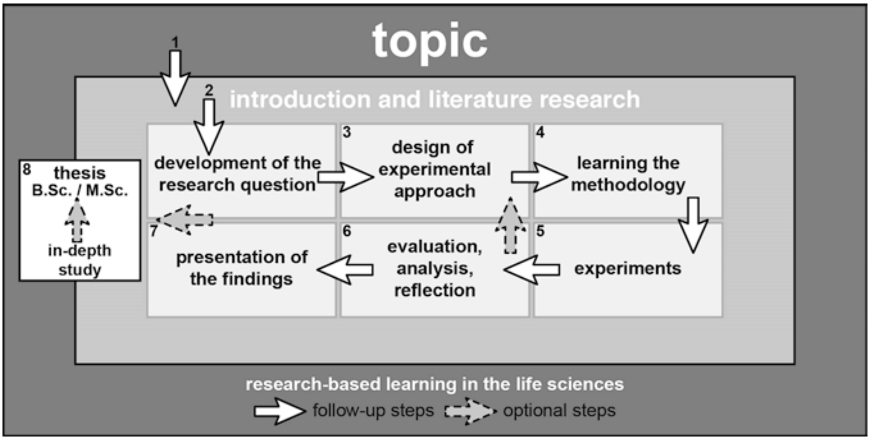

Fig. 16.1 Schematic diagram of the sequential structure of a research-based learning project in the life sciences

Research-based learning is probably firmly established in many curricula in the life sciences, for example in the form of internships or small research projects, which are often not referred to as research-based learning. Last but not least, as in other disciplines, students conclude their studies with a thesis during which they work, in large parts independently, on their research question. Thus, experiencing research-based learning in other formats before is the perfect preparation for a successful bachelor or master thesis.

After selecting a topic (1), students perform a literature review to understand the theoretical background needed for implementation of the research (2). Participants subsequently develop their research question(s) and hypotheses, and design a suitable experimental setup (3). Students practice the methodology (4) before they perform the experiments and collect data (5), which are subsequently evaluated and discussed (6). Finally, the results and conclusions are presented to the (academic) public (7). Optionally, insights obtained during this process may result in a new cycle of questions and experiments (3–6), or the project may connect to a more in-depth course or become integrated into a thesis (8).

The latter reasoning could help motivate supervisors to take part in research-based learning. Lecturers that engage in full-fledged research at the same time (which is the standard at German universities) are often faced with the problem of reconciling their teaching with their scientific projects. The concept of research-based learning provides a workable solution for this conflict of interests. Replacing conventional courses and tutorials, which constitute a significant part of the teaching activity and which do not provide new scientific knowledge, with research-based learning projects may produce novel and exciting results, not only for the students benefits but for the supervisors as well. In most cases these will be preliminary results on for example the variability of methods, the optimization of experimental designs or testing of new methods. Such preliminary experiments are often time- and labor-consuming. Including these experiments in research-based learning allows the supervisor to conduct preliminary research despite the scarcity of resources, and provides students with a sense of achievement. The overlap between a student's research project and the research interests of the supervisor results, therefore, in the increased motivation of both, students and supervisors. Our experience shows that spending time in a research-based context is more meaningful to students than teaching formats, which simulate the research process based on an arbitrarily selected research question.

The high relevance of research for future professional activities implies that students of the life sciences have a keen intrinsic interest in research questions and a pronounced motivation for true research activities (cf. Multrus 2012). Thus, enhanced student motivation constitutes another beneficial factor for the implementation of research-based learning in the life sciences. This is particularly true in cases of research-based learning projects addressing topical issues such as climate change, gene therapy or genome editing, healthy nutrition or conventional versus organic agriculture. Such topics relate directly to the everyday reality of students, which should elicit special interest. In addition, the personal contact to scientists and the favorable ratio of students to supervisors may contribute to a high intrinsic motivation of the students. Students' self-perception as "researchers" can contribute to their satisfaction with the study program in a major way.

16.3 Meeting the Challenges of Research-Based Learning

Favorable conditions that facilitate the implementation of research-based learning contrast with a number of unfavorable factors that restrict research-based learning in the life sciences. These include costs, organizational issues and time-related aspects of research topics and applied methodologies, as well as the rather hierarchical construction of knowledge in the so-called hard sciences (cf. Healey 2005). Significant expenditures of time and money required for research-based learning may be the most limiting factors.

In the life sciences, sizeable costs derive from the use of expensive consumables (e.g. fine chemicals), instruments and equipment. High acquisition costs can be avoided by linking a student's research question to ongoing research projects in the supervising institute or department. Alternatively, expenses can be reduced by restricting the research question to aspects that can be answered using a reduced set of consumables and equipment. If the concept of research-based learning is incorporated in the mission statement of the university, financial and personal resources that are still being used for conventional course work may be reallocated in part or full to research-based learning projects.

Furthermore, limited laboratory space and availability of instruments may constrain the realization of research-based learning projects. This issue again may be solved by integrating students' projects into current research questions of the involved institution. However, it is difficult to circumvent the restricted flexibility of experiments in terms of time management. This may be due to limited infrastructure (workstations and equipment), only temporary availability of biological sample materials (e.g. due to vegetation periods or generation cycles) and the at times considerable duration of experimental procedures (e.g. long-term observations or incubations, sequential extraction steps and the like). Time requirements and progress of an experiment strongly depend on the research question and the methodology applied and may require the students' presence in the laboratory or in the field during a given time window with little chance for rescheduling the tasks. It therefore can be difficult to coordinate research-based projects in the context of inflexible timetables of study programs. Thus, research-based projects may best be placed during semester breaks or other suitable time windows in which students are in charge of their time management.

In the German academia, concepts of research-based learning, that were developed in the soft sciences, often stress the importance of self-dependent development of research questions, decision making, and completion of research projects by the learners, in order to enhance motivation and learning outcome. Laborious analyses and complex experimental approaches in the life sciences, however, prevent pure student-led research-based learning or at least makes it quite difficult. Undergraduates in general lack technical and methodological skills and access to the required instruments in order to plan or carry out such projects completely self-dependently. This problem is further exacerbated by legal requirements and restrictions (e.g. animal welfare legislation, occupational safety regulations, environmental protection act, and genetic engineering law). These can significantly restrict the choice of research questions suitable for student projects and necessitate additional training in good laboratory practice and the specific methodology. Thus, projects need to be planned and carried out in collaboration with experienced supervisors. Supervision may be required as well for the application of statistical methods, as imparting statistical basic knowledge in lectures and tutorials often does not enable students to adequately evaluate individual experiments.

Research-based student projects that are incorporated into ongoing research of the supervising staff are unique with respect to content and preparation and can usually accommodate only a small number of participants, due to the aforementioned limitations. Thus, the time requirements for academic staff to supervise research-based projects are significantly higher compared to standard courses that are given repetitively each year. A reasonable compromise could lie in addressing the same research question in a recurring manner year after year, e.g. to analyze a soil sample or the composition of the vegetation at a given site in order to allow for long-term observations and to illustrate the dynamics by comparing the data to those of previous generations of students. At the same time, the effort for planning and organization can be minimized in such projects. These must relate to ongoing research topics at the supervising institutions, however, in order to qualify as research-based project, and such approaches may not be applicable in every field of research.

If research-based learning is implemented at an early phase of the study program, supervision of undergraduates can be particularly time-consuming, depending on the background of the students, e.g. in terms of general knowledge and skills in literature research, scientific writing, or application of statistics programs, which can be taught in formats with higher numbers of participants. Even if a synergy between teaching and research can be achieved, the increased time requirements compared to standard teaching may negatively impact on research efficiency. Research-related criteria dominate over didactics of teaching, when applying for positions or third-party funding, i.e. research output is considered more important than successful teaching. This reality results in the prioritization of research activities by academic staff and complicate engagement in time-consuming teaching formats such as research-based learning.

A major difference between standardized course work and research-based projects is the frequent failure of experiments in the life sciences, in which even well-established routine methods can fail at times. Failed experiments as well as the rejection of a hypothesis require patience, diligence, and a high degree of tolerance towards frustration. This can negatively impact on student motivation, especially in the context of short-term projects (Linn et al. 2015). However, this experience enables supervisors to familiarize students with the fact that experiments frequently do not precisely result in the expected outcomes. Students recognize right from the start that the research process is tedious and difficult, and progress can only be realized in small steps.

Last but not least, reflection on the concept of research-based learning is not as widespread in the life sciences as in disciplines with higher affinity to didactical issues, social-learning theory and pedagogics. The unfortunate tendencies towards lecturing very large classes and a constantly increasing amount of basic knowledge favor an instructive learning culture aiming at knowledge transfer. The deep expert knowledge of increasingly specialized researchers reinforces the impression that students are not able to conduct their own research. The discipline-specific learning culture and the discrepancy between highly specialized and basic knowledge thus may be another obstacle to the wide-spread implementation of research-based learning in the life sciences.

16.4 Conclusion

It is becoming increasingly difficult to teach an ever expanding and continuously developing knowledge, while the acquisition of competencies such as the ability to self-dependently acquire new knowledge, to critical, analytical and solution-oriented reasoning is becoming increasingly important for a successful professional career. Research-based learning can significantly contribute to the development of these competencies and therefore should be integrated into study programs at an early stage. In the life sciences, programs frequently have structural requirements due to a strong practice-orientation of these disciplines.

For learners and supervisors, research-based learning is an extremely time-intensive format, and requires thorough planning in terms of time management, feasibility and adaption to the individual abilities of students. The dependence on often costly resources together with complex methodologies, legal and ethical issues restrict the idealized concept of free research-based learning in the life sciences, i.e. the engagement in independently developed, intrinsically motivated research question by the learner themselves.

Instead of tying up resources in formats that merely simulate research, we highly recommend to integrate research-based learning into ongoing research projects of lecturers, in order to synergistically use personnel and financial resources for research, learning and teaching, and to achieve a high motivation of students and supervisors at the same time. The implementation of research-based learning undisputedly changes the study content. The intense engagement with a research question fosters the deep understanding of a specific topic but does not provide a broad knowledge base. Thus, research-based learning can be a significant pillar, but not the sole format in higher education. Against the backdrop of sizeable student cohorts, lectures represent important and efficient teaching formats for conveying the necessary basic knowledge. To extent the implementation of research-based learning in the life sciences, several aspects need to be considered: a reflection on study contents in terms of knowledge and skills; a true change in the culture of learning and teaching; the dissemination of the concept of research-based learning in combination with improved didactical training of researchers; and the support of academic staff when introducing research-based learning. In so doing, it is crucial to demonstrate how research-based learning can be used for the mutual benefit of learners and supervising staff and, ideally, for acquiring new scientific insights.

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