Integrating inquiry based learning in physics teacher education through a seminar about processes of gaining knowledge in science

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Abstract. Internalizing the process and methods of scientific research is fundamental both for young people who are getting prepared to work as scientific researchers, as well as for those who participate in social discourses on scientific issues as responsible citizens. In addition, many current problems can not only be solved from a specialist perspective; interdisciplinary cooperation plays an important role in research and society. It is therefore important that teachers know teaching concepts that enable students to acquire competencies to be prepared for these challenges in life. To implement this, a new pre-service teacher study curriculum was developed as part of the MINTplus² (engl. STEMplus²) project at TU Darmstadt, which conveys interdisciplinary teaching approaches, especially about STEM. As a part of this project, we developed a new seminar which focusses especially on didactic concepts like inquiry-based learning in order to prepare pre-service science teachers to convey their students the methodological knowledge of the scientific research process. This paper shows the seminar structure embedded in the whole project and the first evaluation results with n=14 concept maps of seven students that show that there is a measurable increase in knowledge regarding the seminar topic.

1. Introduction

The big problems of our time such as climate change, supplying the world population with water and food, diseases, migration, or the extinction of species are multidimensional problems that cannot be answered from the perspective of one scientific discipline. These problems must be solved by interdisciplinary cooperation.

Schools therefore have a very responsible task: they have to convey students' knowledge and competencies to meet interdisciplinary challenges. Teachers are only able to support their students when they are prepared to design lessons which foster problem-oriented working. Therefore, our approach is to improve teacher education in such a way that future teachers know teaching concepts with which they can prepare the students accordingly.

In this paper, we want to present this approach in detail. In order to this, we first introduce the overall MINTplus² (English translation would be STEMplus²) project, of which we are a part. It mainly deals with the interdisciplinary approach, especially from a STEM perspective [1].

Subsequently, we describe the embedding of our own project: Our part in the project is the development of a new module within the new MINTplus² pre-service teacher curriculum. The module focuses on the "S", thus science education. As we found out in a preliminary study [2], the existing teaching program already concentrates very much on concepts that deal with imparting content knowledge. So, the pre-service teacher students are expected to be well prepared for this aspect. What is missing, however, is preparation for process-oriented learning.

Therefore, we designed a new module, in which we focus on processes of gaining scientific knowledge as well as science research methods from a science didactical point of view. We convey both, on the one hand philosophical-theoretical perspectives and didactic models of gaining knowledge in science, e. g. Nature of Science. On the other hand, it is important that the student teachers also get to know practical examples for their lessons, e. g. inquiry-based learning as teaching concept. We will present this in detail in the main part of the paper.

At the end of the paper, we present some evaluation results that show that the didactical knowledge of the seminar topic has improved in a pre-post comparison.

2. The Project MINTplus²

The project MINTplus² (engl. STEMplus²) is the continuation of the previous MINT^{plus} project. It deals with a systematic and networked development of the pre-service teacher education in a STEM-specific way at the Technical University of Darmstadt. More precisely, the old pre-service teacher study curriculum has been fundamentally revised so that a new study curriculum with new innovative elements is created [3]. Usually, the pre-service teacher education in Germany contains three parts. In Germany, a teacher teaches two different subjects. For every subject you have some courses about the content knowledge and some in which you learn important didactical concepts. In addition to the two subjects a basic knowledge of pedagogy and psychology is essential and thus constitutes the third part [4]. In sum one needs two hundred and forty credit points, which are distributed in the way you can see in Figure 1a [5].

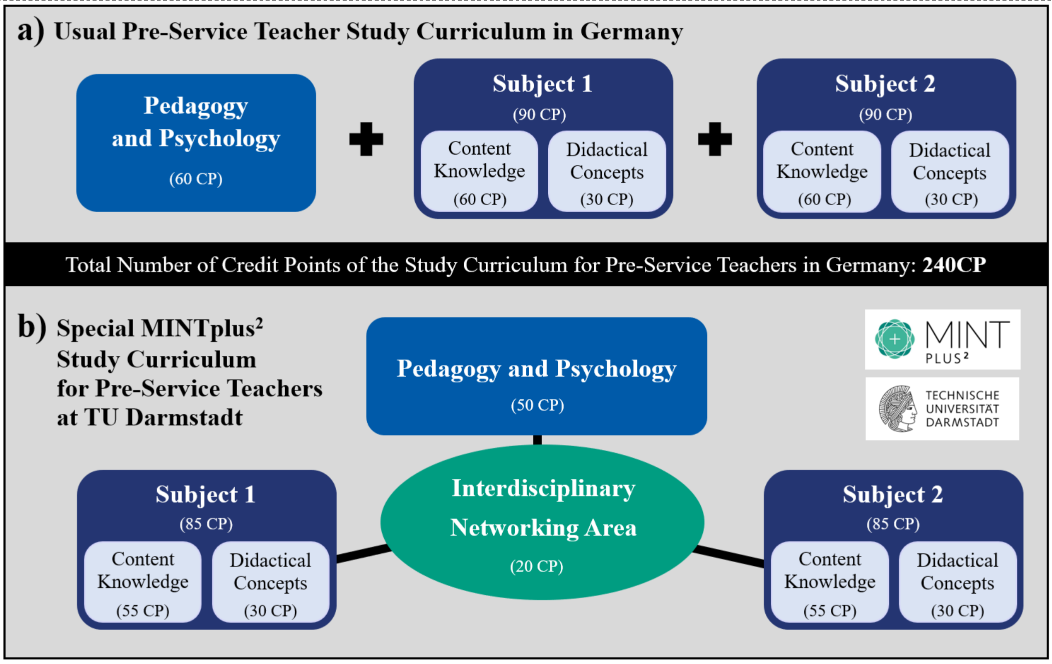


Figure 1. The interdisciplinary networking area in the new MINTplus² study curriculum at TU Darmstadt as a special element compared to the usual pre-service teacher study curriculum in Germany.

In Germany, teacher education is determined by the federal states, not by the federal government. The distribution shown can therefore differ in federal states other than Hesse, but the basic structure is comparable to the Hessian model.

In comparison to the usual German course of study, Figure 1b shows new the pre-service teacher study curriculum of the Technical University of Darmstadt. It was introduced at the Technical University of Darmstadt in October 2017; before that, the study structure corresponded to the usual German study curriculum from Figure 1a. The illustration quickly shows what is special about the new course: the interdisciplinary networking area. It acts as a connecting element between the basic sciences and the two subjects. Hence, in the interdisciplinary networking area the future teachers should primarily deal with two questions: "What connects my subjects with other subjects?" and "What is unique about my subjects?" [3]. In consequence, the pre-service teacher students get ideas for making references to other subjects in their own lessons and prepare themselves for interdisciplinary school projects, and on top of that deepen their subject identity in order to teach the subject even more authentically.

In order to develop the networking area according to its target dimensions, "expanding horizons", "content-related networking" and "social networking", a special project group was formed at the university to develop the MINTplus[2] project.

The module that we designed as a part of this group is intended to enable students to delve into the natural sciences in a targeted manner by focusing more explicitly on their processes of gaining knowledge as well as research methods and thereby getting to know concrete approaches to integrate them into the classroom.

3. Integrating Didactic Concepts in the New Module

Due to our physics didactic background, we decided to design the module primarily from a didactic perspective. This perspective is particularly important for future teachers, as it bridges the gap between the content of subject science (e. g. physics, chemistry, or biology) and the content of educational sciences (pedagogy and psychology). Furthermore, it opens specific links between teaching theory and teaching practice.

In this section, we will present the basic teaching idea of the new module in a first step. Subsequently follows the basic structure of the new module and the selected didactic content. Finally, we briefly describe how the first run of the module took place in the summer semester 2020.

3.1 Basic teaching idea of the module

The basic aim of the seminar is to enable future teachers to design lessons in which the scientific process of gaining knowledge is understandable and comprehensible for their future students. Thereby, the new module represents an important pillar of the interdisciplinary networking area at TU Darmstadt with its basic idea.

A suitable teaching concept in which the scientific research process can not only be understood by the students, but can even be actively experienced, is inquiry-based-learning, which is described by Hofer (2016, p. 4) as the following:

> *"Inquiry-based learning is a teaching concept in which knowledge, skills and abilities or competencies are to be built up, deepened and consolidated in the course of scientific investigations. Through this type of learning, the pupils shall learn how research results can lead to (scientific) knowledge."* [6].

But it is too short-sighted to simply convey this teaching concept to the students. The process of gaining scientific knowledge is very multifaceted. Without background knowledge as well as basic concepts about the complexity of a process, the inquiry-based learning teaching concept can hardly be used profitably in school.

For the module presented here, it can be concluded even though inquiry-based learning is a central conveying aim, a concept is required that prepares the associated context of the acquisition of scientific knowledge comprehensively. In section 3.3, several other teaching contents are presented as important elements of the seminar in addition to inquiry-based learning. To classify these, however, it is helpful to first briefly introduce the basic module structure in Section 3.2.

3.2 Design and Structure of the Module

In order to focus on the goal explained at the beginning – to prepare teachers to design problem-oriented interdisciplinary lessons – we decided to choose a project as the heart of our module which is worked out in small groups with students from different subjects. As a consistent conclusion from the central goal presented in Section 3.1, the project is based on an inquiry-based learning setting. Thus, in this natural science deepening module, the students work out experimental settings for children at school. Experiments in an inquiry-based learning area are very science-specific. At the one hand, natural science competencies are deepened, at the other hand, when embedded in a context, they also enable expertise from other subjects to be brought into the project [7].

In order to prepare such a project, we designed a basic seminar that prepares specially for the project as second part of the module. As shown in section 3.1, the seminar must not be confined to the inquiry-based learning. Therefore, in the following section 3.3, this article focuses on presenting the didactic content of the seminar including much more in addition to inquiry-based learning.

Since reflection is also an important part of the teaching profession [8], the module is continuously accompanied by a learning portfolio, which is used as a speech occasion in a final conversation in which the students reflect the seminar as a whole and their learning progress.

In sum, the module essentially consists of three phases, which are closely interlinked. The first phase is the basic seminar. It usually contains introductory presentations and small practical exercises. Since the students already have their own technical expertise from their subjects, we also set a methodological focus on cooperative forms of learning in which the students can learn and benefit from each other. The second phase contains the interdisciplinary project, which first has to prepared by the pre-service teacher students and subsequently is tested in school with students at the age of about thirteen. The third and last phase of the module consists of the reflection of the whole module.

3.3 Content of the Basic Seminar

The content of the basic seminar is primarily intended to act as a foundation for the project by conveying theoretical and the practical teaching concepts that can be used in the project This should be achieved by using the seminar structure shown in Figure 2. It shows eleven seminars which are subordinated to five main topics. The teaching concept on which the module projects are mainly based, inquiry-based learning, is addressed for the first time in the “Entrance”. However, it is intensified again under the main topic "Practical Examples". Between these two seminar sessions, the numerous facets of the knowledge acquisition process are worked out in order to create the appropriate context for inquiry-based learning. At the end of the seminar, further in-depth school-practical elements are presented, such as inclusive experimentation or experiments in exams, to further deepen the application in school practice.

The course of the seminar will be presented in detail below. This clarifies how the individual seminar sessions from Figure 2 are built on one another and which exact contents are dealt with in them. The sequence of the seminar sessions can be seen in Figure 2 by looking at the columns one after the other from top to bottom.

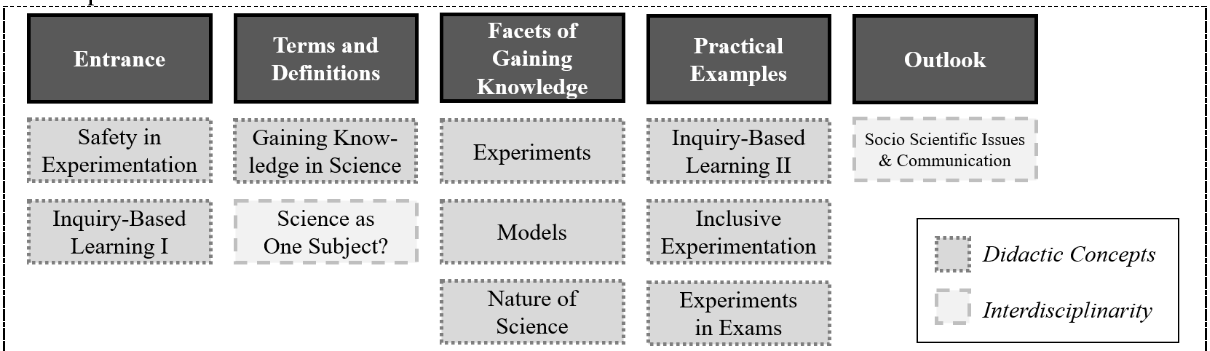


Figure 2. Overview of the structure of the basic seminar. Each box represents a seminar session and can either be assigned to the interdisciplinary approach of the networking area or the integration of a science-specific didactic concept.

As shown in Figure 2 the seminar starts with two sessions to get to know the aim of the seminar. Although many pre-service teacher students are already familiar with it from other study modules [2], we do not forego starting with a safety briefing, as this is mandatory to us even for the very harmless experiments that are planned for the seminar and the project. We also use this opportunity to discuss how safety issues can be discussed in general at school, for example by a security contract for the science classroom [9]. In addition, in the first two sessions we question the students about expectations and attitudes before the seminar, for example in questionnaires or by creating a concept map for the seminar topic. This means that we can also indirectly collect our pre-test data in these sessions. The title "Inquiry-Based Learning I" hides the fact that an outlook on the project is already given, which also indirectly provides an initial introduction to the subject area of “Inquiry-Based Learning”, since the degree of openness of experimental settings is already discussed here.

The next section of the seminar, under the title "Terms and Definition", mainly includes an introduction to the two parts of the seminar title. On the one hand there is the term "knowledge acquisition" and on the other hand the term "natural sciences". In the first session, selected didactic concepts for scientific knowledge acquisition are discussed. Although it can be assumed that the students already know a didactic model for this, it is likely that they do not yet know the breadth of this term. In fact, there is already many relevant didactic models on this topic in the German-speaking area that focus on very different aspects [10, 11, 12, 13]. An integration of all models into one large common model hardly seems feasible [14]. It is therefore important that students learn to orient themselves between so many models. At the same time, this offers a good opportunity to discuss the meaningfulness and benefits of a didactic model as such. In this way, an in-depth introduction to the topic is already possible, in which the students can exchange ideas and discuss new things. The second session about “natural science” includes besides a peer quiz a discussion about science as integrated school subject [15]. There is an education discussion in Germany about this. Although the natural sciences - biology, chemistry and physics - are usually taught separately, there are always voices in Germany that suggest teaching these together as one subject natural science.

The next part of the seminar represents the main content-theoretical part of the seminar. According to the model of knowledge acquisition in science by Wellnitz [16], the seminar section "Facets of Gaining Knowledge in Natural Science" was divided into three separate sessions: firstly, scientific investigations, secondly, scientific models and thirdly, the meta-understanding of natural sciences, summarized under the term “Nature of Science”, whose definitions are summarized by Heering & Kremer (2018) this way:

> *“The use of the term Nature of Science in the context of natural science didactic purposes emphasizes the importance of developing an understanding of the natural sciences in educational processes. This includes, among other things, an understanding of the acquisition of scientific knowledge, of social structures within the natural sciences and of the epistemic status of scientific statements. The learners should be able to orientate themselves in a society and professional world characterized by natural sciences (Höttecke 2001; Hößle et al. 2004)."* [17]

The first session on scientific investigation deals with the diverse didactic functions that experiments can fulfil in school lessons, the second deals primarily with the informative value of models in science lessons. Above all, it is emphasized which types of models there are in the classroom and which difficulties of understanding are possible. Using exemplary model analyses from various subjects, the students practice how to deal with such comprehension difficulties in a targeted manner. The session on the topic of "Nature of Science" is intended to confront the students with the places in everyday life and in school where unfavourable images of natural sciences are conveyed. In response to this unfavourable communication, the didactic concept “Nature of Science” is used to develop how this problem can be addressed explicitly in the classroom. In this context, the role of experiments in science teaching, as opposed to the role of experiments in science research, is to be discussed [18] to derive consequences for teaching. This session also prepares the topic of inquiry-based learning, since inquiry-based learning in the narrower sense is to be perceived as a teaching concept that can above all change, improve, and deepen the knowledge of students about Nature of Science.

The last major section of the seminar focuses on application orientation. Here, the students try to implement presented concrete teaching concepts in a subsequent exercise. In addition to inquiry-based learning and based on the preliminary study we decided that the other two practical concepts that will be presented are inclusive experimentation [19] and the integration of experiments in exam situations [20], as these two concepts are not dealt with in other courses in the teacher training course and thus are not dealt with at all represent an enrichment for the students.

The outlook of the seminar is designed to bring the whole thing back together from an interdisciplinary perspective. For this purpose, socio scientific issues are discussed as possible contexts in which scientific knowledge and research results must be applied, weighed up and evaluated together with other disciplines. The discipline-specific form of communication is also discussed. The final session offers the opportunity to examine the didactic concepts learned in this seminar over the course of the semester from a perspective that includes all school subjects.

3.4 Summary in the context of the basic teaching idea of the module
The topic inquiry-based learning serves as a central theme, which supports the other seminar themes continuously, in an implicit manner. One example is the role that experiments play in natural sciences under the heading “Nature of Science” which clarifies ideas about scientific working methods that should be conveyed in school.

The subsequent seminar sessions are also linked to inquiry-based learning by showing how this concept can be adapted to inclusive learning groups or how elements of it can be integrated into exams. In our point of view the extensive preparatory work before the actual seminar session is particularly necessary in order to be able to fully understand the actual concept of inquiry-based learning. In this sense, inquiry-based learning takes a significantly larger share of the seminar than Figure 2 suggests. In the entire module, very is even larger, as aspects of this teaching concept are applied and tested in the project.

3.5 First Run in the Summer Semester 2020
The official module start was planned for the summer semester 2020 with a seminar on site at the university and the project was worked out on the assumption to take place in the university student laboratories and in school. But suddenly the schools and universities were closed in April 2020 due to the corona pandemic [21]. To deal with this situation we had to change methodical elements of the module, but the content-related aspects and learning objectives remained because of this adaptation to the pandemic situation.

Instead of an on-site seminar, the basic seminar took place as an online seminar under pandemic conditions. Furthermore, no project could be worked out in the university's laboratories and testing in school was not possible. Instead, the projects were created at home by the pre-service teacher students. The final projects include experiments that children can do at home. The project results were thus adapted very well to the current pandemic situation, depending on closed or open schools, the experiments can be carried out at home and in school.

4. Evaluation of the New Module
The presented design of the module is closely linked to its evaluation. A suitable research approach for closely coordinating development and evaluation is the design-based-research approach [22]. We will briefly introduce our design-based-research approach in the following and then present the results of the first run, which can be used to improve the second run.

4.1 Evaluation Design
A design-based research project consists of several cycles in which development and evaluation take place. The starting point is the goal of creating an innovative new teaching situation or concept, in our case a new module for the interdisciplinary networking area.

In a design-based research project the new development is based on a theory-driven development, supplemented by research-driven inputs. As already shown, we based the module mainly on didactic theory, but also included a student survey from the summer semester 2019 [2].

The next step of a design-based research project is to create a design, which includes the theory-driven and research-driven inputs. This has to be implemented for the first time and the implementation is analysed in order to improve the original design in a redesign. Through several cycles of this procedure, the whole design should be continuously improved.

The descripted module development led to the first implementation during this summer semester. We are therefore able to present the first evaluation results from this run of the module. These have already been used to improve the module in the 2020/21 winter semester, which represents a new development evaluation cycle in terms of design-based research.

In the summer semester, seventeen students took part in the seminar, seven of them only in the basic seminar because they were able to use this event for an event in the old course. Ten attended the complete module including the project.

4.2 Evaluation Instruments

In order to check whether our new module is effective, we in the evaluation first examined the question how the knowledge about the topic "Processes of Gaining Knowledge in Science" changes through the module. To answer this question, we decided to use concept maps because concept maps represent our networked mental structure better than a linear spoken or written text [23]. In order to support the interpretation of the concept maps, interviews were conducted at the end of the module.

There are quite different assessment methods for concept maps and as a rule these must be adapted to the exact evaluation question [24, 25]. It is fundamental, however, that when evaluating the concept maps, one can focus on the terms on the one hand and on the relationships between the terms on the other hand [25].

The concept maps were used in a pre-post design at the beginning and at the end of the seminar. In contrast to this, the interviews were only used at the end to gain additional qualitative insights that cannot be captured by concept maps. In the summer semester 2020 this meant for the eleven students who fully attended the module that they did the pre-surveys at the beginning of the seminar and the post-surveys after the project. The seven students without a project, on the other hand, did the post-surveys directly after the seminar.

4.3 Results of the Evaluation of the First Run

For an initial evaluation, the seven concept maps of the participants who only attended the seminar without the project were used. At first, we have initially concentrated on the evaluation of the terms by counting them. We were able to observe a significant increase in conceptual knowledge [26].

But it is important to learn more about the increase in knowledge relating to the singular seminar sessions, because the seminar structure is based on the versatility of the singular facets of knowledge acquisition. By evaluating the individual facets, it is possible to improve the seminar in a targeted manner based on the facets. ~~In order~~ So, we have conceived these facets respectively the seminar sessions as individual clusters (where inquiry-based learning I and inquiry-based learning II form a common cluster). We then classified each term in a corresponding cluster, whereby terms that could not be clearly assigned were not considered. We then used the number of terms per cluster in the pre-post comparison to determine the increase in performance. Since this procedure does not consider the total number of terms that are possible per cluster, we also analysed which clusters were newly discovered. Newly discovered means that the cluster only appears in the post concept map and has not yet been considered in the pre concept map. With the same weighting of the meaning of "increase in performance through a high numerical increase in terms" and "increase in performance through new discovery of a cluster", the result is shown in Figure 3 [25]. The learning increase was differentiated into five levels from "nearly none" learning increase to "very big" learning increase.

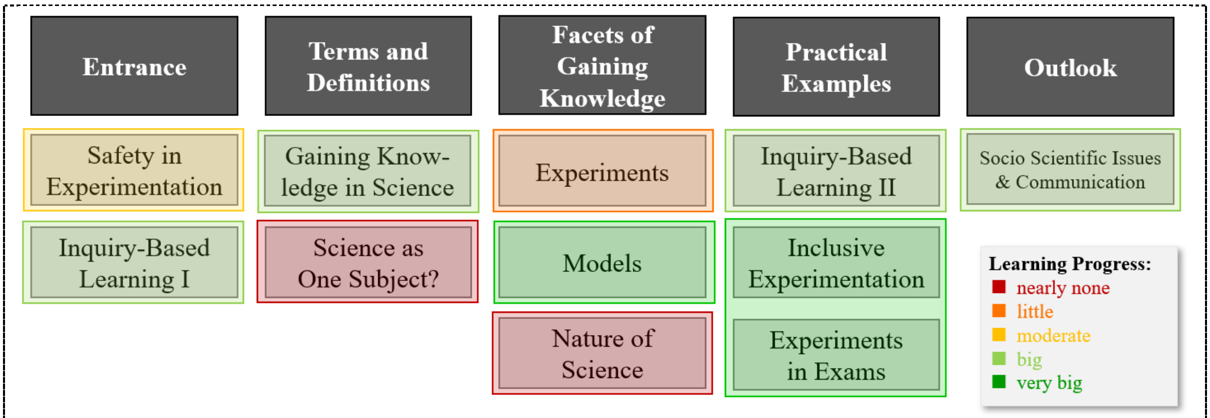
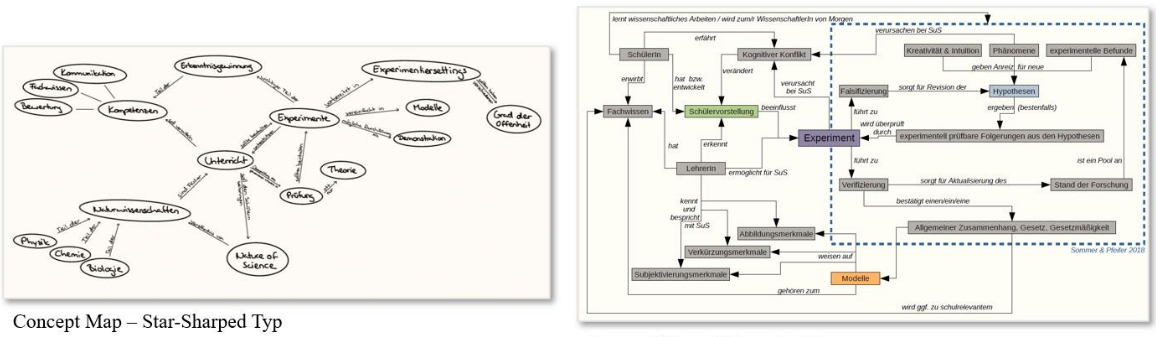


Figure 3. Results of the Evaluation of the counting terms of the Concept Maps.

The results show that most of the seminar sessions are already provided with a large or very large increase in learning, although there are also seminar sessions that need to be improved for the following cycle of design-based research development.

An important second interest for us, however, is whether the basic idea of the interdisciplinary networking area is also visible in the concept maps, for example whether the newly acquired knowledge has been networked. To analyze this, we examined the concept maps regarding the networking dimension. In this analysis, we differentiate between terms in the concept maps and relations. A graph-theoretical analysis of the links is therefore suitable [27]. The terms represent nodes, the relations represent edges, so that the concept map can be identified as a graph in the sense of graph theory [27]. This allows statements about the degree of linkage. Based on these considerations, we were able to identify two main types and thus defined them as the star-shaped type (low degree of linkage, all terms are arranged in a star shape from the term "knowledge acquisition") and the interlinking type (high degree of linkage, no central term) (see Figure 4). While the star-shaped type, mainly based on the seminar topic, supplements its knowledge outwardly, topic by topic, the networked types work with many cross-connections also under the terms and topics. Counting the types of concept maps of all seventeen concept maps we find seven times the star-shaped type and ten times the networked type. In more than half of the cases, a high degree of networking can be observed, but the mental structure of 41% still shows increased island thinking in the individual seminar topics.



Concept Map – Star-Sharped Typ

Concept Map – Networked Type

Figure 4. Comparison of the star-shaped type and the networked type.

Finally, we would like to use a quote from an interview to show that they support us in understanding the concept maps more precisely. The quote from Figure 5 shows that this student consciously arranged the terms chemistry, physics, and biology differently after the module than before, because after the seminar she sees them as more networked. This aspect is not apparent simply by looking at the concept map, but thanks to the interview, the motive of this design becomes apparent.

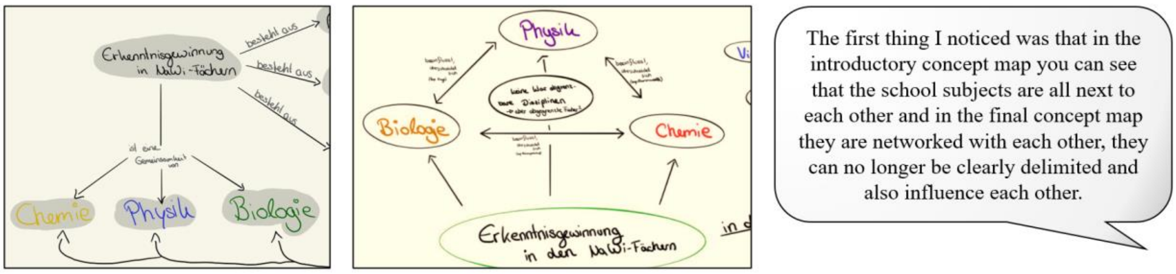


Figure 5. Results of the Evaluation of the counting terms of the Concept Maps.

This example shows on the one hand how the interviews necessarily support the interpretation of the concept maps and on the other hand that the goal of networking among the natural sciences was considered important by the student.

5. Discussion

One can observe an increase in knowledge on the module topic in many aspects via the concept map. Thus, results show that the seminar is already effective in the first cycle of the design-based research project. However, it is noticeable that there are also seminar sessions with little increase in learning. In some aspects this is due the previous knowledge which is already very high in the beginning. The case of safety while experimenting or in the topic experiments might serve as examples. In other aspects, however, it also shows weaknesses of the module. The seminar topic nature of science was hardly noticed. In the interviews it became clear that the students were able to remember when asked. Then they also name the topic as important, but obviously it has not reached into their active knowledge. We have therefore expended the session on this topic for the following semester: in addition to the theoretical input, we added an application task in which the students are asked to describe how they would like to actively integrate nature of science into their future teaching. We hope in this way the students will deal with the topic more intensively. The session about natural sciences also performed poorly. In the interviews, the students criticized the fact that the large number of texts was too demanding. Therefore, we have reduced the text selection for this session and hope that this will enable the students to focus better on the topic itself.

The concept maps show that the module already leads to a comprehensive networking of the seminar topics for more than the half of the students. Regarding the project, however, it would be desirable if the proportion of networked concept maps were even higher which would indicate that the topics are understood less as individual islands, but rather as a whole. Some interviews also show that networking in the sense of a module which is embedded in the interdisciplinary networking area was perceived as a success.

The first cycle of the design-based research project was of course not only an important test for the content and design of the module, but also for the evaluation instruments. We have found out that concept maps in combination with interviews are suited to investigate the increase in the mental structure of knowledge related to the seminar topic. The concept maps are straightforward to evaluate and compare, and the interviews provide qualitatively important additions. However, compared to this content-based evaluation, there is still no process-based evaluation that measures the extent to which the students can apply the knowledge they have learned. For this purpose, vignettes were developed which the students can use to formulate thoughts on applications in classroom practice. A pre-post comparison of this exercise can provide information about the process-oriented learning growth.

6. Conclusion

This paper presents a module structure that focuses on the inquiry-based learning teaching concept in the context of interdisciplinary learning. The heart of the module is a project which is based on this teaching concept. This project is being prepared intensively by a basic seminar.

It becomes clear that inquiry-based learning can play a role not only in the context of physics teacher education, but also in a holistic, interdisciplinary teacher education. The first evaluation results of both the concept maps and the interviews show that in this context an increase in knowledge becomes measurable and networked thinking becomes evident, even if it is stronger in individual facets than in others. The facets with weaker learning growth (e. g., Nature of Science) must be emphasized more strongly in the next module runs and a more detailed look at the process-oriented learning in the seminar is also necessary.

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