Chapter 24
Adaptation of Constructivist Learning and Teaching Models for Non-formal Science Education Research

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24.1 From the Constructivist Learning Theory to Models of Teaching–Learning-Interaction

24.1.1 Criteria for Teaching–Learning Models

In the three studies we present, we investigated the actions and cognitive processes of students and adults in the non-formal learning environments when they interact with exhibits or work on problem-solving tasks. We conducted the studies because, especially in Germany, very high expectations exist for learning in non-formal educational environments: They aim to inspire students, stimulate interests on a long-term basis, help with career orientation, and support the school. In addition to motivational effects, informal institutions should support subject-related learning. In the studies, we ask in what form this is the case, to what extent the exhibits and tasks are suitable for cognitive activation, and what role the special atmosphere of the non-formal learning venue plays in this context.

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funds the GINT program. Five universities in Greece, Denmark, and Germany participate in the program.

Empirical research requires methods that allow the researcher to be close to the students, to accompany them in the non-formal learning environment, and to question and observe them. Research in out-of-school learning venues places special demands on the modeling of the processes taking place. From an epistemological point of view, we proceed from a constructivist view of learning (Duit & Treagust, 1998), according to which learning means the self-activity of the learner in the construction of meaning, building up knowledge, and developing explanations.

We follow the basic constructivist belief that learning, and teaching are mutually dependent subjective constructions. Scientific subject structures are constructions in which priorities and contextual embedding of subject-related content are made. Representations of subject-related structures pursue certain educational aims with a certain freedom and the need to analyze and reconstruct subject-related structures. This view is part of our self-image as science education researchers. Within this view, subject-related education is not just a mediator between the given knowledge and the learner. Rather, subject-related education is the authority that re-structures the subject-matter structure for specific purposes, strictly considering the possibilities and limits of the learner and empirically checking the fit between the re-structured subject matter structure and learning again and again. Therefore, this requires models that meet certain properties; they must be complementary, critical-analytical, and adaptive–recursive at the same time.

24.1.1.1 Complementary

The models must look at learning and teaching equally concerning one another. Thus, the models explicitly must represent and emphasize the complementarity of teaching and learning.

24.1.1.2 Critical-Analytical

The models must allow critical analysis of learning environments. This includes the design of entire learning environments, learning materials (such as exhibits or tasks), and subject-matter structures constructed with educational intent. It is precisely the critical-constructive approach to subject-matter structures that distinguishes genuinely subject-matter-oriented education from those of general didactics and educational sciences.

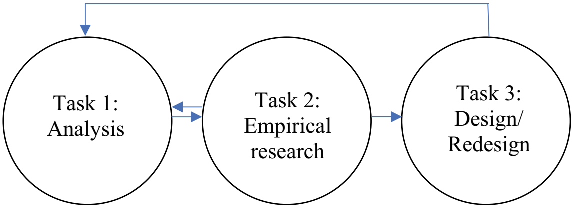
24.1.1.3 Adaptive–Recursive

The models must have an adaptive–recursive approach. This means on the one hand; the models allow modeling processes. On the other hand, the models explicitly must support the repeated adaptation of constructed subject-matter structures, teaching designs, and educational products based on empirical findings.

In the following, we present models that either fulfill all three properties (models of genuinely subject-related education) or largely do this in a combination of various general education models. We argue that subject-related education very often uses models from other branches of science, such as social sciences, general didactics, or educational science, and adapts them to tasks of subject-related education. This approach always is allowable if results demonstrably improve educational reality inside or outside of school. The first study from Sajons (2020) considers the combination of the offer-usage model with the design-based research approach (Chap. 24.4.1), in order to redesign an already existing learning environment in an out-of-school student laboratory. The second and the third study both rely on the Model of Educational, a proven, genuine subject-related model: In the second study we use the model to design a *new* learning environment in a national park house (Chap. 24.4.2) and in the third study, we use the model to improve an *already existing* learning environment in a science center (Chap. 24.4.3).

All three presented studies have three main steps, or so-called tasks, in common. As presented in Fig. 24.1, the first task is the “Analysis”. In case the educational structure already existed, the researcher first must analyze the existing learning environment and identify its strengths and weaknesses. In case a new learning environment was designed, the subject matter structures must be analyzed first. The second common task is the “Empirical study”. In this step the learners’ perspectives and, in some cases, the perspectives of other stakeholder groups were investigated. The third Task is the “Design” or, in case an educational structure already existed, “Redesign” of the learning environment, based on the previous analysis and empirical study. Because the models have an adaptive–recursive approach, the repeated adaptation of constructed subject-matter structures, teaching designs, and educational products based on empirical findings, is a key element of each model.

Fig. 24.1 Three tasks that all models used have in common



24.2 Combination of the Offer-Usage Model and the Model of Design-Based Research (Used in Study No. 1)—And Their Application in the Literature

If using models of general didactics or educational science for subject-related tasks, one must combine them in such a way that they meet the criteria we set out above. Our aim is to show this is largely possible for the combination of the offer-usage model (Helmke, 2012) and the design-based research approach (Design-Based Research Collective, 2003). Only the critical-analytical characteristic concerning subject-matter structures is not referred to by the combination of the two approaches. This is unnecessary in the present study because the out-of-school student laboratories we examined offer predetermined subject-matter.

The offer-usage model which is widely used in the German tradition of educational effectiveness research reflects the constructivist view of learning (Helmke, 2012), according to which the learning environment has no sole and direct influence on the actual learning, because many factors on the part of the learner are jointly responsible for the learning process and the learning outcome. Similar to the internationally used CIPO model (e.g. Scheerens, 1990) the offer-usage-model is based on a system theory that describes student learning by a transformation process of inputs (e.g. teacher background, given tasks, used material and objects) into outputs (e.g. student learning processes, motivational processes and effects). Accordingly, the transformation process is embedded in a context providing enabling or disabling conditions that influence how learners perceive the instructions offered. The offer-usage model by Helmke systematizes the various influencing factors as the teacher, classroom instruction, individual learning potential, learning activities, family, the context in order to analyze the transformation process and to integrate empirically grounded aspects of instructional quality into a comprehensive model. While Helmke focuses primarily on school processes, Meier (2015) transfers the model, also concerning Labudde and Möller (2012), to non-formal learning environments: The effect of the individual learning process and outcome depends on the background and goals of the learning location, the educational structure of the offer, the individual perquisites of the students as well as the preparation and follow-up in school lessons (Meier, 2015) (Fig. 24.2).

The offer-usage model by Meier used in this study, therefore, fulfills the above criterion of the explicit complementarity of learning and teaching. However, it is not intended to be a recursive model. To meet the requirement of recursivity, we added the cyclical approach of design-based research (Design-Based Research Collective, 2003) to the offer-usage model (Fig. 24.2). The design-based research approach fulfills the criterion of recursivity particularly well because it pursues the goal of improving the design by gradually adapting a design to the conditions of real learning, thus generating innovative educational practice. The goal of gaining generalizable and transferable knowledge (Tulodziecki, 2013) supplements this fundamental idea of optimization. These should make it possible to grasp and model the complex dynamics of real learning environments. Particularly, the focus of the design-based

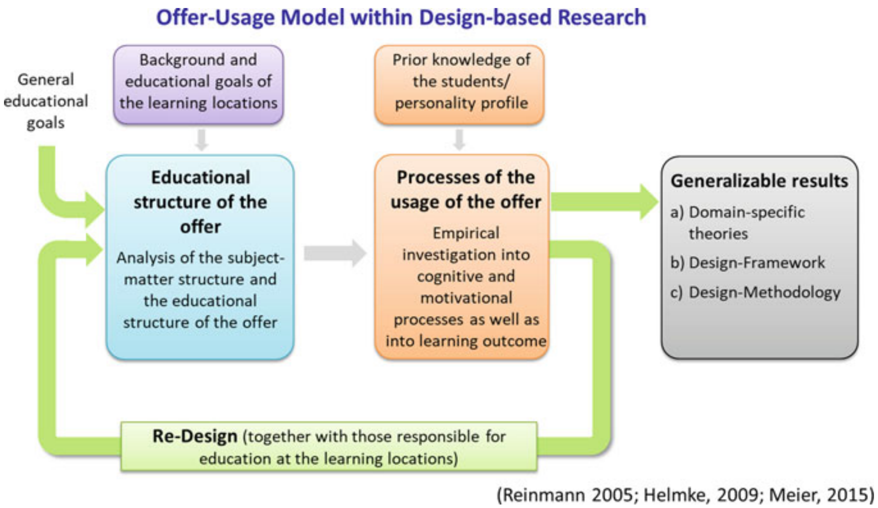


Fig. 24.2 Offer-usage model combined with the design-based research approach

research approach is to obtain general knowledge about, "how students and teachers respond to specific features of the design suggested by the theory" (Walker, 2006, p. 9). Accordingly, Reinmann (2005) formulates three levels of generalization based on Edelson (2002):

- *Domain-specific theories:* These are contextual theories that involve understanding teaching and learning from, and learning about, the effects of a design.
- *Design frameworks level:* Representing guidelines for the design of learning environments and formulated in a practical manner using tried and tested designs, these are transferable to other learning situations.
- *Design methodology level:* These relate to collaboration between researchers and workers in the formal learning environment. Joint educational development and personal interactions between both groups are central to the research and development process. Findings of this serve other research and development communities.

Reports of the combination of both models hardly exist in the extant literature. Figure 24.2 shows the combination of both models in a schematic and simplified manner. The offer-usage model expands in that way; that the empirical knowledge about how students use the tasks and objects offered in a learning environment leads to further development of learning environments based on empirical data. This yields implementation of the basic idea of the design-based research approach, providing an empirical check again of the changed offer.

24.3 The Model of Educational Reconstruction as a Genuine Subject-Matter Education Model (Used in Studies No. 2 and No. 3)—And Its Application in the Literature

Only through the constructivist view, learning gained recognition as a knowledge construction process decisively influenced by the learners' perspectives (Ausubel, 1968), which are worth examining. In the sense of the constructivist view, one must see the subject matter structures, as part of the teaching side, as constructions created by scientists. As Duit et al. (2012) point out, one cannot simply adopt subject-matter structures for teaching–learning environments but must *re-construct* to adapt them to the learners' perspectives. While reconstructed subject-matter structures must be scientifically adequate, there is a lot of freedom of representation, accentuation, setting priorities, and contextualization in the process of reconstruction for creating a new learning-teaching environment (Kircher, 2015).

This illustrates that in every teaching–learning situation three areas play a role, from the interplay from which construction of new knowledge arises: scientific content, perspectives of the learners, and design of the teaching–learning environment. The Model of Educational Reconstruction (MER) (Duit et al., 2012) represents the connection between these areas. The MER aims to address the scientific content from the perspectives of the learners through teaching–learning environments. The base of the model is thus a constructivist epistemology (Duit & Treagust, 1998). Moreover, the MER is a genuine model from science education because it explicitly considers a *reconstruction* of the subject-matter structure. Here, we do not interpret the perspectives of the learners as annoying misconceptions to eradicate, but as a necessary additional source of inspiration for the design of scientifically adequate and effective teaching–learning environments that one cannot create solely considering the scientific content. This expresses the content and needs of learners are symmetrical and equally important.

MER can serve as both a recursive research and a development approach (Duit et al., 2012) (Fig. 24.3). On one hand, we can investigate an existing teaching–learning environment by examining what construction of scientific knowledge is the target and to what extent we consider the learners' perspectives. On the other hand, we can develop new teaching–learning environments by analyzing scientific subject-matter structures, empirically examining the learners' perspectives, and ultimately relating both. Regardless of whether we develop new teaching–learning environments or further develop existing ones, we always examine them empirically for their learning effectiveness. The generated data leads to empirically justified changes to the educationally reconstructed subject-matter structures to adapt further the teaching–learning environment to the perspectives of the addressees. We again empirically examine the revised teaching–learning environments after the adjustments. We use this recursive research-and-development process steadily to approach

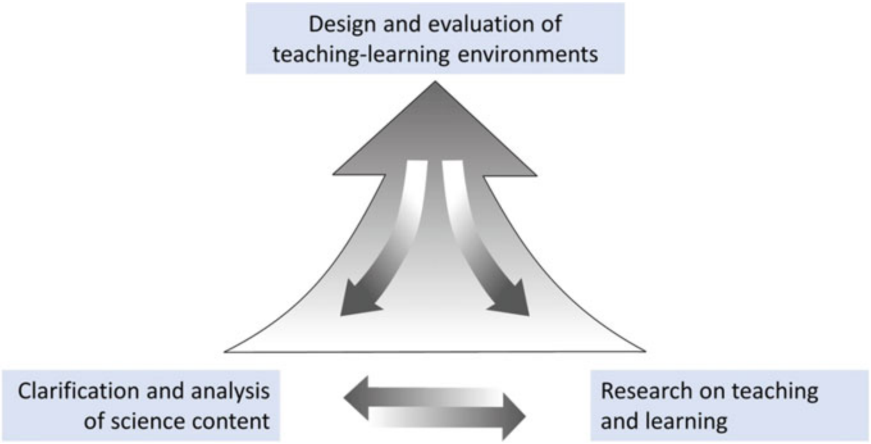


Fig. 24.3 Model of Educational Reconstruction (MER)

a learning-effective environment based on empirical data. The process of Educational Reconstruction is recursive in much the same way as the cyclical progression in design-based research (Psillos & Kariotoglou, 2016).

Although traditionally used for classroom purposes, there are attempts to transfer MER to out-of-school learning environments. Following Rennie's (2007) approach that the processes of learning are not restricted to certain settings, the findings of research on science education combined with the findings of museum research are useful when laying the groundwork for changing existing teaching–learning environments or constructing new ones (Laherto, 2013). Out-of-school learning environments such as a science center have the advantage of no imposition of constraints by a curriculum. Therefore, they can provide a wider range of cutting-edge topics and highlight socio-scientific issues while MER helps to address the topics from the learners' perspectives. For example, Stavrou et al. (2018) used MER as a theoretical framework to develop an inquiry-based teaching–learning sequence on nanoscience and nanotechnology topics that incorporates socio-scientific issues and out-of-school learning environments.

Laherto (2013) uses MER as a theoretical framework to develop new exhibits but specifically with an interpretation of visitors' interactions with the exhibits and the aim of the visit. Therefore, he suggests using the model as a general framework to involve analytical and empirical research in the development of learning environments to improve the long-term learning profit of exhibition visits. However, he points out that MER is unusable as a complete model of exhibition engineering, as there are more complex variables to take into consideration beyond the reconstruction of subject-matter structures based on empirical investigations of learners' perspectives. Laherto (2013) furthermore points out the need to adapt MER in such a way that it can model the visitors' learning through the interaction with exhibits.

24.4 Examples of the Application of Science-Education-Research Models to Non-formal Learning Environments

In this chapter we successively present the three studies in which the two models described in Chaps. 24.2 and 24.3 (the extend offer-usage-model and the Model of Educational Reconstruction) were used.

24.4.1 The Offer-Usage Model in a Study to Investigate the Cognitive and Motivational Dynamics in Out-of-School Student Laboratories (Study No. 1)

This example shows the application of the offer-usage model in combination with the design-based research approach in a study with three out-of-school student laboratories to model/describe teaching–learning processes in student laboratories. We use the findings to develop further their offers. The three laboratories are the ZNT in Aurich, the Learning Center Technology and Nature in Wilhelmshaven, and the DLR_School_Lab in Bremen.

Student laboratories are important elements of non-formal STEM education in central Europe. The so-called “student laboratories” are institutions that exist independently of schools. They belong to companies, to research institutions, to regional environmental education institutions, and sometimes are part of science centers. There are around 400 of these in Germany (Lernort Labor, 2019). Most often, classes attend a specific course for a day to stimulate scientific thinking and working, as the student laboratories claim that students can work there independently and the laboratories are more self-determined, more problem-oriented, and more context-oriented than at school. Because of that, some say student laboratories compensate for certain deficits in central European schools. The specific offers sometimes complement school lessons on topics found in the curricula and sometimes go beyond and focus on non-curricular topics such as space travel or biotechnology.

There is empirical evidence of the impact of student laboratories on situational interest and students’ motivation. Through a focusing, semi-structured, qualitative guideline interview with the pedagogical staff of the student laboratories, we see that the learning venues pursue not only the development of interest in STEM topics, but also the professional learning and the understanding of contexts such as sustainability. We see a lack of research concerning cognitive and motivational processes taking place there. Besides, there is little research on how to develop learning environments in student laboratories regarding specific educational goals. The aim of the study was therefore to elucidate the complex dynamics in STEM student laboratories and to model how the characteristics of the offers (tasks, material, objects) stimulate students to cognitive processes. These findings will be used to further develop the three specific student laboratories in this study as well as to learn more about how further to develop student laboratory offers in general concerning generally discussed educational goals.

To achieve these goals, we need a research model that explicitly distinguishes between the structure of the offer and its usage by students, systematically relates both sides to each other, and allows a recursive adaptation of the offer to the needs of the users. The combination of an offer-usage model and a design-based research approach seems to meet these requirements. Thus, the first task is to analyze the educational structure of the offer. Subsequently, we must investigate the cognitive and the motivational processes of the students (usage side) to find out what effects the educational structure of the offer show. This information can be useful in the design-based research process to consider how to develop further the educational structure (design). The DBR approach does not prescribe a specific procedure but leaves didactic and methodological freedom. Therefore, the analysis of the educational structure (the design), the empirical survey of its impact, and revision of the design are the three central tasks in the present study. The analysis of the educational structure is a strength-weakness analysis, which also highlights opportunities and risks (Task 1). The results of this analysis are then hypotheses regarding the actual cognitive and motivational processes (usage processes) of the students, which we must survey (Task 2). From this, we will derive reasoned suggestions for changes to the offers, which should lead to an optimization of the structure of the offers and provide more general knowledge about learning in student laboratories (Task 3).

24.4.1.1 Task 1 "Analysis": Identify the Strengths and Weaknesses of the Educational Structure

The educational analysis aims to find out how the tasks and didactic means fit in with the goals of the course and to what extent they are suitable for stimulating and supporting certain cognitive processes (e.g., perception, concept formation, learning) in the students. In this way, we can identify potential strengths and weaknesses, as well as development opportunities and risks. This analysis of strengths and weaknesses is a necessity for a recursive approach, which constitutes the DBR approach. The analysis tool allows us to develop an understanding of processes and to interpret problems in practice. The study focused on three aspects we can legitimize by current educational concepts in the field of STEM education (including scientific literacy (Organisation for Economic Co-operation and Development, 2019)) and by the expressed goals of the student laboratories. The three aspects are the contextualization (contextualized vs. decontextualized) during the offer, the integration of problem-solving tasks, and the support of student autonomy (self-directed vs. externally controlled). Regarding these three aspects, we examine cognitive and motivational processes the program potentially can support on the students' side. These processes include perception, conceptualization, contextualization and decontextualization, planned action, and problem solving (see Anderson, 2013; Edelmann & Wittmann, 2012), as well as the perception of autonomy, competence, and relevance as motivational processes (Lewalter, 2005).

Example Below, we illustrate the analytical procedure using an identified weakness in terms of contextualization as an example. In the DLR School-Lab, students investigate various vacuum phenomena in a vacuum bell, which stands for space. They test various everyday objects in a vacuum. The students make hypotheses about what happens to objects in the vacuum bell, where sucking out the air reduces the pressure. They should describe the behavior of the objects and explain what they see. Explanations from the laboratory staff supplement the students' hypotheses. The objects are a balloon and a marshmallow, which expand when the pressure drops in the vacuum bell, and an alarm clock, whose ringing is no longer audible in a vacuum.

> A didactic weakness regarding contextualization is that these student experiments do not address explicitly the context of space travel. Thus, didactic dramaturgy is lost, especially because the transfer of the students' experiment results back to the context of space travel is not supported explicitly. This may affect how relevant the students' perception of the vacuum experiments is for the context of the laboratory visit, to learn something about space travel/space.

On the aspects of problem orientation and autonomy, we found further examples that show explicit strengths of the offer.

24.4.1.2 Task 2 "Empirical Research": Examination of the Identified Strengths and Weaknesses

Whether strengths and weaknesses we analyzed from a didactic point of view come to bear and to what extent or with which students, we must test empirically. For this purpose, we must investigate which cognitive processes we can reconstruct from observation data and interview data. We equally use this data for confirming and refuting arguments regarding hypothetical strengths and weaknesses of the offer structure (the design).

Methods

We observed and interviewed some of the students using a semi-structured guideline. We used interview techniques from the ethnographic field research (see Döring & Bortz, 2016). We asked the students about their current activities, the subject matter they perceive, the connections they make between actions or objects, and motivational aspects. We pre-formulated and specifically integrated short, understandable questions into the flow of the conversation. For example, with the question, "What are you doing right now?", we intended to examine the extent to which students can understand and describe their activities and the task, or the extent to which they can appropriate the task. When joining a group of students during a laboratory day, we observed the activities and interactions of the students and we asked about certain aspects, if possible, without disturbing the students in their activities. As part of the group, the researcher adopts the students' perspective and thus can understand better how the students perceive and use the tasks and the means they used.

Example We asked the students about the vacuum experiments. In most cases, they cannot answer, for example, how the experiments on the expanding marshmallow relate to phenomena in space travel. The following transcript excerpt of the ethnographical data illustrates this, giving insight into the failure of students to think about the astronauts' food; they fail in establishing a concrete connection between the experiment of the expanding air-filled marshmallow and problems in space travel:

Interviewer: Why did you test the marshmallow there; what does this have in common with space or with space travel?
Student 1: Because if you have food in space, for example, I don't believe that you have…
Student 2: Strawberries with cream.
Student 1: Yes, and then you want to eat it and then like this [makes an extending movement with her hands]?

The weakness we identified in the analysis, that the rather context-free vacuum station is an obstacle to understanding properties of space/space context, we confirmed by the empirical data. Although the students make a general reference of the station to the context of space travel, the concrete examples, balloon or marshmallow, cannot refer to situations in space. However, in the sense of the offer-usage model, not only is the cognitive inability of the students the sole explanation of the problem, but also the educational structure is an explanation for cognitive processes that do not occur or occur with restrictions.

24.4.1.3 Task 3 "Redesign": Consequences for the Educational Structure

Due to the Design-Based-Research approach, the research process does not stop at this point. We are developing ideas for changing the educational structure of the learning environment. The goal is to exploit the potential of the student labs in terms of contextualization, problem orientation, and autonomy support. To this end, we will compare the results of the analysis of the offer structure with the empirically determined cognitive and motivational processes to identify the need for change and derive ideas for change. This requires creativity because there can be many solutions for changes based on the identified need for change. Following the design-based research approach, we then re-implemented, analyzed, and empirically investigated this changed structure of the offer.

Example In the example of the vacuum experiments, we need to establish explicitly the connection between the phenomena studied and the context of space travel. Therefore, in cooperation with the school lab operators, we further developed the offer so the students investigate different materials in a vacuum to find out what a spacesuit must do because it must not expand; even if there is overpressure in the spacesuit, it must be airtight and movable. We show that by further developing the vacuum experiments in this way, students can establish a clearer and more explicit relationship between the experiments and the spacesuit as part of the overall space/space context, as illustrated by the following quote from one student:

Interviewer:	What did you just do now?
Student:	Well, we talked about the vacuum. And… a balloon was our model of a spacesuit. We tried to adapt it in a way that it wouldn't burst. But that it's not stiff either so that it cannot stand in one position only. So, that it is movable. Yes.

24.4.1.4 Results of the Study Regarding the Optimization of the Offer

The modeling approach of the study allows the investigation of the educational structure of the offer as well as cognitive and motivational processes. Additionally, the approach allows us to relate both levels of results to each other and to derive ideas for change. We can show that in all the student labs we considered, similar strengths and weaknesses in stringent contextualization, integration of problem-solving tasks, and support for student autonomy are present. The contextualization, for example, shows that, although their focus is on contexts to motivate and introduce scientific topics, hardly any reference occurs during the offer to the established context or new sub-contexts included in the experimental activities, which are not well anchored in the overall context. These "context levels" and the change between them are not transparent for the students. The potential for integrating problem-solving tasks in the programs is not fully exploited and support for autonomous action by the students is limited. The significance of the offer-usage model is that recognized problems are not one-sidedly attributed to the students, but the influence of the educational structure on successful cognitive and motivational processes is high priority. The changes in the considered offers mainly are found in these areas:

- Increasing use of narrations anchored in the context (narrative anchors) and the contexts are explicitly a subject of discussion. This way, the tasks of the laboratory day relate to the context. Decontextualizing phases became emphasized as such in their meaning.
- Increasing embedding of contextualized problem-solving tasks; however, phases of direct instruction still had their place by creating a good sequence. Cognitively more challenging problem-solving tasks and increased perception of the relevance of the tasks and the perception of self-efficacy.
- Explicit establishment of phases of self-determined working with problem-solving tasks. They increased the students' perception of autonomy and overall motivation. Externally determined plenary phases, however, retained their function in that way that the students can become aware of the importance of individual activities for the overall goal of the laboratory.

Through these measures, the students gained a better understanding of the subject matter and the interrelationships, as the empirical data show. Besides, their motivation to deal with the tasks could increase while at the same time intensifying their perception of self-efficacy.

24.4.1.5 Results of the Study Regarding Generalizations for Learning in Student Laboratories

In addition to the optimization of offers, generalizations play an important role in the design-based research approach. In the present study, we achieved the following levels of generalization (according to Reinmann, 2005):

- We achieved area-specific generalizations concerning the offer-usage-processes by obtaining findings for all considered student laboratories. It was possible to formulate a generalized description of how we used the offers concerning contextualization, integration of problem-solving tasks, and support for student autonomy. This was possible because we recognized the educational structure and processes on the student side as equally important factors for the improvement of the offers. The recursiveness of the DBR approach allowed an adaptation to the needs of all participants.
- The "Design Methodologies" (according to Reinmann, 2005) provided insights for the cooperation between researchers and practitioners at the learning sites. In particular, the ethnographic approach not only referred to investigating the student's side, but also to the social context of the employees of the student laboratory. We can show how it is beneficial to the quality of the joint work to find a mutual hearing.
- At the level of "design principles", it was possible to formulate guidelines for the analysis and further development of offerings that relate to the three aspects of context orientation, problem orientation, and autonomy support.

On the one hand, the offer-usage model supports considering both an analysis of the educational structure of the offer as well as the survey of the learning process of the students. On the other hand, the design-based-research approach supports comparing the results of these two sides to optimize the offer and therefore represents a recursive approach. To sum up, the combination of these two models allowed elucidation of the dynamics of teaching and learning processes in student laboratories and development of their offers based on the findings.

24.4.2 Model of Educational Reconstruction in a Study to Develop an Exhibition on the Physics of Coastal Dynamics and the Exploration of Learner Perspectives (Study No. 2)

To illustrate the MER (Duit et al., 2012), we describe a project in which we used the model in cooperation with an out-of-school learning venue. The project aims to investigate and to develop new exhibits on currents and structure formations in the Wadden Sea. The project came about because there are many out-of-school learning venues in the German Wadden Sea, which use exhibitions to inform visitors of all ages about the Wadden Sea. However, the learning venues primarily are run by biologists and environmental scientists. According to Roskam (2020) and Bliesmer (2020), this results in two deficits:

- Thematic: The exhibitions are mostly about biology or ecology. Physical phenomena such as currents and structure formations (for example, ripple marks and dunes) so far are unaddressed, although they occur everywhere in the Wadden Sea.
- Disciplinary: The operators of the learning venues are unable to develop new exhibits based on findings from science education research. Exhibits are developed only together with exhibition agencies, whereby the learners' perspectives are systematically absent.

Because of these deficits, we established cooperation between physics education research and the out-of-school learning venues. The operators report that visitors often observe currents and structure formations in the Wadden Sea and seek more information about them. However, so far no related exhibits are present in the out-of-school learning venues. Through cooperation, development and examination of new exhibits happen with methods from science education research. The researchers chose MER as the conceptual framework.

The model demands both an analysis of the scientific content and an investigation of the learners' perspectives to develop new teaching–learning environments. Therefore, it fits very well with the objectives of the project: On the one hand, we must analyze the new topic (currents and structure formations) to clarify the subject-matter structure. On the other hand, we must appreciate and examine the learners' perspectives on the topic, since their pre-knowledge and their conceptions are important predictors for the construction of new knowledge (Ausubel, 1968; Duit & Treagust, 1998). We must then relate the scientific knowledge and the subject-related perspectives of the learners to one another. On this basis, we developed teaching–learning environments that have the pursuit of continuous learning pathways or that deliberately trigger cognitive conflicts (Scott et al., 1992; Duit & Treagust, 1998). We investigate whether we achieved this through an empirical study of the developed teaching–learning environments, then used the empirical data for revision and improvement.

24.4.2.1 Task 1 "Analysis": Clarification of Subject Matter Structures

From a constructivist perspective, the subject-matter structures in the scientific literature express a consistent representation of scientific knowledge. However, as stated in the introductory chapter, they are usually unsuitable for learners and therefore must undergo *reconstruction* with a special emphasis on the learners' perspectives to support the addressees to construct scientific knowledge. In preparation for reconstruction, we must analyze the subject-matter structures in the scientific literature. We used the concept of elementarization for this, which means we analyzed scientific literature to clarify the elementary scientific ideas (key concepts) suitable to explain the topic and related phenomena (Duit et al., 2012). To elucidate key concepts for currents and structure formations, we analyzed scientific literature from the fields of continuum mechanics (Haupt, 2002), non-equilibrium thermodynamics (Demirel, 2014), and complex systems (Bar-Yam, 2003). Besides, we examined journal articles on various structure formations: ripple marks (Anderson, 1990), dunes (Durán et al., 2010), and tidal channels (Fagherazzi, 2008). The following are examples of key concepts we worked out for the topic "currents and structure formations".

(1) *Gradients cause currents:*

Currents occur in fluids such as air and water. They are collective movements caused by temperature and concentration gradients (natural convection) or when external forces act on a fluid (forced convection). The latter means that momentum density gradients arise.

(2) *Currents are equalization processes:*

Currents caused by gradients reduce the gradients. That means currents counteract their cause. Therefore, currents are a phenomenological expression of an equalization process in nature.

(3) *Irregularities and currents initiate structure formations:*

When water or air currents move sand, irregularities, such as a shell in the sand, cause sand to get caught and accumulate there. These obstacles represent the trigger mechanism for structure formations in the sand.

(4) *Positive and negative feedback lead to self-organized structure formations:*

An obstacle, which acts as a trigger mechanism, results in positive feedback: If sand sticks to the obstacle, it becomes larger and even more sand piles up there. At some point, however, the build-up reaches a size and steepness at which more sand rolls down from the pile. Besides, the currents become turbulent through a larger pile of sand. Both have the effect of preventing further growth (negative feedback). In total, the structure formation stabilizes due to the interplay between positive and negative feedback, which is self-organization.

24.4.2.2 Task 2 "Empirical Research": Investigating Learners' Perspectives

We pursue two research approaches here. The focus is initially on what the terms "currents" and "structure formations" mean for the learners. This is relevant because phenomena and contents presented in the scientific literature often are named and described using terms that occur in everyday life but have a completely different meaning there. In German, this is the investigation of "Begriffsbildung" (Edelmann & Wittmann, 2012) and means the features and meanings of the terms from the learners' perspectives are under investigation. Subsequently, we examined the pre-knowledge and conceptions (Posner et al., 1982) learners use to explain the topic. Therefore, we conducted two interview series of semi-structured and problem-centered guideline interviews (Witzel, 2000) for both research areas. We described them below and anyone can use them in the same way for a topic other than currents and structure formations.

Interview series 1: Investigating what features learners associate with the phenomena

Research question: What are the features of currents and structure formations from the learners' perspectives?

We used 30 images as stimuli in the first interview. They show currents, structure formations, and phenomena that are scientifically neither currents nor structure formations. We asked the interviewees to select images they believed to represent currents. We then discussed the features for classifying currents. We asked them to name synonyms and antonyms of currents and justify them. We repeated the entire procedure for structure formations. We interviewed 16 out-of-school learning venue visitors (ages 15–75). We recorded and transcribed all interviews to evaluate them using a qualitative content analysis (Mayring, 2014). Exemplary results are as follows:

- Currents: They are dangerous because they can put people in the water at risk. Furthermore, currents are collective movements of individual parts, whereby the extent of the parts must be small compared to the overall movement.
- Structure formations: Central features are irregularity and regularity. With "irregularity", they make clear that structures stand out from a homogeneous environment. "Regularity" refers to the spatial and temporal periodicity of structures. Interviewees consider them unique and call them "nature's fingerprint", as they only reappear similarly, not exactly.

Interview series 2: Investigating how learners explain the phenomena

Research question: What scientific ideas do learners use to explain currents and structure formations?

We carried out two experiments, which act as stimuli. We structured the interview using the POE procedure (White & Gunstone, 1992). The letters stand for predict, observe, and explain. We asked the respondents to name and justify their predictions before experimenting. While carrying out the experiment, the respondents are to

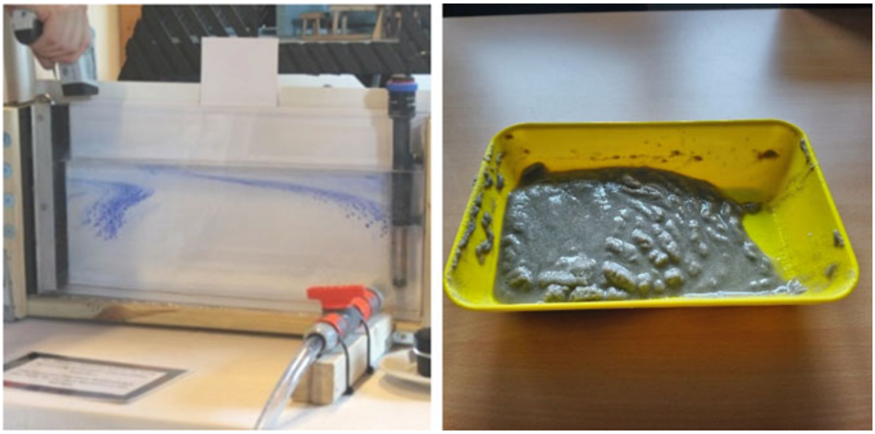


Fig. 24.4 Experiments are to create convection cells and structure formations

verbalize their observations. Finally, we asked them to explain their observations. The first experiment is a water basin heated on one side and actively cooled on the other (Fig. 24.4 left). The resulting temperature gradient creates a convection cell made visible by adding ink. The second experiment consists of a bowl of sand and water (Fig. 24.4 right). By moving the bowl back and forth rhythmically, one causes structure formations to develop inside.

In the later course of the interview, the questions also went beyond the specific experiments concerning currents and structure formations in general. We interviewed 15 of the people from interview 1. We transcribed the interviews and performed a category-generating, qualitative content analysis (Mayring, 2014). Exemplary results are as follows:

- Currents: Although the phenomenon in the experiment is natural convection, the respondents focus on forced convection caused by external forces. In this regard, they argue with a *transfer principle*, according to which matter already in motion transfers its dynamics to air or water. The learners are unable to explain the natural convection that occurs in the experiment.
- Structure formations: Learners argue that irregularities in environmental conditions (for example, temperature or sand speed) produce irregularities in the sand. Learners interpret these irregularities as structures. However, the learners cannot explain the processes in structure formation. Furthermore, respondents apply a *transfer principle* here too; they assume that pre-structured matter (a water wave) transfers its structure to unstructured matter (sand), which leads to structure formation (ripples marks). Because they explain structures with structures, they create an argumentative dead-end, a chicken-egg problem.

24.4.2.3 Task 3 “Design”: Design and Evaluation of Teaching–Learning Environments

Here we relate the results of the two previous tasks to each other by systematically comparing the scientific key concepts with the examined learners’ perspectives (Duit et al., 2012). The aim is to reconstruct the subject-matter structure of the subject area in such a way that the learners’ perspectives serve as a starting point for building up new knowledge (Scott, 1992). Teaching guidelines express the reconstruction of the subject-matter structure (Niebert & Gropengiesser, 2013) for the creation of new exhibits that address currents and structure formations. We then use the guidelines in cooperation with an exhibition agency to jointly develop new exhibits. The guidelines are therefore not recipes for the creation of exhibits (or teaching–learning environments in general), but rather emphasize what to consider from the viewpoint of physics education research to create new teaching–learning environments. We described three exemplary guidelines:

Guideline 1: Focus on features of the phenomena from the learners’ point of view

The learners see currents as dangerous. That is why we introduce “collectivity”, the directed movement of water, as a central feature of currents. We explain that currents are dangerous because the directed movement pushes people far into the sea. Concerning structure formations, we introduce “similarity” as a feature, because this ties in with the learners’ perspective, as they explain characterization of structures by periodic sequences and patterns that repeat imperfectly but similarly and therefore stand out from their homogenous environment.

Guideline 2: Address forced convection before natural convection

Because the learners concentrate on currents that, from a scientific viewpoint, are forced convection, an exhibition starts with this type of convection. The *transfer principle* the learners use will link to the scientific concept of energy transmission: Energy transfers to water or air and converts into kinetic energy. Based on this, we introduce that currents represent an equalization process (a scientific key concept). The kinetic energy distributes in the fluid, gradients reduce, and ultimately disappear. Finally, we thematize natural convection, which results from temperature and/or concentration gradients; we also represent free convection as an equalization process because it reduces the gradients as well.

Guideline 3: Interpret irregularities as the starting point of structure formations

Learners explain structure formations with irregularities in environmental conditions. Because this is also the first step in a scientific explanation, we take into account the learners’ perspectives as follows: We reinterpreted the irregularities as starting points for structure formations but clarified that irregularities in the environmental conditions cannot explain the processes in the formation of structures. To motivate the need for further clarification, we confronted the learners with their *transfer principle*. We underlined that by using that principle they explain structures with structures. This creates a chicken-egg problem. To show them a way out of the problem, we offered explanations based on feedback processes. Proceeding from irregularities that function as starting points, positive and negative feedback processes set in, which establish self-organization.

24.4.2.4 Conclusion and Further Tasks in the Recursive Research Approach

Because we chose MER as conceptual framework in the present study we did consider both the scientific content (through elementarization) and the learners' perspectives (through empirical research). Only if we examine both can we systematically compare them with one another. This comparison represents the nature of MER since the reconstruction of the subject structure aims at the central endeavor to consider teaching and learning equally when developing teaching–learning environments.

In the present project, we used the guidelines in cooperation with the operators of out-of-school learning venues and exhibition agencies. By using the guidelines, we fed a perspective from science education research into this cooperation, in which new exhibits developed. After integrating the exhibits into the exhibitions, we examined their effect on visitors in another empirical study. Using the data from this empirical study, we will revise and improve the exhibits. MER therefore represents a recursive approach in which research and development closely link (Duit et al., 2012).

24.4.3 Model of Educational Reconstruction as a Framework to Study Students Learning Through Exhibits of a Science Center (Study No. 3)

In this study, we applied the MER (Duit et al., 2012) to situations where learning takes place by interacting with exhibits in a science center during a school visit. We needed to analyze the scientific and educational structure of the exhibits (Task I). From a constructivist point of view, we must relate the results of these analyses systematically to the empirical results of the learning processes (Task II) to suggest changes (Task III) that could support the learning processes of the users. The current example study took place at the Phänomenta Bremerhaven science center in Germany, where we selected five hands-on exhibits (Camera obscura, Visible light, Bernoulli Effect, Pulley system, and Brachistochrone) with varying interaction challenges. We used the four interaction challenges to explore fourth-grade students' learning processes as they interacted with the exhibits. Our goal was to investigate to what extent learning of scientific content occurred and what actions could be observed while interacting with the exhibits. Additionally, we wanted to determine to what extent the intentions of the science centers' administrators and the classroom teachers fit the learning processes of the students.

24.4.3.1 Task 1 “Analysis”: Analysis of the Teaching–Learning Environment

It is necessary to clarify the scientific concepts represented at the exhibit. One of our objectives was to determine to what extent the understanding of visitors deviates from the socially shared knowledge of science. Afterwards, we consider how scientific knowledge is restructured and acquired by learners on the basis of their preinstructional conceptions. To clarify the preinstructional key concepts of the exhibit, we completed an analysis of scientific literature and journal articles.

For example, the Visible Light (Fig. 24.5) exhibit includes three colored filters (red, green, blue) and a prism. Each filter and the prism may be folded down one by one or simultaneously in front of a light source. The written task at the exhibit is: “Look at the spectrum of visible light with the prism, and the filters will let the light pass only through a certain area”. Key concepts from the Visible Light exhibit that were color subtraction and light refraction and dispersion.

To analyse further the educational structure of the exhibit, we formulated the possible interactions with the exhibits. By seeing the epistemological similarities between MER and the anthropological theory of didactics (ATD), the concept of “praxeology” (Chevallard, 2007; Bosch & Gascón, 2006) may be used for operationalizing the link between the identification of tasks proposed for certain exhibits and the conceptual knowledge that is offered by interacting with these exhibits (Mortensen, 2010). The four elements of praxeology proposed by Achiam (2013) are:

(1) Task: Students identify relevant components and perceive the explicit task of the exhibit.
(2) Technique: Students perform or apply a procedure in each situation to solve the task.

Fig. 24.5 Exhibit “Visible Light”

(3) Technology: Students justify their actions. They explain what happens while they interact with the exhibits and why it happens.
(4) Theory: Students justify their actions and the exhibits' response by theoretical concepts.

In each element, cognitive processes play a key role like recognizing, remembering, interpreting, classifying, summarizing, comparing, explaining, executing, implementing, differentiating, organizing, reviewing, generating, planning, developing etc. (Bloom, 1956; Anderson & Krathwohl, 2001).

Example: Potential praxeology at the exhibit Visible Light

We took into consideration the key concepts the exhibit could support when someone interacted with it. We used these concepts to create a praxeology showing the possible actions and learning processes that could occur. We describe these below.

(1) Task: Identifying all components of the exhibit (Lamp, Button, Three Colored Filters, Prism, Text). Retrieving previous knowledge about the subject (visible light) and how to use the recognized objects.
(2) Technique: Understanding/interpreting objects and text in the exhibit and applying previous knowledge to conduct the activity and observe what will happen at each step. For example: press the button to turn on the lamp, place the prism in front of the light source, place the filters between the light and the prism, etc.
(3) Technology: Explanation of the user's manipulations at the exhibit and their reasoning, explanation of the phenomenon observed, and differentiating between relevant and unrelated variables that may affect the phenomenon. Users could explain that the prism splits the white light into a spectrum and that each filter lets a different part of the spectrum through.
(4) Theory: Users will be able to justify their observations by using theoretical science concepts, such as color subtraction and light refraction and dispersion (e.g. the prism causes different colors to refract at different angles, splitting white light into a spectrum, the filters absorb different parts of the spectrum). However, we did not expect the fourth-graders (provide ages because this is an international book) in our study to attain this level of knowledge.

24.4.3.2 Task 2 "Empirical Research": Students, Centers Operators and Teachers Perspectives

We should take into consideration the complexity of the learning situation during a school visit in out-of-school learning settings (Griffin, 2012; Falk & Dierking, 2000). Empirical studies should examine students' individual learning processes from a constructivist point of view (Driver et al., 1985). Moreover, researchers should consider the expectations and learning goals of the centers' administrators and the classroom teachers in terms of students' interactions with the exhibits. By reconstructing the expected praxeologies of the centers' operators and the teachers of certain exhibits and comparing them to the praxeologies of the students, which are empirically observed during their interaction with these exhibits, we can suggest possible changes for the informal teaching–learning environment.

Example: Investigated praxeology of center operators' expectations

To learn more about the praxeology the center operators expect from the students, the operator of the science center was interviewed with questions like: "What do you think a student would do and understand when interacting with this particular exhibit?". To determine the actions and learning paths that were expected to occur while interacting with the exhibits we evaluated the empirically obtained data using qualitative content analysis (Mayring, 2014).

(1) Task: Identifying all items in the exhibit (Lamp, Button, Three Colored Filters, Prism) and text. Retrieving previous knowledge about the subject (visible light) and how to use the recognized objects. The students will realize that the task is to look at the spectrum of visible light with the prism and see that the filters will let the light pass only through a certain area.
(2) Technique: Understanding/interpreting objects and text in the exhibit and applying previous knowledge to conduct the activity. For example, pressing a button to turn on the lamp, place the prism in front of the light source, placing the filters between the light and the prism, etc.
(3) Technology: Explanation of the user's manipulations in the exhibit and their reasoning, explanation of the phenomenon observed and differentiating between relevant and unrelated variables that may affect the phenomenon. Users could explain that the prism splits the white light into a spectrum and that each filter lets a different part of the spectrum through. For example, when white light shines solely through the red filter, students see that all colors but red are absorbed by the filter. When red and the blue filters are in front of the light source, students observe that little to no light is shining through, which occurs because most of the light is absorbed by the two filters.
(4) Theory: Students will not use more abstract terms, such as color subtraction, to explain why the light did not go through the filters.

Example: Investigated Praxeology of students

Interview techniques from the ethnographic field research were used (citation needed). While students interacted with the hands-on exhibits, we use participatory observations to observe 24 students. Additionally, we questioned those 24 students in groups of two using a semi-structured guideline to reconstruct their praxeology. For example, we asked, "What can you do about this particular exhibit? Can you explain what is happening to the exhibit?". Furthermore, students completed questionnaires with open-ended and multiple-choice questions before and after the school visit. We sought to determine what ideas emerged from the phenomenon of the selected exhibits and students' expectations of the science center visit. To determine the actions and learning paths, we evaluated the data using qualitative content analysis (Mayring, 2014) and related the data systematically through data triangulation (Flick et al., 2004). By analysing all students' interactions and learning processes with the exhibit we came to a praxeology that represented most of the students:

(1) Task: Identifying almost all items in the exhibit (Lamp, Button, Three Colored Filters, Prism). They understood how to use the recognized objects. However, they ignored the text and did not realize the task was to look at the spectrum of visible light with the prism and determine the prism will let light pass only through a certain area.
(2) Technique: Understanding/interpreting objects in the exhibit and applying previous knowledge to conduct the activity (e.g. press the button to turn on the lamp. Place the prism in front of the light source, place the filters between the light and the prism, etc.) However, as there was no specific order given, in which the students should conduct the possible activities, each student group used each object of the exhibit in a different order.
(3) Technology: Explanation of the user's manipulations in the exhibit and his reasoning, explanation of the phenomenon observed that are not aligning with scientific knowledge that is scientifically accepted. Students explained their actions and the phenomenon observed by using their preconceptions and object-related explanations (e.g. when the light goes through the red filter, the light is being colored by the filter, that's why it's red or when the light goes through the red and blue filters it should become purple if the filters were not too thick.)
(4) Theory: Students will not be able to justify their observations by using theoretical concepts such as color subtraction, as it was expected by the centres' operator.

Example: Investigated Praxeology of the teacher's expectations of students

We conducted video-based interviews with formal classroom teachers to investigate their praxeology concerning the actions and learning processes expected from the students. Because of time limitations, we were not able to interview the classroom teachers simultaneously with the students on the day of their school visit. Therefore, we made videos of the exhibits in which the possible manipulations and the phenomenon shown at the exhibits were presented. By using those videos, we interviewed teachers by asking them questions like "What do you think a student would do and understand when interacting with this particular exhibit?". We implemented complementary teacher questionnaires with open and multiple-choice questions before and after the school-visit, based on categories by Cox-Peterson et al. (2003) and Griffin and Symington (1997). The questionnaires asked about the teachers' views of the learning outcomes they expected from the students' visits, and how the visit to the science center could be integrated into the school curriculum (preparation, expected learning outcomes to be achieved by the visit, etc.).

(1) Task: Identifying all items in the exhibit (Lamp, Button, Three Colored Filters, Prism) and text. Retrieve previous knowledge about the subject (visible light) and how to use the recognized objects. By reading the text students would perceive the task to see the spectrum of visible light with the prism and what filters do with it.

(2) Technique: Understanding/interpreting objects and text in the exhibit and applying previous knowledge to conduct the activity (e.g. press the button to turn on the lamp. Place the prism in front of the light source, place the filters between the light and the prism, etc.).

(3) Technology: Explanation of the user's manipulations in the exhibit and his reasoning, explanation of the phenomenon observed that are not aligning with scientific knowledge that is scientifically accepted. Students explain their actions and the phenomenon observed by using their preconceptions.

(4) Theory: Students will not be able to justify their observations by using theoretical concepts such as color subtraction, light refraction etc.

Merging the three perspectives

The results of this study indicate that when students visit the science center, they recognize how to use the objects (buttons, filters, light source, prism) at the exhibit. However, because they do not read the text they do not realize the goal of the exhibit (Task). Students are nonetheless able to carry out all work procedures (e.g. press the button, place the filters and the prism in front of the light source) (Technique). They can give explanations (Technology) to their actions on the exhibits. However, these explanations do not always agree with the ones desired of the exhibition supervisor (Achiam, 2013). Students tend to explain their actions and the phenomenon observed by using their preconceptions and object-related explanations. Moreover, students have difficulties in justifying themselves with abstract concepts (Theory). Our work confirms previous studies that the students, teachers, and center operators' views are not aligned (Griffin, 2012). We suggest further research is needed to bridge the gaps between the science center operators' intended use and the learning processes experienced by students, the teachers' views of their students learning, and the students' actual use and learning processes while interacting with the exhibits.

24.4.3.3 Task 3 "Redesign": Re-designing the Teaching–Learning Environment

In this final step, we are developing ideas for changing the educational structure of the teaching–learning environment. Our goal is to exploit the potential of school visits at a science center. To this end, we compare the results with the empirically determined cognitive processes to identify the need for change and derive ideas for change. There are three ways in which this study could support the re-design of the teaching–learning environment:

I. Providing guidelines for exhibit developers on how to build a new exhibit or change an existing exhibit based on the empirical data and the literature-based exhibit evaluation.

II. Providing guidelines for teachers for pre-post preparation of a school visit at a science center (Geyer, 2008; Stern et al., 2008; Behrendt & Teresa, 2014; Coll et al., 2018; Lee et al., 2020).

III. Providing guidelines for the centers' educators on how to include certain exhibits during the school visit.

Example for re-designing the Visual Light exhibit

After systematically relating the results of the scientific and an educational structure analysis to the empirical results of the learning processes from a constructivist point of view, we are suggesting some of the following changes/additions that could support the learning processes of the students during a school visit:

- To change the students' idea that the light goes through the filters because of the phenomenon of color addition (e.g. green, blue and red filters makes black light—not the absence of light seen on screen), it is not only important to use monochromatic filters, but also to instruct that the prism should be folded down before the filters are. If the spectrum is explicitly marked on the screen, students should more easily realize the color of the light at that moment and that the other colors of the spectrum are no longer visible on the screen.
- Students believe that the filters do not let light pass through because they are too thick. This belief could be changed by providing an additional exhibit or suggest to teachers to follow up with post-visit experiments (Behrendt & Teresa, 2014; Coll et al., 2018; Lee et al., 2020). Students could experiment with thinner foils in the colors green, red, and blue and varying light source intensity.

24.5 Importance to Research

Our examples show how subject-related models, or the combination and adaptation of general education models can improve research in non-formal learning environments. Our work indicates how generalizable knowledge about non-formal learning arises and how learning objects and exhibition designs can be further developed. The choice of models is tied to criteria that are closely related to the research objectives. In the field of non-formal learning, one research goal is to understand and model the complex dynamics of teaching–learning situations. This is only possible if one does not focus one-sidedly on learning, but at the same time analyzes the learning environment, its educational structure and methods of presentation. A learning environment can take on a broad spectrum of manifestations, starting with simple objects in the museum and interactive exhibits in the science center to guided explorations in an out-of-school laboratory. In all these cases, models are required that explicitly allow an analysis of the learning environment. The learning environment itself becomes the object of research because it is part of the dynamic of the teaching–learning situation and not a simple static prerequisite for learning.

MER as a research and development model allows an explicit analysis of the teaching side. The offer-usage model is also suitable for studies that seek to understand teaching and learning in their complex, complementary interaction. Furthermore, MER explicitly allows and requires the subject matter structures be criticized, questioned, or re-constructed. Educational Reconstruction can be applied in studies in which new topics are prepared for non-formal education or in which the scientific content has so far been insufficiently analyzed and elementalized, resulting in learning difficulties.

In our studies, we present the importance of the enrichment of knowledge about complex teaching–learning dynamics as a goal and further develop the out-of-school learning environment. We conclude models are required, which explicitly represent the development process and suggest a certain expressive approach. These models should be recursive and adaptive. We combine the MER, the complementary offer-usage model, and the DBR to meet the criterion of recursivity by repeatedly testing educational structures and adapting them to the students' recognized learning opportunities and learning difficulties. The merging of the models enables the gradual adaptation and improvement of learning environments for the learners. The MER additionally allows a constant readjustment of the subject-matter structure.

The models shown help to understand the dynamics of a wide variety of teaching–learning environments and thereby allow to develop them further based on empirical data. Therefore, a variety of research questions and development tasks can be approached in non-formal learning environments. This is important because the non-formal learning opportunities are increasing in number and importance, reflecting a world of education that is becoming more differentiated and should be explored. After all, a very large educational potential can be recognized here in terms of supplementing school education and in terms of lifelong learning.

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