MODELING-BASED LEARNING ABOUT CHEMICAL PHENOMENA IN PRIMARY EDUCATION

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National and international studies demonstrate that students at primary level are able to express their mental models by drawing. These findings illustrate that modeling-based learning in primary school is partly possible. However, a deeper look at the results shows that the drawn models do often not correspond to scientific ideas or are inadequate to explain a phenomenon. Furthermore, most of the current research in primary education is focused on physical phenomena, e.g., the hydrologic cycle. Chemical topics, like solubility, are rarely represented in scientific research on this topic. One assumption to underline this research gap could be that modeling-based learning about chemical phenomena in primary education might be difficult because the chemical process takes place at the submicroscopic level. Because of that, a qualitative study was planned, which aims to clarify to what extent chemical phenomena are suitable for modeling-based learning in primary education. The study was conducted at a German primary school with ten fourth grade students. During the intervention, the students are confronted with two different phenomena: Boiling water in a kettle and dissolving table salt in water. These phenomena are the starting point for the student modeling process during the study. The data is collected through teaching experiments which are videotaped and then transcribed for the analysis. In addition to the teaching experiments, the drawings and the videotaped drawing process are available for the evaluation. The results of the study show that modeling-based learning about chemical phenomena is fruitful in primary education if appropriate interventions are available. The students are able to express their mental models by drawing. However, most of the built models can hardly be used to explain the phenomenon and do not correspond to scientific ideas. Because of that scaffolds are needed for modeling-based learning in primary school. Therefore, a study is following which focuses on support measures in modeling-based learning about solubility.

Keywords: Mental Models, Modeling-based Learning, Primary School

BACKGROUND AND RATIONALE

National and international science standards show that explaining and understanding scientific phenomena is important for science education at school in all grades (GDSU, 2013; National Research Council [NRC], 2012). Following NRC (2012), students should learn to explain phenomena with the help of (self-generated) models. Modeling is one method to achieve this goal in school (Constantinou et al., 2019; NRC, 2012; Nicolaou & Constantinou, 2014).

Forbes et al. (2014) demonstrate in their study that 3rd-grade students are able to draw a model of the hydrologic cycle. In order to analyse the drawn models, Forbes et al. (2014) set three levels of learning performances. These three levels are defined among other things by the explanatory process. The explanatory process describes how the verbalised elements, e.g. the connection between temperature and state of matter, are represented in the drawn models. Although the students are able to express their mental models by drawing, it is noticeable that the drawn models have gaps in their explanatory process. Lange et al. (2014) confirm these results in their study in a 4th grade at a German primary school. This study also illustrates that
students at primary level are able to construct and revise the model. However, the built models do not correspond to the scientific models (Lange et al., 2014).

These results are focused on physical phenomena, like the hydrologic cycle. Phenomena of the chemical domain are hardly represented in current research to modeling-based learning in primary school. This could be due to the fact that modeling on a submicroscopic level might be more difficult than on the macroscopic level. Because of that further research of modeling-based learning about chemical phenomena in primary education is needed. The following article is focused on this research gap. Firstly, the theoretical framework of modeling-based learning is presented in more detail. After that, the conducted study and the achieved results are presented and discussed. Finally, an outlook on further research is given.

THEORETICAL FRAMEWORK

In the educational context, modeling plays an important role in order to explain a phenomenon with the help of a model and to gain new conceptual knowledge. Following Clement (1989) the modeling process is “used to develop an explanation for a newly recognized phenomenon” (p. 346). In primary education, students are confronted with those phenomena that are part of the students’ living world. One aim of science education in primary school is to take up real-life phenomena as a topic of learning and to gain new insights about the phenomenon during the lesson (GDSU, 2013). For such a knowledge acquisition it is important to perceive the students’ initial mental models and to develop them into a scientific mental model, which is described by Vosniadou (1994) as conceptual change. In order to reach a conceptual change, it is necessary that the students actively engage with their mental models, discuss explanations and test and revise their mental models. Only through such an active engagement and a conscious design of the learning setting it is possible to achieve a conceptual change (Gilbert & Justi, 2016; Vosniadou, 1994).

In order to reach a conceptual change, modeling-based learning could be useful. Gilbert and Justi (2016) developed a Model of Modelling v2 that focuses on the modeling practices and is a complement to the original ‘model of modelling’ framework by Justi and Gilbert (2002). Following Gilbert and Justi (2016) modeling is a process, which is dynamic and cyclic. In order to build a model through modeling, the modeler goes through four phases: First, a cognitive representation of a phenomenon – the mental model – is built. This mental model will be expressed in various ways of representation, e.g., in a 2D model by drawing it. Afterwards, the expressed model can be tested in experiments or simulations. Finally, the built model must be evaluated. In this phase, it is necessary to identify the limitations of the model by testing it in different contexts. After identifying the limitations, the model should be revised, which requires a new cycle of the modeling process. During this modeling process, various cognitive processes take place, e.g., analogical reasoning (Gilbert & Justi, 2016).

However, a closer look at the term modeling shows that modeling is used in different ways in scientific discourse. According to the literature review of Constantinou et al. (2019), modeling is described as a skill or, as mentioned above and following NRC (2012), a practice to explain phenomena with the help of models. In the educational context, modeling-based learning is linked to teaching strategies, like described by Louca and Zacharia (2012), or defined as a
scientific method to achieve scientific literacy (Constantinou et al., 2019). To summarize these facets of the concept of modeling, Constantinou et al. (2019) develop a framework for modeling-based learning based on the concept of competence according to Weinert (2001). Understanding modeling as a competence combines both practical skills and metacognitive knowledge about models and modeling (Constantinou et al., 2019; Nicolaou & Constantinou, 2014).

In addition to the current research by Forbes et al. (2014) and Lange et al. (2014), the following study will focus on the modeling practices. Therefore, students go through the modeling process in a non-linear and dynamic way to construct a self-generated model, as shown by Gilbert and Justi (2016).

RESEARCH GAP AND RESEARCH QUESTIONS

As mentioned before, modeling-based learning about chemical phenomena is rarely represented in current research. Therefore, it is necessary to identify suitable phenomena as learning contents for modeling-based learning in primary school. Following the national standards for science education in primary school, three different chemical topics are suitable for learning science at primary level: State of matter, solubility of solids in liquids and burning processes (GDSU, 2013; MSB NRW, 2008). The extent to which these phenomena are a suitable learning content for modeling in primary education is the core of the following study. In concrete terms, the following research question can be formulated from this:

To what extent are primary school students in the 4th grade able to model chemical phenomena?

RESEARCH DESIGN AND METHODS

In order to investigate the above research question, the students are confronted with three different phenomena: State of matter, solubility of salt in water and the burning process of a candle. After the presentation of each phenomenon, further experiments are shown to focus on specific aspects of the phenomenon. To discuss the change of state of matter with the students, the boiling of water in a kettle is first presented as a phenomenon. After that, a plate is held over the opening of the kettle during the boiling process. In this short experiment, the students can observe the condensation of water on the plate. In addition to the change of state of matter, the students are confronted with the solubility of salt in water. For this purpose, salt is put into a glass of water so that the students can observe the solution process. To check whether the salt has been dissolved and is still present, the evaporation of the solution is shown. Finally, in order to examine the burning process of a candle more closely, the students are also confronted with the phenomenon in this case. For this, a candle is lighted, which is observed by the students. In order to examine the partial processes of burning, four short experiments are shown. First, the wick is observed more closely and it is investigated whether it also burns without the candle wax. Then the extent to which air plays an essential role in the burning process is examined. For this purpose, a glass is put over the candle. Finally, the products of the burning process are investigated. To do this, a glass is held over the candle in such a way that water and soot becomes visible.
The presented intervention is part of the planned qualitative study. A qualitative study enables to get insights into the personal ideas and thinking process. Common research methods are observation and interviews in order to get such personal insights (Creswell, 2013, 2014). In educational context, qualitative methods, e.g. teaching experiments, are used to investigate learning processes (Scheck et al., 2014). The teaching experiment represent a specific qualitative method in educational context, where “the researcher acts as teachers” (Steffe, 1991, p. 177). The benefits of the teaching experiment are that the researcher can react individually to what the participant says in the situation and make decisions on the spot (Steffe, 1991). Because of this benefit, a teaching experiment is planned for the following study. In order to plan the data collection more precisely, the teaching experiment is pre-structured with questions and stimuli. The pre-structured guide includes the following structure, shown in Table 1:

Table 1. Pre-structured guide of the teaching experiment using the example of the solubility of salt in water.

<table>
<thead>
<tr>
<th>Teaching experiment</th>
<th>Mental model</th>
<th>Stimuli</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Let's take a closer look at salt now.</td>
<td>The salt dissolves. The salt melts. The salt evaporates. The taste has transferred. Water absorbs the salt. The water becomes salty. The salt is gone or is disappeared.</td>
<td>➔ What do you mean by the salt ‘dissolves’/ ‘melts’ / ‘evaporates’ / ‘is gone’?</td>
<td>Salt, glass, water</td>
</tr>
<tr>
<td>I have taken salt and a glass of water with me.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>If I put salt in the water, what happens?</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As shown in Table 1, the teaching experiment includes little experiments that focus on specific aspects of the phenomenon. While conducting the experiments, questions are asked in order to gain insights into the mental models of the participants. In addition to these questions, possible statements related to the underlying mental models are included in the above pre-structured guide. The statements in this case relate to the literature review by Grüß-Niehaus and Schanze (2011). In their overview, Grüß-Niehaus and Schanze (2011) summarise possible learners’ conceptions about solubility. According to these possible answers, the stimuli are planned. This allows the researcher to react to the participant’s statements on the spot. In addition to the questions and stimuli, the material for the experiment is also included in this structure to ensure that the study runs smoothly and comparably.

Next to the superordinate structure explained here, the teaching experiment on the three phenomena has the following structure:

Figure 1. Structure of the teaching experiment.

According to the modeling process by Gilbert and Justi (2016), the students are confronted with the phenomenon in order to create an initial mental model. After that, the students have to draw the chemical process, which represents the expression of the mental model. In order to test their models, the students are confronted with short experiments that focus on certain aspects of the
phenomenon. The students are then asked to revise their 1st drawing and explain the phenomenon using the model they drew before.

During the teaching experiment the students have to describe their thinking process by using the think aloud technique. Think aloud is a method to gain insights into the students’ thinking process. Meanwhile, the “participants are explicitly instructed to focus on the task while thinking aloud and merely to verbalize their thoughts […] rather than describe or explain them to anyone else” (Ericsson & Simon, 1998, p. 181). In the conducted teaching experiment, this method is explicitly used for the drawing process in order to get a deeper look at the elements represented in the drawings. This protocol of think aloud is also necessary for the correct interpretation of the drawings.

The teaching experiment is videotaped and forms the basis for the analysis. The drawings are analysed with the help of the recorded video-data. The audio-data of the videotaped teaching experiment is transcribed afterwards. This transcription is the basis for the qualitative content analysis according to Mayring (2014). Mayring (2014) defines different types of techniques: Summarising, inductive way of categorisation, explication and structuring by deductive categories. For the study described and data collected, the inductive categorisation and structured content analysis by using deductive categories are useful. According to Mayring (2014), the category system is formed by the theoretical background and literature review. In this study the category system includes studies about possible learners’ conceptions, e.g. conceptions about solubility by Grüß-Niehaus and Schanze (2011). Derived from the theory, categories and sub-categories are formed and defined in the coding guidelines. The coding guidelines contain the category, a definition, an anchor example and coding rules, which are presented in Table 2:

Table 2. Coding guidelines using the example of learners’ conception of the solubility of salt in water.

<table>
<thead>
<tr>
<th>Learners’ conception of solubility (by Grüß-Niehaus &amp; Schanze, 2011)</th>
<th>Definition</th>
<th>Anchor example</th>
<th>Coding rules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conditions for solubility (Why is the salt dissolved?)</td>
<td>Stirring with a spoon to promote the solution process</td>
<td>Stirring with a spoon promotes the solution process. This also means that without stirring the substance will not dissolve.</td>
<td>B6: Because we have shaken and stirred that. #00:26:12#</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>The statements listed under the phenomenon solubility are analysed.</td>
</tr>
</tbody>
</table>

With the help of the coding guidelines, the transcribed statements can be clearly assigned to a category. Furthermore, the coding rules are necessary to determine which passages in the transcript should be analysed. In addition to the deductive categories, inductive categories could also be added during the analysis process. This process is necessary because further learners’ conceptions might appear that have hardly been applied in literature so far. Moreover, inductive categories are useful to describe the explanatory process during the teaching experiment. This is due to the fact that the explanatory process during the modeling process cannot be determined deductively in advance because of the exploratory nature of the study.

**SAMPLE**

In order to test the planned teaching experiment, a pilot study is conducted with a nine-year-old girl attending the fourth grade of a German primary school. This participant has a high level of
scientific knowledge and seems to be interested in scientific experiments. The following main study is conducted in December 2019 at the same primary school that the participant of the pilot study attends. The study involves ten students in the fourth grade who have heterogenous learning levels. The sample includes four boys and six girls at the age of nine to ten. According to the teachers’ evaluations, three participants have a low level of scientific knowledge, four students have a medium level and three children have a high level of knowledge. Two of the three students at the highest level took part in an additional course in biology.

RESULTS

Pilot study

The pilot study shows that the planned teaching experiment is well implementable. Only minor improvements to the guide are necessary. The participant is able to draw and revise the mental model of the phenomena. Especially the topics ‘state of matter’ and ‘solubility’ show good and detailed results. In comparison, it can be seen that the burning process is presented in less detail. There is no explanation of the underlying chemical process. For this reason, only the two phenomena – state of matter and solubility of salt in water – are dealt with in the following main study.

Main study

State of matter

The change of state of matter takes place on the submicroscopic level and depends on the temperature increase. The connection between change of the state of matter and temperature increase is described by almost all of the students at the beginning of the teaching experiment. Most of the participants describe that the water boils and bubbles appear. However, a deeper look into the students' explanation shows that most of the probands cannot describe what causes the bubbles during the boiling process. Seven out of ten students explain that the bubbles are hot air. This demonstrates that the participants know about the temperature increase in this phenomenon. The connection to the change of state of matter is mostly not recognised. A deeper look at the expressed models shows that the bubbles are represented as blue circles. The temperature is not explicitly shown in the model for the majority of the participants. Only two out of ten students draw the temperature increase during the boiling in the 1st model. The temperature is shown in red lines or red bubbles. One student is not able to explain the connection to the temperature increase.

After the experiment, the students should revise their 1st models with the new insights. Four out of ten students explain after the revision of their models that the boiling process depends on the change of the state of matter. However, only two of the built models represent the connection between state of matter and temperature increase. The other drawn models have gaps in their explanatory process. Furthermore, the analysis shows that the learners’ conception that hot air is responsible for the boiling process is deeply embedded. A conceptual change is rarely achieved in this teaching experiment.
Solubility of salt in water

The solubility of salt in water cannot be observed directly because the solution process takes place on a submicroscopic level. Many learners’ conception about solubility can be identified in the main study. Five out of ten students explain that dissolving salt in water is due to stirring with a spoon during the solution process. Therefore, the drawn models of those participants show a spoon in the representation. Two out of ten students explain that the taste of the salt is transferred to the water. The drawn models show the term ‘salt taste’ or a yellow shading representing the salty water. Furthermore, three participants explain that the salt disappeared in water. This conception is represented in the model by drawing and erasing the grains of salt or crossing out the drawn salt. A deeper look at the other explanations shows that some students explain the solubility with animistic properties. One student explains that the salt would hide during the solution process. Three participants explain the solubility like a change of the state of matter. For these students, the salt would melt in water. This process is not expressed in the model. In particular, one model should be highlighted. The student describes the solution process by distributing the grains of salt in water. In her conception, the grains of salt become smaller and divide more and more until they cannot be seen visually:

“And then there are little […] grains of salt. They pop up. And then there are such small particles. So, grains of salt you can no longer see” (B2, #00:28:58#).

For this purpose, the dissolved salt is shown as pink circles that are evenly distributed in the water. This student’s drawing comes close to a model on the submicroscopic level.

After confronting the students with the short experiment, the students should revise their 1st drawing. Most of the students add elements of the experiment on the phenomenological level, like the drawing of the experimental setup or a writing about conducting the experiment. The revision of the model does not take place. Furthermore, the built models have gaps in their explanatory process and the models can hardly be used for the explanation of the phenomenon.

All in all, it can be summarised that modeling-based learning in primary school could be fruitful if appropriate interventions are available. This was partially successful in the context of the state of matter, as the models were revised after the interventions and used for explanation. However, most of the models still have gaps in their explanatory process. Furthermore, the built models only correspond to a few aspects of the scientific concept, e.g., the influence of the temperature increase or the fact that the boiling process depends on the state of matter. A similar result is seen regarding the topic of solubility. Here, only one model comes close to a submicroscopic level and can be used for the explanation of the phenomenon. Most of the other models can hardly be used to explain solubility and also show gaps in the explanatory process.

**DISCUSSION**

The study shows two main results: 1. The built models only correspond to a few aspects of the scientific concept. A conceptual change is hardly to be found in the data presented. The students’ alternative concepts are often so well established that a conceptual change does not seem plausible. This problem is also presented by Vosniadou (1994). Conceptual change is an
ongoing process and requires a variety of learning situations as well as active engagement. The interventions in the framework of the study are hardly sufficient for this.

2. The built models for both phenomena show a rather low explanatory process. In this context, the models are hardly used for the explanation. This is due to the fact that elements that are necessary for describing the process are inadequately represented. This problem is also evident in the study by Forbes et al. (2014).

From these findings it can be concluded that modeling-based learning about chemical phenomena is partly possible in primary education but should be supported by scaffolds.

OUTLOOK

Based on the presented results, further research on modeling-based learning about chemical phenomena is needed. Therefore, a study is planned to investigate possible support measures for modeling-based learning about solubility.

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