On the roots of difficulties in learning about cell division - Process-based analysis of students´ conceptual development in teaching experiments

Tanja Riemeier, Harald Gropengiesser

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Abstract

Empirical investigations on students´ conceptions of cell biology indicate major misunderstandings of scientific concepts even after thorough teaching. Therefore, the main aim of our research project was to investigate students´ difficulties in learning this topic and to study the impact of learning activities on students´ conceptions. Using the Model of Educational Reconstruction, a four-phase design was carried out. First there was the clarification of science subject matter. Secondly, students' conceptions were investigated, and finally, the learning activities were designed. An evaluation of these learning activities was carried out using five teaching experiments, each with three 9th grade students (15-16 years, Grammar school). Interpretation of students' 'pathways of thinking' and their conceptual change during instruction was framed theoretically by experiential realism. Theoretical framework, methods and outcomes of the study may contribute to a deeper understanding of students´ ways of thinking in the field of cell biology and reveal the process of conceptual development by using well planned learning activities.

Learning and teaching cell division would seem to be an easy task because there are many published papers and school books which propose teaching materials for this topic in biology. In contrast, research on students´ conceptions often indicates that, even after being taught, students use conceptions which are different from scientific concepts (e.g., Hackling & Treagust, 1984; Dreyfus & Jungwirth, 1989; Díaz de Bustamante & Jiménez Aleixandre, 1998; Lewis, Leach & Wood-Robinson, 2000). When searching for reasons for this gap between the learning efforts and outcomes, at least two aspects are relevant. (1) Usually the main emphasis is put on the content of science matter whereas students´ perspectives, like conceptions, interests, needs etc., are neither integrated into the development nor into the teaching process. (2) In addition, learning materials are often published without a thorough evaluation of the impacts on students´ knowledge. Even if the impact of learning material is evaluated, it is usually done by focussing on the outcomes of the learning post to instruction (e.g., Mikkilä-Erdmann, 2001). Although such procedures certainly give information about the learning outcomes, they cannot (in detail) clarify the impact of the learning material on students´ conceptions. To investigate how students develop their conceptions while working on the learning activities, process-based studies are necessary (Vosniadou & Ioannides, 1998; C. von Aufschnaiter & S. von Aufschnaiter, 2003). Thus, the more process-oriented an evaluation is, the more it can help to identify the learning difficulties students encounter and what in detail helps them to overcome these difficulties.

The Model of Educational Reconstruction offers an opportunity to link student orientated development of learning material to its scientific evaluation (e.g., Duit, Gropengießer & Kattmann, 2005). The three components of this model – clarification of science subject matter, investigations into students´ perspectives and design of learning sequences –interact with each other in order to create effective learning sequences consisting of several activities. In this study we identified students´ pathways of thinking while working on learning activities to answer the following questions:

- What difficulties do students encounter while learning about cell division?
- How will learning activities, planned within the Model of Educational Reconstruction, influence students´ conceptions?

Theoretical Framework

The framework used is based on three theoretical approaches: constructivism (e.g., Duit & Treagust, 1998), conceptual change theory (Strike & Posner, 1992; Duit & Treagust, 2003) and experiential realism (Lakoff, 1987; Lakoff & Johnson, 1999; Gropengießer, 2003). The latter was used to interpret students´ conceptions in order to gain a deeper understanding of students´ ways of thinking (an example for this kind of analysis is given in 'Students´ understanding of division as multiplication of cells' in the section on results). We hold the view that thought is embodied, that is, our basic conceptions grow out of bodily experience. Our basic categories and concepts arise out of perception, body movement, and experience with our physical and social environment. The core of our conceptual system is embodied by these experiences. Thought is imaginative as well. For concepts which cannot be directly experienced we need to think in an imaginative way to explain them. We employ, for instance, metaphors and analogies. Thus, the framework used distinguishes between embodied conceptions and imaginative conceptions. The latter are not directly grounded in experience, but they draw on the structure of our experience. A metaphor 'has a source domain, a target domain, and a source-to-target mapping' (Lakoff, 1987, p. 276). For example, generally, we have no direct experiences of viruses themselves but nearly all people have some conception of what viruses do. When explaining influenza, people often use the concept of a fight to describe the relationship between a virus and the human body. If the body ''wins'' and the virus ''loses'', you become healthy. Therefore, the concept of a fight, a domain, that is well understood, structures our common understanding of how a cold virus acts. With the use of metaphor we shed the light of understanding into domains where direct experience is impossible.

Since understanding of cell theory is not embodied, learning cell division will require suitable experiences with cells and careful use of metaphor and analogy in order to allow adequate understanding.

State of research into conceptions of cells and cell division

Research into students´ conceptions of cells and cell division could be differentiated into two sections. On the one hand, students´ conceptions were collected after students had been taught following their respective national curricula (e.g., Hackling & Treagust, 1984; Dreyfus & Jungwirth, 1988, 1989; Zamorra & Guerra, 1993; Díaz de Bustamante & Jiménez Aleixandre, 1998; Lewis, Leach & Wood-Robinson, 2000; Lewis & Wood-Robinson, 2000; Marbach-Ad & Stavy, 2000; Flores et al., 2003). On the other hand, there are a few empirical investigations that collected students´ conceptions before, during and after a specific learning-strategy (e.g., Knippels, 2002; Verhoeff, 2003). A review of these studies shows many general and significant problems in learning cell biology:

- Confusion about terms such as cell, cell wall, cell membrane, gene, chromosome, allele etc. (e.g., Díaz de Bustamante & Jiménez Aleixandre, 1998; Lewis, Leach & Wood-Robinson, 2000; Hesse, 2002; Flores et al., 2003).
- Problems in understanding the different levels of organisation of multi-cellular organisms (e.g., Schäfer, 1979; Hackling & Treagust, 1984; Dreyfus & Jungwirth, 1988, 1989; Zamorra & Guerra, 1993; Knippels, 2002; Verhoeff, 2003; Flores et al., 2003).
- Problems in understanding cell processes such as mitosis or DNA replication (Lewis & Wood-Robinson, 2000; Marbach-Ad & Stavy, 2000).
- Use of an anthropomorphic view (Zamorra & Guerra, 1993; Dreyfus & Jungwirth, 1988, 1989; Flores et al., 2003).

Methods

The Model of Educational Reconstruction

The Model of Educational Reconstruction was used to design learning activities on the topic of cell division. The model comprises three components in which a) the science subject matter is analysed, b) students' conceptions are investigated and c) results from the previous two components are used to design learning activities (Figure 1; e.g., Kattmann et al., 1997; Duit, Gropengießer & Kattmann, 2005).

[Insert Figure 1 about here.]

For the 'Clarification of science subject matter' we used historical research papers and recent leading scientific textbooks as major sources (e.g., Hooke, 1667; Schwann, 1839; Virchow, 1855; Campbell, 1997; Kleinig et al., 1999). These sources were analysed critically from the point of science education to construct the core ideas of cell and cell division. This was necessary because the information in academic textbooks addresses experts (e.g. scientists and students who may become scientists) and is often expressed in an abstract and condensed way. Furthermore, in academic textbooks linguistic expressions of old and outdated thoughts are often used, and though these do not hamper understanding in a scientific community, for novices these expressions can be often misleading (Duit, Gropengießer & Kattmann, 2005). For example, the expression "hereditary disease" may lead to the conception that the disease itself is inherited. Rather, "disease caused by genetic factors" would be appropriate to express the scientific view.

For the second component of the model, the 'Investigation into students´ perspectives' (Figure 1), we employed two different methods to gather knowledge about students´ conceptions:

(1) A reanalysis of empirical investigations on students´ conceptions of cells and cell division. Thirteen published papers with empirical findings on students´ conceptions in the fields of

cell biology, genetics, microbiology and growth were reanalysed within the framework of experiential realism (see also previous section on state of research).

(2) An analysis of the key words ‘division’ and ‘growth’: We employed the methodology of cognitive linguistics (Lakoff, 1987; Kövecses, 1990; Gropengießer, 2003) to study the common use and meaning of words that are important for understanding cell division. We also used German dictionaries for word meanings as sources. In this way we could identify the conceptual structure of ‘division’, ‘growth’, and ‘cell division’ respectively.

An example for the analysis of ‘division’ is given in Figure 2 in the section on the results. Comparison of scientists´ and students´ conceptions reveals which concepts students need to develop to understand cell division in a scientific way (‘Design of learning sequences’, Figure 1). From this comparison we developed guidelines for the development of learning sequences (see Appendix A). Conceptions of students and scientists are regarded as equally important for the construction of learning material. However, students´ conceptions are the preconditions of learning whereas the analysed scientific concepts are the sources of the aims. The design of learning sequences is primarily determined by the specific needs of the learner to reach these aims. For this, students´ conceptions and scientific concepts are compared with each other to identify similarities and differences. For instance, the analysis of other workers research findings showed students´ confusion about the number of chromosomes after cell division. Often students think there is a decrease in the number of chromosomes after mitotic division. To change this student conception there is a need for replication of the genome to be recognised. As a consequence the guideline ‘To understand the replication of genome during mitotic cell division’ was formulated for use in the teaching experiment. This is one of a series of guidelines developed in this research (Appendix A). Based on these guidelines 16 learning activities were designed of which four (‘Growth of onion roots’, ‘chocolate bar’, ‘Division of information’ and ‘Computer simulation of cell division’) are described in this paper. We have chosen these four activities as they provide insights into students´ conceptual development while they are working on these. Furthermore the activities are related to the topic of mitotic cell division, while most of the others are used to gather students´ conceptions about cells and to trigger conceptual development within this topic.

Teaching experiments for evaluating learning activities

In order to study the effect of the learning activities on students' learning processes, we used teaching experiments (e.g., Steffe & D'Ambrosio, 1996; Katu et al., 1993; Komorek & Duit, 2004). This empirical method offers an opportunity to combine teaching (interventional aspect) with interview situations (investigational aspect). This means that the analysis of our teaching experiments gave information about students´ pre-instructional conceptions as well as their development during the teaching process. The role of the researcher is, on the one hand, to be an interviewer and to identify students´ conceptions and, on the other hand, to be a teacher and to organise learning activities depending on students´ progress. This means that throughout the teaching experiment the students were able to discuss their pre-existing ideas about different topics, e.g. structure of cells, process of cell division etc. Depending on which conceptions they showed, the students worked on different learning activities.

In our teaching experiments, which lasted about 75-90 minutes, we examined teaching and learning processes in five small groups, consisting of three 9th grade (15 years) students and a researcher each. The sample in this study was taken from different grammar schools (Gymnasium) in a large city in northern Germany. These five groups were invited to our Institute in order to participate in the teaching experiments. We deliberately tried to maximise the variety within the sample with a view to social background, performance and gender. However, we were not aiming at a representative sample for this study. Before the teaching experiment, students had not received any formal instruction on cell division, but had had instruction on the cell concept.

All data were gathered on video and investigated by qualitative content analysis (e.g., Mayring, 2003). Using this method, the video material was condensed, interpreted and analysed in a systematic way through five steps (Sander et al., 2006):

- Word by word transcription
- Editing (this means to transform students´ utterances into grammatically correct statements)
- Condensation (this means to combine almost identical statements)
- Explication (this means to interpret students´ statements, to explain underlying conceptions and to find experiences on which these conceptions are based)
- Structuring (this means to formulate students´ concepts)

All transcripts were analysed independently by at least two researchers to ensure reliability and validity.

Based on this method learners´ ‘‘pathways of thinking” were inferred and linked to the learning activities. Thus, we were able to identify the conceptions that students had developed prior to the instruction, as well as conceptions they developed during the learning activities. Taken together, the process of conceptual development for each student within the group allowed us to study the effect of the learning sequence on students’ conceptions.

Results

Findings from this study are related to all three components of the Model of Educational Reconstruction (Figure 1). In this paper we concentrate on students´ understanding of cell division that was gathered in the teaching experiments. For the sake of clarity, data from only one of the five groups are shown. This all female group (Lisa, Sarah and Ute) was chosen because it displayed conceptual changes typical of all the groups. Their ‘pathway of thinking’ is presented step by step. To make it explicit what the girls said and did, the transcripts are presented. All dialogues were translated from German to English and therefore underwent slight changes.

Students´ understanding of mitotic cell division as multiplication of cells

In order to gather students´ conceptions of growth, all of our teaching experiments started with the same instruction: We put an onion with roots reaching into a water-filled jar on the desk. We then asked the students what had happened. Lisa, Sarah and Ute answered this initial question that the roots 'come out of the onion', because the onion matured. They thought about this development as a normal process that happens every day. Onion roots grow – so what? This means, they thought about experiences on the macroscopic level and did not see any connection between growth and cells. When the researcher asked how onion roots arise, the girls enumerate conditions of growth like the need for water or nutrients. After a while, Lisa remembered the cellular structure of the onion, and then the girls answered as shown in box 1.

Sarah:	You asked me how the roots arise from the onion and then I remembered a cartoon: Cells go there like human do and accumulate together, or increase and unite, or divide and heap on each other and once there are enough, because cells are enormously small, then humans see small roots. And if there are billions or so, one then sees a longer root. […]
Lisa:	Yes, specialized cells string together. And there have to be a lot [of cells] for the human eye to be able to see a root. […]
Instructor:	And how could this multiplication of cells happen?
Lisa:	The multiplication of cells could happen by cell division.
Ute:	Division can lead to multiplication of cells [makes a cut in two with her hands]
Sarah:	Cell division can be always watched in films about sex education. There is one cell that divides itself, then we have two, then they divide once more, then we have four, then they divide again, then we have eight and sometimes they have divided so many times that a baby is formed.
Lisa:	Yes, I just thought that myself.

Box 1: Transcript after learning activity 'growth of onion roots'

Initially, Lisa, Sarah and Ute thought that roots grow by multiplication of cells. In this sense growth means to them: Becoming more cells. When asked how the cells multiply the girls mentioned cell division, where they imagined the cell would divide into two halves. Division meant to get more cells, which in turn lead to the growth of onion roots. In contrast, the analysis of scientific conceptions revealed that the scientific view of cell division combines the concepts of growth and dividing in a special way: After division the two small cells have to grow before a new division starts. We called this concept ‘division and enlargement’. The girls’ conceptions indicated no idea of cells growing in connection with division. In order to explain this gap between students´ way of thinking and scientific concept we drew on the theory of experiential realism. We explored the conceptual scheme of ‘division’. Grounded in our everyday experiences, at least three different meanings of ‘division’ can be distinguished according to the outcomes of the process of parting (Figure 2): (a) there can be *more* single pieces, (b) pieces can be *smaller* than the whole object, (c) a collection of pieces can be shared among people. In this case, each one gets *less* than the whole collection.

Viewed from this perspective, it makes sense that the girls thought about growth by cell multiplication and to imagine this multiplication through division – even though ‘becoming smaller’ escaped their attention. They were not aware of the decrease in size of individual cells through division. To think of division in terms of ‘becoming more’ and ‘becoming smaller’ at once seems to be difficult. It was obvious to them that division and the resulting multiplication of cells seem to explain growing onion roots. In solely paying attention to the words used by the students one would judge the term ‘cell division’ as accurate. But the crucial point is the understanding of the concept of ‘cell division’ in a scientific way thereby combining the ideas of division and enlargement.

[Insert Figure 2 about here.]

In order to change students´ understanding of cell division, we recognised the need for students to reflect upon different meanings of 'division'. Therefore, we used a bar of chocolate to demonstrate an instance of division. Sarah, Lisa and Ute divided it and subsequently compared this process with cell division. During this learning activity the following dialogue took place (box 2):

Sarah:	The number has changed by splitting.
Ute:	One has more pieces but […] it's still chocolate.
Lisa:	The weight is still the same and the pieces look completely the same.
Sarah:	But if it would be done to a cell then it wouldn't achieve anything, because it would be the same size. I think the cell doesn't divide in the sense of getting smaller but rather, the two new cells are of the same size.
Lisa:	Exactly, if the cell always divided itself it could never get bigger. […] And as for me, the cell would divide five hundred times and still it wouldn't get any bigger but it had divided quite often. This wouldn't achieve anything.
Ute:	Okay, the cell divides in the middle, but it gets bigger, it will grow to normal size. The two halves will grow back to normal cell size.

Box 2: Transcript during learning activity 'chocolate bar'

At first, the girls affirmed their conceptions of 'becoming more' through division: There were more pieces of chocolate. But then Sarah realised that the pieces were smaller than the whole bar of chocolate. Reasoning by analogy she, and in turn Lisa and Ute, recognised that division of cells will increase the number but decrease the size. At this point they felt a cognitive conflict. The students found it impossible to accomplish growth of roots by division of cells only. The girls developed their conception further: The cell divides and then the two new cells increase to a normal size, enabling the roots to grow.

Students´ understanding of division as decrease in the number of chromosomes

The reanalysis of empirical investigations revealed that some students imagined cell division as a division of the cell into two halves, thereby reducing the number of chromosomes as well (e.g., Lewis, Leach & Wood-Robinson, 2000). These students did not consider any replication of the chromosomes. Viewed from the perspective of experiential realism, this conception makes sense. If chromosomes are viewed as a collection of pieces, and this collection is shared between two cells, each cell gets fewer chromosomes than the original cell (Figure 2). Again, a notion grounded in our everyday-experience is employed to make sense of a process not known in everyday life. But the scientific concept of cell division is more sophisticated. Based on these results, we designed a learning activity called 'division of information'. It used the analogy of information given in a construction manual to explain the need for replication of genetic information before division. We asked the students to explain how division 'exerts influence on' the construction manual. In a second step, they had to draw an analogy of the division of a genome.

Initially Sarah, Lisa, and Ute said that the nucleus would divide during cell division, too, and then it would grow to a normal size. It is obvious that they employed the newly learned concept of 'division and enlargement'. The girls remembered the instance of cell division, and they consequently developed the concept of nucleus division and enlargement. Regarding the chromosomes however, they were not sure how to conceptualise its division (see box 3).

Ute:	If you split the construction manual in the middle, each person would only build half of the furniture. […]
Lisa:	It would be fragmentary. It would make a mistake. […] The genetic material has to be always complete otherwise there would be a mistake. […]
Instructor:	What does it mean for the genetic material in cell division?
Sarah:	It is copied ...
Ute:	… copied.
Lisa:	The genetic material has to be complete, because each cell must have the complete genetic information.

Box 3: Transcript during the learning activity 'division of information'

Sarah, Ute, and Lisa pointed out that the genetic material has to be copied because each cell has to gain a complete set of genetic information. At this point, the girls recognised the need for duplication of the genome.

Students´ understanding of division as division and enlargement of the nucleus

In order to challenge the idea of 'division and enlargement of the nucleus', we had designed a computer simulation which teaches the changes of the nuclear envelope during cell division. It shows the phases of mitosis in a simplified way. When Sarah, Lisa and Ute watched this simulation, they reacted as follows (see box 4):

Sarah:	Oops.
Ute:	Oops. Now the chromosomes are swimming about in the cytoplasm. Without any protection.
Sarah:	By now the nuclear envelope has dissolved, now the genetic material can be split much easier and when the cell has divided, a new nuclear envelope is developed.

Box 4: Transcript during the learning activity 'computer simulation cell division II'

When Sarah and Ute watched the breakdown of the nuclear envelope, they were very surprised. They did not expect this process to happen. The nuclear envelope breakdown did not fit into their concept of its function. At a later point in this teaching experiment, Ute explained how surprised she was about the function of the nuclear envelope. She thought the function of the nuclear envelope was to protect the genetic material just like a wall protects the interior. Thus Ute conceptualised the nuclear envelope in terms of a wall. She metaphorically projected her conception of a wall protecting an enclosed room to the nucleus.

At the end of the teaching experiment, students´ conceptions of cell division were tested in two different ways: They had to explain the growth of a flower bud and healing of cut in human skin. After this the girls were asked to write a short paragraph to explain the growth of organisms. Ute formulated the following answer presented in box 5.

For growth, one needs cells that divide themselves. This happens in this way: The two chromosomes in the nucleus duplicate themselves […]. Then they divide themselves […] Then the nuclear envelope dissolves itself, and each of the two halves go to one side of the cell. Each of these new halves is now enclosed with a new nuclear envelope. Then a new wall is built that splits the cell. The cells thus developed will then grow to normal size. […] Everything in our body or in plants grows in this way.

Box 5: Ute's cellular explanation of growth at the end of the presented teaching experiment

The pathway of thinking of Lisa, Sarah and Ute

Figure 3 illustrates a pathway of thinking. It shows students´ conceptions before, during and after working with the learning activities for the period of the teaching experiment. Students´ conceptions are the stations and the conceptual developments from one conception to another are the stages on this path. The learning activities that foster the specific conceptual development are demonstrated along the arrows. From this research perspective, there are three options in which students´ conceptions could be developed: a) The learning activity fosters a conceptual development toward scientific understanding. b) The learning activity does not foster a conceptual development toward scientific understanding. c) Based on the learning activity the student develops conceptions that are contradictory.

The pathway of thinking for Lisa, Sarah, and Ute is shown in Figure 3: First, the girls explained the growth of onions roots with the every day experience of becoming mature. Secondly, the girls thought about growth as a multiplication of cells. They imagined that division would produce more cells while they had no idea of the following growth. At this point they used the concept 'growth through division of cells'. Then, with the aid of our learning activity 'chocolate bar', they learned about the meaning of becoming smaller parts by division. They were unsatisfied with their old concept ‘growth through division of cells’ and subsequently developed it further and used the concept ‘division and enlargement’. Fourthly, during the learning activity ‘division of information’, they recognized the duplication of genetic material, but they still conceptualised a division and an enlargement of the nucleus. And finally, with the aid of the learning activity ‘computer-simulated cell division’ they figured out a conception of cell division closer to the scientific way of thinking. This conception includes information about the genetic level.

[Insert Figure 3 about here.]

Discussion

Outcomes of the study indicate major difficulties in learning cell division (Table 1): Difficulty 1. Students´ understanding of growth as becoming mature. The students did not think about the levels of cells to explain the growth of onion roots. Difficulty 2. Students´ understanding of cell division as multiplication of cells. Growth meant to them becoming more cells. Difficulty 3. Students´ understanding of cell division as a decrease in the number of chromosomes. They did not think about the duplication of chromosomes before cell division. Difficulty 4. Students´ understanding as division and enlargement of the nucleus. By comparing these data with results of international empirical investigations on students´ conceptions of cells and cell division, there are several similarities (e.g., Dreyfus & Jungwirth, 1989; Díaz de Bustamante & Jiménez Aleixandre, 1998; Lewis, Leach & Wood-

Robinson, 2000), for example, students´ understanding of cell division as a decrease in the number of chromosomes. Viewed from the perspective of experiential realism, it was possible to identify the roots of students´ difficulties (Table 1): Root 1. There are no direct experiences for growth on the microscopic level, so students´ first use their macroscopic experiences to explain the growth of onion roots. Root 2. The scientific term 'cell division' puts stress on the division process neglecting the necessary enlargement of the two new cells. Root 3. Chromosomes are viewed as a collection of pieces which is shared between the two cells during cell division. Each cell has fewer chromosomes than before division. 4: Students transfer their conceptions about the division and enlargement of cells as developed in the teaching experiment to the nucleus.

[Insert Table 1 about here.]

As opposed to some other topics in biology, such as movement, there are no experiences of cells in everyday-life. If there are no experiences, there are no pertinent conceptions. Hence no direct understanding of cells is possible. In order to develop an understanding of cells, students must rely on their imagination, that is, they need to choose a source domain with a well-known conceptual structure (e.g. division) and carry out a source-to-target mapping to understand the target domain of cell division. These conceptual metaphors allow us to reason about the unfamiliar microcosm using the inferential structure of a familiar macrocosm. In doing so, students often develop conceptions that are not or not fully compatible with the scientific understanding of cells and cell division. Even though terms like cell division are used that does not mean the scientific conceptual structure is imagined. The metaphorical understanding of an unfamiliar domain like cells has to be developed painstakingly. Each pair of corresponding conceptual entities has to be mapped from the source domain to the target domain in order to establish understanding.

According to our results, we were able to identify conceptions of cell division on three different levels:

1. On the level of cells, students explained the growth of onion roots by division of cells, but without considering the growth of the new cells.
2. On the level of nucleus, they imagined the division of the nucleus, but without thinking about previous breakdown of the nuclear envelope.
3. On the level of chromosomes, they thought about division of chromosomes, but without the prior copying of these.

These conceptions have a great deal in common:

- All of them are metaphorical conceptions.
- Their source is the structure and logic of the conceptual domain of 'division'.
- In each case an obvious mapping is chosen, leading from entities in the source domain to the corresponding entities in the target domain of cells.
- The conceptual structure as the target domain (i.e. cell) is kept as simple as possible in the first instance. For example 'cell division' is conceptualised as 'becoming more' cells.
- Conceptual change took place in case of contradiction, e.g. when the students noticed that 'becoming smaller' arises inevitably from 'becoming more'. Then students were open to elaborate their conceptions.

Students are often confused by the words used to describe the process of cell division, for example replicating, dividing, copying, etc (e.g., Lewis et al., 2000, 197). Without a doubt, words are important in gaining understanding in a new domain. They can lead a learning process as well as mislead it. But in many cases (mis)understanding is not achieved by words but rather by the construction of conceptions. To gain understanding in nearly any domain of scientific thought metaphor is employed. In metaphorical thinking the choice of the source domain and the source-to-target mapping are crucial.

Guided by experiential theory, we were able to develop learning activities that fostered students´ conceptual development. Some of these activities demand that students reflect on the everyday meanings of division before they compare these to scientific understanding. As Beeth (1998) and Linder and Marshall (2003) have pointed out, this reflection of their own conceptions seems to be an important step in learning. The data from the teaching experiments demonstrates the impact of the learning activities on the students' learning of cell division. We were able to observe steps of conceptual development towards scientific understanding.

Conclusion

The Model of Educational Reconstruction provides a fruitful means to develop learning activities that are systematically based upon both the scientific view *and* students' conceptions. Theory-based development and research of teaching and learning sequences could be linked closely in this framework. Furthermore, the model also helped to identify students' conceptions in the domain of cell division.

Methods and outcomes of this study may contribute to a process-based analysis of students´ conceptual development as several researchers have attempted to find out how students develop new knowledge while working with learning sequences (Vosniadou & Ioannides, 1998; C. von Aufschnaiter & S. von Aufschnaiter, 2003). Certainly, our learning strategy is not the only one promoting the development of scientific understanding. There are other successful strategies for teaching cell biology (e.g., Knippels, 2002; Verhoeff, 2003). Their focus is about different levels of the organism and system thinking. We concentrated on the learning activities planned within the Model of Educational Reconstruction that foster students' conceptual development. Subsequent investigations will have to prove whether this success could be found in natural settings in science classrooms as well.

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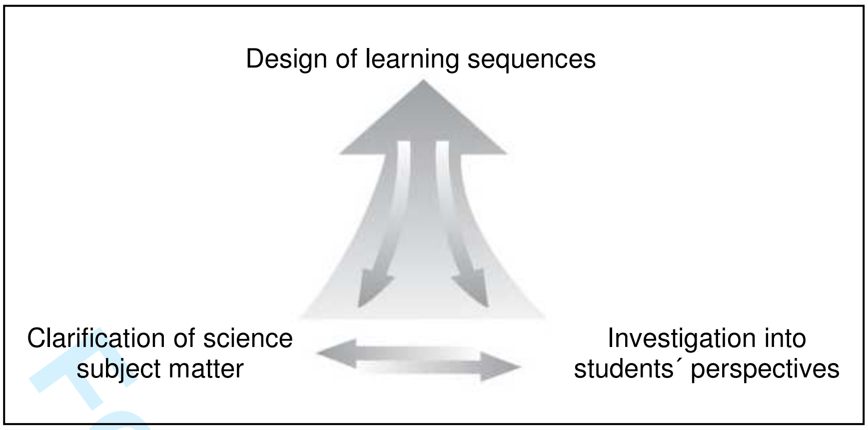


Figure 1. The Model of Educational Reconstruction

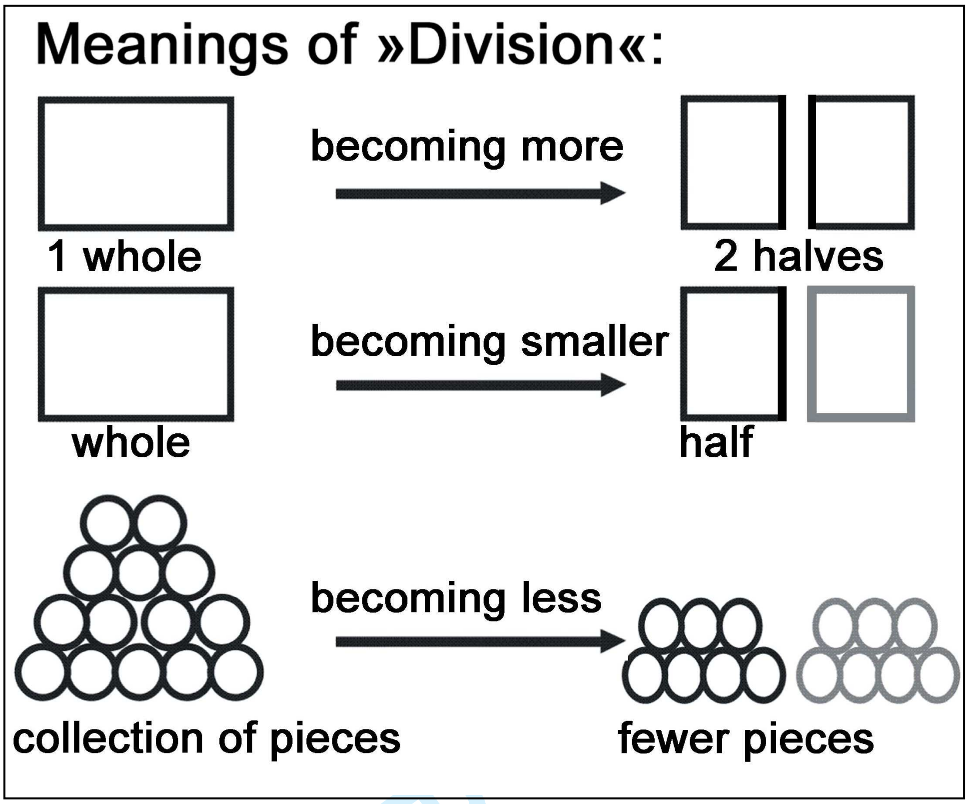


Figure 2: Meanings of »division« extracted and compiled from German dictionaries of word meanings

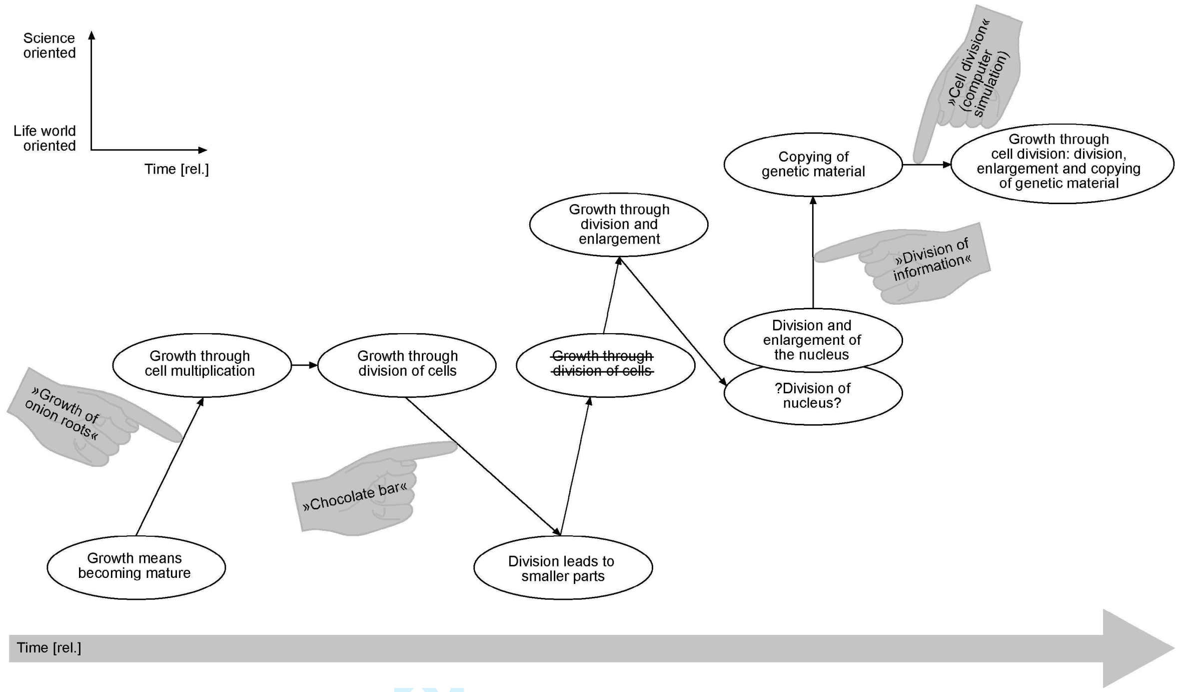
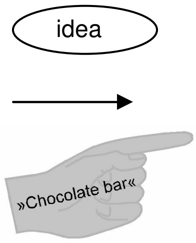


Figure 3: The pathway of thinking of Lisa, Sarah, and Ute

Explanation: students´ conception

conceptual change

learning activity



Students' conceptions	Scientific conceptions	The root of the difficulty
Growth as becoming mature	Growth as a cellular process	There are no direct experiences for growth on the microscopic level.
Cell division as multiplication of cells	Cell division as a process of division and enlargement of cells	The scientific term "cell division" highlights division and hides the intermediate growth.
Decrease in number of chromosomes during cell division	Replication of chromosomes and subsequent distribution	Chromosomes are viewed as a collection of pieces to be shared between two cells. This mental model of division suggests a decrease in the number of chromosomes during cell division.
Division and enlargement of the nucleus during cell division	Mitosis includes the breakdown of the nuclear envelope	Students transfer their newly learned conception of division and enlargement of cells to the nucleus.

Table 1: Difficulties in learning cell division and roots of students´ difficulties

Appendix A: **Guidelines and associated learning activities developed for use in the learning experiments**

Guideline	**Learning activities:** Students are asked to
To discuss and reflect anthropomorphic perceptions applied to cells	Drawing cells: – draw a plant cell structure
	Modelling cells: – model a plant cell 3D structure with plasticine
To understand growth as a cellular process	Growth of onion roots: – describe the growth of onion roots
	Longitudinal section: – draw a connection between the longitudinal section of onion roots and the process of growth
To understand that organisms exist either as single cells or are made up of many cells	Choosing between the conceptions of having cells or to be made of cells: – compare the statements “Organisms are made up of cells” and “Organisms have cells”
To understand growth as a process of cell multiplication and cell enlargement	Cell division: – draw the process of cell division
	Chocolate bar: – divide a bar of chocolate and compare this process with cell division
	Cell size: – measure different cells in a longitudinal section
	Cell division I (computer simulation): – confront their own conceptions with the scientific conception of cell division (nucleus not considered)
	Growth analogy: – compare bricklaying with growth of an organism
To understand the replication of a genome during mitotic cell division	Division of information: – compare the tearing apart of a construction manual with genome division
	Cell division II (computer simulation): – confront their own conceptions with the scientific conception of cell division (fate of nuclear envelope and chromosomes included)
To augment experiences in microcosm	Nucleus (information-card): – read about bacterial structure
	Cell division? (information-card): – read about bacterial replication
	Seeing cells? (information-card): – read about cell size
	Growth needs (information-card): – read about the needs of cells for growing