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Understanding Starts in the Mesocosm: Conceptual metaphor as a framework for external representations in science teaching

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In recent years, researchers have become aware of the experiential grounding of scientific thought. Accordingly, research has shown that metaphorical mappings between experience-based source domains and abstract target domains are omnipresent in everyday and scientific language. The theory of conceptual metaphor explains these findings based on the assumption that understanding is embodied. Embodied understanding arises from recurrent bodily and social experience with our environment. As our perception is adapted to a medium-scale dimension, our embodied conceptions originate from this mesocosmic scale. With respect to this epistemological principle, we distinguish between micro-, meso- and macrocosmic phenomena. We use these insights to analyse how external representations of phenomena in the micro- and macrocosm can foster learning when they (a) address the students' learning demand by affording a mesocosmic experience or (b) assist reflection on embodied conceptions by representing their image schematic structure. We base our considerations on empirical evidence from teaching experiments on phenomena from the microcosm (microbial growth and signal conduction in neurons) and the macrocosm (greenhouse effect and carbon cycle). We discuss how the theory of conceptual metaphor can inform the development of external representations.

Keywords: *Embodied cognition; Conceptual metaphor; External representations; Mesocosm*

Introduction

In the teaching of science, students' conceptions have come into the focus of science educators during the last four decades (overview in Duit, 2009). This research

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draws primarily on the perspective that was expressed by the educator Adolph Diesterweg as early as 1835 (p. 131): 'Without knowing about the students' viewpoints no proper instruction is possible'. Over the years, the research on students' conceptions has been embedded in various theoretical frameworks with epistemological, ontological and affective orientations (Duit & Treagust, 2003). Within the framework of educational reconstruction (Duit, Gropengiesser, Kattmann, & Komorek, 2012), we published a number of interview studies and teaching experiments on various topics. To interpret the nature of the students' conceptions, we referred to the theory of conceptual metaphor of Lakoff and Johnson (1980), in which they state that all of our knowledge draws on bodily and cultural experience. We have adopted this perspective of 'embodied conceptions' (Lakoff, 1990) to analyse and categorise students' conceptions on topics like cell biology (Riemeier & Gropengiesser, 2008), climate change (Niebert & Gropengiesser, 2014), physiology (Gropengiesser, 1997) and on scientific processes like experimentation (Niebert, 2007). When analysing these conceptions, we found that often very basal experiences—like those of containers, moving on a straight path or in a circle, being in or losing balance, or sharing and dividing things—constitute our basic understanding of scientific phenomena. These experiences are conceptualized in terms of image schemas, abstractions from sensorimotor experience (Johnson, 1987). For adequate understanding of science, both the selection of an embodied source and also the way this source is mapped to the phenomenon to be understood play major roles (Niebert, Marsch, & Treagust, 2012).

In these prior studies, we used the notion of embodied conceptions as a lens to analyse conceptions. The study at hand here is motivated by our interest to find out if, and how, an analysis of students' and scientists' embodied conceptions can not only help science educators to understand the origin of these conceptions but also inform the way we teach science. Therefore, in this paper, we are widening our perspective from how conceptions can be analysed regarding their embodied basis to how we can use embodied conceptions to teach science and develop learning activities.

Conceptual Metaphor as a Theory of Understanding

A growing number of researchers in cognitive science have discussed evidence that grant the body a central role in shaping the mind (Fauconnier & Turner, 2002; Johnson, 1987; Lakoff, 1990; Lakoff & Johnson, 1980; Rohrer, 2001, 2005). The various frameworks used in this research can be summed up under the umbrella term of embodied cognition, which refers to the view that cognitive processes are rooted in the body's interactions with its physical and cultural environment. This position houses a number of claims (for an overview see Wilson, 2002), from which we will mainly focus on one in our analyses: cognition is body-based.

Consider the following constructs where scientists make use of everyday experience to explain their theories. Robert Hooke was the first to denote the *cell* using the term 'cell' when an image of a piece of cork under his microscope reminded him of the small rooms, or cells, occupied by monks in monasteries. Kepler developed his concept of planetary motion by comparison with a clock. Huygens used water waves to theorise that light is wavelike. Arrhenius described the greenhouse effect by referring to his experience with hot pots. In ever new variations, scientists employ experiences from everyday life to understand scientific phenomena. Semino (2008) has pointed out that those metaphorical constructs are not only used with a pedagogical purpose, but also in many cases have a theory-constitutive function as well. But why do even scientists have to rely on bodily experiences to construct and explain their scientific ideas?

In the 1980s, linguists began exploring how understanding abstract concepts are regularly based on bodily concepts through metaphor (Lakoff & Johnson, 1980). An important finding from their research is that many concepts are not understood literally but metaphorically in terms of another domain of knowledge. Lakoff and Johnson argued that their findings of the omnipresence of metaphors were not only a linguistic phenomenon but also reflect 'general principles of understanding' (1980, p. 116). The referral to everyday experience and the use of metaphors are not just a matter of figurative language but are of a conceptual nature. This notion led to the development of the theory of conceptual metaphor.

Each conceptual metaphor has the same mode of operation: the structure of the (embodied) source domain is metaphorically projected to the target domain to achieve understanding. The embodied conceptions in the source domain provide an inference pattern to reason about the target domain. When the inferential logic is carried over from the source domain to the target domain, we regard that as a conceptual metaphor. A conceptual metaphor can be defined as a unidirectional mapping of entities from a concrete conceptual domain to what is usually more abstract conceptual domain. The ability of metaphorical thought makes abstract scientific theorising generally possible (Lakoff & Núñez, 2000).

The embodied sources of metaphors are often what Lakoff and Johnson (1980) call 'image schemas'. These image schemata—like the start-path-goal schema, an up-down schema or a front-back schema (Lakoff, 1990) —arise from recurrent experience, i.e. the interactions of our sensorimotor system with the environment. For example, the container schema emerges from our experience with our bodies as three-dimensional containers into which we put certain things such as food, water or air and out of which other things such as air, blood and waste emerge (Johnson, 1987). Image schemata give coherence and structure to our conceptions and are directly meaningful for orientation in our physical and social environment. We use the structures of these image schemata to understand abstract ideas that are not directly grounded in experience.

Embodied Conceptions from an Epistemological Perspective

The theory of conceptual metaphor helps us explain why we have problems understanding science concepts such as the theory of relativity, the theory of evolution and the cell theory. One line of reasoning points to the abstract nature of these theoretical notions and the necessity of imaginative thought (Lakoff, 1990). Closely related but more basic is the argument for the lack of direct experience of these processes.

Vollmer (1984) argues that our sensory system is not able to perceive or process phenomena like these. Based on approaches from evolutionary epistemology, he argues that the principles that underlie our cognitive processes were developed during human evolution. Our sensory and cognitive systems fit—at least partially—to the world we live in because they have emerged in a process of adaptation to the world. Vollmer calls the parts of the real world to which man has adapted his perception, experience and actions the mesocosm. It is a world of middle dimensions: medium distances and times and low velocities and forces. It extends from a blink to a lifetime, from light as a feather to heavy as an elephant, from a hair's breadth to the horizon and so forth (Table 1). These dimensions explicitly refer to human sensory abilities and are perceivable and tangible. The mesocosm is 'that section of the real world we cope with in perceiving and acting, sensually and motorically [. . .]' (Vollmer, 1984, p. 87).

Whereas perception and experience in general are primarily influenced by the mesocosm, scientific evidence and theories often exceed the mesocosm; macrocosmic structures such as the biosphere and the solar system are not part of the mesocosm because our cognitive system is not adapted to these dimensions. The same holds for microcosmic entities such as cells or structures such as molecules. To extend the mesocosmic boundaries, scientists often rely on complex technology and inquiry to open phenomena in the micro- and macrocosm to experience. In the macrocosm and microcosm, we encounter entities that are imperceptible, at least in our everyday experience.

These epistemological considerations support the theory of conceptual metaphor and explain the findings of researchers in science education investigating topics such as entropy (Amin, Jeppsson, Haglund, & Strömdahl, 2012; Jeppsson, Haglund, Amin, & Strömdahl, 2013), energy (Amin, 2009), thermodynamics (Fuchs, 2007), different mathematical concepts (Lakoff & Núñez, 2000), climate change (Niebert & Gropengiesser, 2013b), glacial movement (Felzmann, 2014) or physiological aspects like 'seeing' (Gropengiesser, 1997) that scientific concepts are regularly understood by using conceptual metaphors.

Some of these authors propose to make these findings applicable to science teaching. One of the most concrete proposals was made by Amin (2009, p. 192), who stated that the 'tools of conceptual metaphor can also support the design of instructional representational tools'. But an analysis of how embodied conceptions can inform the development of external representations is still a desideratum.

Table 1. Dimensions and boundaries of the mesocosm (cf. Vollmer, 1984)

	Lower boundary	Upper boundary
Time	seconds (e.g. heartbeat)	decades (e.g. lifetime)
Range	millimetre (e.g. hair: 0.1 mm)	kilometre (e.g. daytrip: 30 km, horizon: 20 km)
Speed	$v = 0$ (e.g. rest)	$v = 10$ m/s (e.g. runner and preying bird)
Acceleration	$a = 0$ (e.g. steady motion)	$a = 10$ m/s^2 (runner and free fall)
Weight	gram (e.g. ping-pong ball)	ton (e.g. tree, animal and rock)
Temperature	0°C (e.g. freezing point)	100°C (e.g. boiling of water)

External Representations in Science Education

Teaching always involves some way of representing information about scientific concepts and the phenomena to which they relate. But what a representation is, is difficult to define (Gilbert & Treagust, 2009). In accordance with science education literature (e.g. Gilbert & Treagust, 2009; Tsui & Treagust 2013), we use the term 'representation' to refer primarily to constructs of phenomena that come in the form of models, analogies, figures, diagrams, written or spoken text and so on. Even experiments and observations often serve as representations, as they represent, 'by example', some concept or phenomenon.

From a constructivist perspective, external representations can help students make sense of complex phenomena by constructing their own conceptions and avoiding alternative conceptions. Furthermore, research shows that learners can benefit from learning with more than one external representation (Tsui & Treagust, 2013). However, in an analysis of learning with external representations, Van Someren, Reimann, Boshuizen, and de Jong (1998) argue that students are often unable to make connections between different external representations or between an external representation and their prior conceptions. Moreover, there is evidence that in more than a few cases, representations used with an instructional purpose are not adequately understood by students (Harrison & de Jong, 2005), nor are they understood in the anticipated way (Harrison & Treagust, 2006). These empirical findings give evidence for what every science teacher knows from his own practise: some external representations are more effective than others.

In chemistry education, Johnstone's (1982) level-based description of external representations has become a dominant framework. Johnstone proposed that chemical knowledge is generated and communicated at three different levels: the symbolic, submicro and macro levels:

- External representations on the macro level[1] describe learning activities focussing on empirical properties of chemicals that are perceptible (e.g. mass, density, concentration, pH and temperature).
- Submicroscopic external representations are models or diagrams to explain macroscopic phenomena. These models represent entities that are too small to be perceived such as atoms, molecules or ions.
- Symbolic external representations involve conventions to represent atoms or molecules, signs to represent electrical charge, equations to show the conservation of matter during a reaction and so on.

This triplet of external representations has served as a framework for many studies and inspired the work of chemistry teachers and researchers as well (Gilbert & Treagust, 2009). While the triplet relationship has become a key model for chemical education, there is considerable evidence that students have problems in using the triplet relationship for understanding chemistry, as often no suitable experience is provided to the students (Nelson, 2002). Students are uncertain about how to connect the experience to their prior knowledge (Hodson, 1990), or they have difficulties translating between the macro and the submicro levels of representation (Davidowitz & Chittleborough, 2009). Moreover, Johnstone's representation triplet has a limited scope when it comes to teaching concepts from life and earth sciences, as knowledge in these domains extends to multiple entities—e.g. from evolution as an overall framework to different levels of explanation (molecule, cell, organism, population, biosphere, etc.).

To address these problems, Tsui and Treagust (2013) developed a three-dimensional model for teaching and learning biology with external representations. Within this model they argue that learning can take place by translating across:

- modes of representations with increasing abstraction from real-life worldly objects and actions to more abstract graphs, equations or verbal descriptions;
- levels of representation from the symbolic level (explanatory mechanisms), the submicro level (molecules), the micro level (organelles and cells) and the macro level (tissues and organs);
- content areas of biology, for example, connecting the ecological aspects (i.e. the carbon cycle) with physiological activities (i.e. photosynthesis and respiration) as discussed in our case three.

This model and the findings on students' difficulties in working with external representations show why learning the life and earth sciences is challenging: Understanding these sciences demands moving mentally in structurally and functionally related content areas (like evolution, homeostasis, energy, etc.) and skipping back and forth between the different levels of familiar and concrete vs. unfamiliar and abstract representations.

External Representations and Conceptual Metaphors

The notion that understanding is embodied, even when it comes to concepts far from the mesocosm, should have implications for how we conceive external representations to teach science. Often a scientific concept is given an abstract definition or characterisation, which is viewed as the learning objective. This may take the form of a verbal definition, a formula, a model, a concept map and so on. In their discussion of the implications of the conceptual metaphor perspective for mathematics education, Núñez, Edwards, and Matos (1999) noted that teaching solely with abstract characterisation of concepts misses the reality of their roots in embodied conceptions. Taking the importance of embodied conceptions into account, experiential resources can support the design of external representations (e.g. Amin, 2009). Embodied conceptions can be accounted for by designing external representations that embody the abstract relations among the target concepts.

Research Questions

The purpose of this study is to find out how students' and scientists' embodied conceptions can serve as a framework to support developing external representations of micro- and macrocosmic phenomena. Therefore, we are dealing with two research questions in our paper:

- On which embodied conceptions do students and scientists draw to understand selected phenomena from the micro- and macrocosm?
- How can embodied conceptions inform the design of external representations of selected micro- and macrocosmic phenomena?

To serve this purpose, we draw on previous studies on students' conceptions and new empirical data to analyse students' and scientists' embodied conceptions. Based on these findings, we present data from teaching experiments on microscopic phenomena (microbial growth and signal conduction) and macroscopic phenomena (greenhouse effect and carbon cycle) in which we developed and probed external representations that engage students' embodied conceptions.

Research Design and Methods

The empirical data that we refer to in the analysis reported in this paper were collected as part of a larger project carried out within the model of educational reconstruction. The model of educational reconstruction is a widely used research programme that was developed to improve content specific learning and teaching (Duit et al., 2012; Kattmann, Duit, & Gropengiesser, 1998; Niebert & Gropengiesser, 2013a). As a research programme, the model of educational reconstruction identifies and interrelates three relevant research tasks of subject matter education: (a) critical analysis of science content, (b) investigation into students' perspectives and (c) analysis, design and evaluation of learning environments. Using the model of educational reconstruction as a research design, we conducted several teaching experiments (Komorek & Duit, 2004; Steffe & Thompson, 2000) in order to analyse students' conceptions of different phenomena and to evaluate their conceptual development when interacting with external representations.

In this study, we report the results of teaching experiments with 118 students on concepts from microcosm (cell division and neurobiology) and macrocosm (greenhouse effect and carbon cycle; see Table 2). Each teaching experiment starts with a short interview investigating students' conceptions. This interview is followed by a sequence of teaching episodes. The teaching experiments lasted 45–90 min and were conducted with dyads or triads of students on the premises of the University of Hannover and the Leuphana University Lueneburg.

The external representations probed in our teaching experiments were based on data on students' conceptions from prior studies on cell division (Riemeier & Gropengiesser, 2008), signal conduction (Fichtner, 2013), the greenhouse effect (Niebert & Gropengiesser, 2014) and the carbon cycle (Niebert & Gropengiesser, 2013b). In the study at hand here, we reanalyse these data with the aim of identifying the students' embodied conceptions so as to inform the design of external representations. Following the principles of the model of educational reconstruction, we also analysed the embodied conceptions of scientists from textbooks and research reports (Table 2). To analyse the mesocosmic experience guiding students' and scientists' conceptions, we conducted a metaphor analysis (Table 3). We present the results at the level of conceptual metaphors

Table 2. Sources of data presented in this study

Topic	Students' conceptions	Scientists' conceptions
Microbial growth	48 secondary school students (16 triads), (15–16 yrs.)	Campbell et al. (2008)
Signal conduction	13 undergraduate students (5 dyads, 1 triad; 19–24 yrs.)	Campbell et al. (2008)
Carbon cycle	39 secondary school students (9 triads, 6 dyads, 17–19 yrs.)	IPCC (2013)
Greenhouse effect	18 secondary school students (2 triads, 6 dyads, (17–19 yrs.)	IPCC (2013)

as *Target Is Source* (Lakoff & Johnson, 1980). This level seems appropriate as (a) the nearly unlimited variety of linguistic expressions that can describe an aspect can be categorised into a limited number of conceptual metaphors (Niebert et al., 2012; Schmitt, 2005) and (b) a conceptual metaphor clearly makes visible the mesocosmic experience that guides understanding. We take this analytical level for our design of external representations informed by conceptual metaphor theory.

Table 3. Steps used in metaphor analysis

Steps	Examples, metaphors are marked in italics
1. *Identifying Metaphors* We identified all metaphors in the material and chose the metaphors that were crucial for understanding neurobiology.	'[. . .] Schwann cells *wrap themselves around* axons, *forming layers* of myelin' '*In* a myelinated axon, the *depolarizing current during an action potential* at one *node* of Ranvier *spreads along* the *interior* of the axon to the next *node* [. . .], where it *reinitiates itself*. Thus, the action potential *jumps from node to node* as it *travels along* the axon'. (Campbell et al., 2008, p. 1056)
2. *Finding Conceptual Metaphors* We arranged all metaphors with the same target and source domains.	• *Wrap themselves around, forming layers*: Myelin Is Forming Layers; • *In* a axon, *interior* of the axon: Axon Is Container; • The action potential *jumps, travels* and *reinitiates itself*: Action Potential Is Travelling Agent; Action Potential Is Jumping Agent
3. *Interpreting Conceptual Metaphors* We described the metaphorical patterns used by students and scientists guided by embodied cognition. The conceptual metaphors described in this paper are denoted by capitalised letters (Target Is Source)	Action Potential Is Moving Agent When using terms like *jumping, travelling* and *reinitiating*, the process of an action potential is reified as an active agent. This agent travels through the axon (which is imagined to be a long drawn out container with a path inside), where every node of Ranvier is a start and a goal of saltatory signal conduction

For our metaphor analysis, we analysed conceptual metaphors in the transcripts of the interviews, in science textbooks and research reports by discerning terms or sequences that have, or may have, more than one meaning. Our adaption of the metaphor analysis is presented by way of example in Table 3 with the example of saltatory signal conduction (Campbell et al., 2008, p. 1056).

Based on the analysis of students' embodied conceptions, we developed external representations that relate to these conceptions. To base these external representations on embodied conceptions, we first defined the students' learning demand by comparing the embodied conceptions scientists and students hold. We then evaluated the effects of the external representations on students' conceptual development in teaching experiments. The external representations we probed are presented and described in the results section. To analyse the students' conceptual development we conducted a qualitative content analysis (Mayring, 2002) in which: (1) we transcribed the students' interactions during the teaching experiments and edited the texts to improve readability; (2) we arranged the statements by content and (3) we interpreted the statements about the underlying conceptions. In addition, we conducted a metaphor analysis of the students' conversations during the teaching experiments to compare the students' conceptual metaphors before and while interacting with the external representations.

Results

In this section, we illustrate how the theory of conceptual metaphor can inform the analysis of student conceptions and the design of external representations. Therefore, we present teaching experiments on microbiology, neurobiology, the carbon cycle and the greenhouse effect. The external representations applied in these teaching experiments were developed based on analyses of students' and scientists' embodied conceptions. Therefore, every subsection starts by explicating these embodied conceptions and analysing the learning demand.

External Representations of Microbial Growth

In a previous study on students' conceptions of the concept of growth, Riemeier and Gropengiesser (2008) found that 7th grade students are able to explain the growth of onion roots by referring to the phrase cell division: 'The growth happens by cell division'. From a scientific perspective, the students refer to an adequate scientific concept. But a deeper analysis of their understanding of the concept 'cell division' reveals a conceptual misunderstanding of the term *division*: Asked to explain their conceptions of cell division, a typical student's answer was, 'Division can lead to multiplication of cells [makes a cut in two with her hands]'. One student outlined her conception in a drawing (see Figure 1).

For the purposes of this study, our reanalysis of the embodied conceptions forming students' understanding of cell division reveals that the students adhere to a *division image schema* that is combined with a *part–whole schema*. In these schemata, division is conceptualised as resulting in (a) more single parts than the whole and (b) smaller

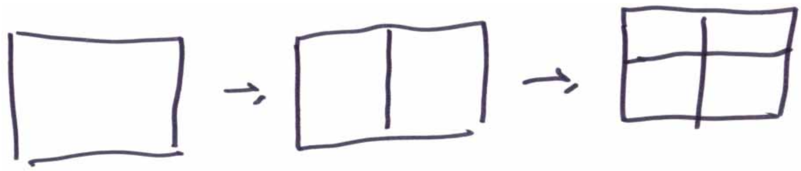


Figure 1. Drawing of cell division by a student aged 15 years

parts than the whole. A division of a whole (cell) results in two parts (cells). But these cells are not identical to the whole; they are half the size of the original part (cell).

To conceptualise growth, the students think of division, exclusively, as becoming more cells. They construct their understanding of cell division and thus, the growth of organisms, based on the conceptual metaphor *Growth Is Division.* In this conceptual metaphor, students construe division as *becoming more and more* cells which is rashly equated to growth. The second element of the division schema *becoming smaller* is not mapped to the target domain. Thus, the students get the idea that *more cells* suffice to accomplish the growth of organisms. To scientists, cell division (mitosis) implies the division of cells accompanied by the growth of cells (Campbell et al., 2008). They construct the conceptual metaphor *Growth Is Division and Enlargement.*

In our interpretation, the mapping of the elements of the division schema (Dividing Is Becoming More and Dividing Is Becoming Smaller) and the part–whole image schema causes obstacles to understanding the concept of cell division. The students' learning demand requires a meticulous mapping of the elements of the schemata. Further analysis of the students' learning demand based on their conceptual metaphors reveals that they have to understand that *cell division* is based on the concept of *enlargement* as well.

We developed two external representations to support students' conceptual development in the topic of cell division and probed them in a Ph.D. study on students' understanding of bacteria (Schneeweiss, 2008). This context is comparable to the setting of Riemeier and Gropengiesser (2008) since growth of bacteria is based on the same principles (mitosis) as the growth of onion roots.

- The external representation 'colony growth' aimed to project cell division to a mesocosmic level: While one bacterium (one cell) is part of the microcosm and invisible to the naked eye, a colony of bacteria (cells) is part of the mesocosm. Therefore, some bacteria were incubated in a petri dish with agar-agar for 24 hours. After incubation, the students were able to see the grown bacteria colonies.
- The external representation 'tearing paper' aimed to encourage students to reflect on the use of the division schema and the part–whole schema: The students were asked to tear a sheet of paper into squares and subsequently compare this process to cell division. When tearing paper, the mass of the whole remains the same, the number of parts doubles, but the parts are smaller. This external representation aimed to offer an opportunity for reflecting on the contradiction between the reduction of the size of one cell by division and the growth of an organism or a colony of bacteria.

Initially, asked to explain the growth of a bacteria colony, these students used the same conceptual metaphor as the students in the study of Riemeier and Gropengiesser: *Growth Is Division*:

> Kim: The colony grows because the cells divide at the membrane. Then there are two bacteria and so on, until a colony becomes visible.

The student Kim imagines that an increase in the number of bacteria is sufficient to explain the growth of a bacteria colony. But division by itself cannot explain an increase in biomass, which is a precondition for the colony to become visible to the naked eye. To address this use of the conceptual metaphor *Growth Is Division* the external representation 'tearing paper' is introduced, and Kim argues while working with the external representation:

> Kim: The cells must divide and grow again to the size of the mother cell. If the bacteria just divide you cannot see them. Then we would have a lot of small bacteria, but the size of all bacteria would be as small as the one before.

Kim maps her experience with tearing paper to the growth of a bacteria colony. She recognises that dividing has two meanings: *becoming more* and *becoming smaller*. By reflecting in this way, she infers that growth must be a result of a regrowth of the smaller parts to the size of the former cell. A mapping of the part–whole image schema to cell division becomes obvious: The parts (daughter cells) have to regrow to a whole (size of the mother cell) to form a visible colony. Reflecting on the part–whole image schema and the use of the conceptual metaphor *Growth Is Division* initiated a conceptual development to resemble the conceptual metaphor used by scientists: *Growth Is Division and Enlargement*.

In another case, the external representation 'colony growth' was sufficient to initiate a conceptual development. Another student, named Tom, explains the occurrence of a visible bacteria colony based on nutrition of bacteria:

> Tom: The bacteria form a colony, because they take nutrients from the agar. These makes the bacteria grow and they divide and form a colony.

Tom constructs a conceptual metaphor based on another everyday experience: *Growth Is Enlargement by Nutrition*. He construes the agar as nutrition for the bacteria, which enables them to grow. After they have grown, they can divide again. This explains the visible increase in biomass. His argumentation is based on two conceptual metaphors: *Growth Is Enlargement by Nutrition* and *Growth Is Division and Enlargement*.

External Representations of Saltatory Signal Conduction

The conduction speed in axons of vertebrates that are insulated by myelin sheaths is considerably faster than in unmyelinated axons. The insulation is interrupted by nodes of Ranvier where the depolarising current triggers an action potential. The action potential at one node will depolarise the neighbouring node sufficiently. Fichtner (2013) found that teaching saltatory signal conduction solely based on figures of the anatomy of nerves and the physiology of action potentials by figures from a science textbook (Campbell et al., 2008) poses problems for students. Asked to describe the role of insulation by myelin for the conduction speed in neurons, the student Tina answered: 'I cannot imagine how myelin affects the traveling time of signals, it prevents ions from leaving the neuron. The distance a signal has to travel in the neuron is the same with or without myelin.'

Our reanalysis of these data shows that in her attempt to grasp the role of insulation in signal conduction, Tina imagines the nerve as being a container (*in* the neuron, *leaving* the neuron: *Neuron Is Container*). Within this conceptual metaphor myelin is the boundary of the container, which keeps the ions inside (*Myelin Is Boundary*). Asked how she conceptualises the conduction speed, Tina refers to the start-path-goal schema (*distance, travel: Neuron Is Path*). The start-path-goal schema consists of a start, an agent (signal) that moves in a certain direction and a goal (Lakoff & Johnson, 1999). In the mapping of this schema the signal is reified as a travelling agent that moves (*Signal Is Travelling Agent*). The travelling time (conduction speed) of a signal depends on the *range of the path* as the determining element (*Conduction Speed Is Depending on Range of Path*). For Tina the myelin is conceptualised within the container schema (Myelin Is Boundary) but not within the start-path-goal schema.

Scientists use the container *and* the start-path-goal schema to construe saltatory signal conduction, too (Campbell et al., 2008, p. 1056), see Table 3: *Neuron Is Container, Myelin Is Boundary, Neuron Is Path.* While using similar conceptual metaphors as Tina, the scientists refer to different elements of the start-path-goal schema to construct the idea of conduction speed: For them the conduction speed depends on the length of the path and the speed of the signal (*Conduction Speed Depends on Range of Path/Speed of Signal)*. The speed of the signal is enhanced by myelin: Scientists construe the role of myelin not only within the container schema as a boundary, but also within the start-path-goal schema: Within the start-path-goal schema myelin has the role of a barrier. This barrier forces the signal to 'jump [. . . over it . . .] from node to node' (Campbell et al., 2008, p. 1056): *Myelin Is Barrier* and *Signal Is Jumping Agent*. When jumping, the speed of the signal is enhanced.

Students and scientists use similar conceptual metaphors to construct an understanding of signal conduction: *Neuron Is Container, Neuron Is Path, Signal Is Travelling Agent, Myelin Is Boundary.* Since these conceptual metaphors are the same in students' and scientists' thinking, obviously they are not sufficient to construct a scientific understanding of saltatory conduction. To construe saltatory signal conduction, scientists additionally use the conceptual metaphors *Myelin Is Barrier*, *Signal Is Jumping Agent* to construct the concept *Conduction Speed Depends on Speed of Signal.* As long as the students see signal conduction only as a journey of an agent at a certain speed, insulating of the path will not lead to the idea of faster travel. In our teaching experiments, we provided the external representation 'Toppling dominoes' with domino-bricks and drinking straws to model how the speed of signal conduction can be enhanced by bridging parts of the way (Figure 2). We aimed at bringing the use of the start-path-goal schema to the students' mind and introduce the straws (myelin) as a bridge and the impulse (signal) jumping over this bridge.

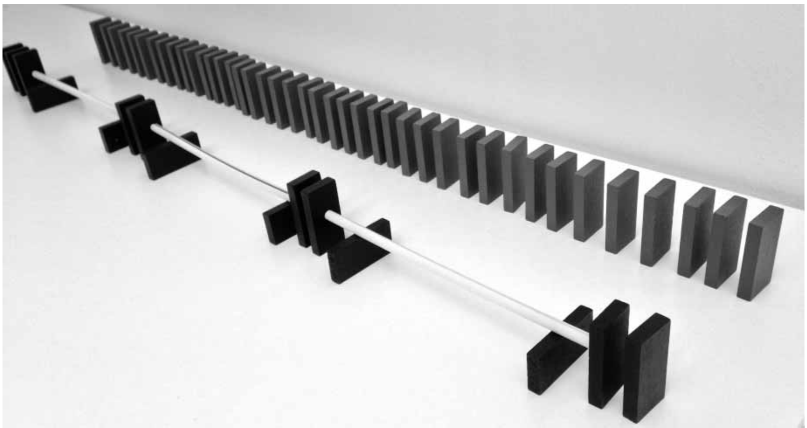


Figure 2. External representation of signal conduction (a) and saltatory conduction (b) the self-propagating process of falling dominoes models a chain reaction, where one event starts off a chain of similar events. This step-by-step process works only if the next domino is toppled (a). A straw widens the step from one falling domino-brick to the next (b)

The following episode shows the discussion of two students (Amy and Ben) who were asked to model both axons (myelinated and unmyelinated) with domino bricks:

Amy: The conduction in the domino line with the straw was much quicker than in the line without straws. The straw kind-of bridges some dominoes.

Ben: The straws are the myelin and the dominoes between the straws are these Ranvier rings. The straws and the myelin make the signal jump from one point to another.

Amy: The time of the falling dominoes is the time the ion channels need to open. The fewer channels need to open, the faster the signal is transferred.

Ben: Yes, it is like playing handball: You can quickly throw a ball or slowly hand over a ball from one player to another to get it goalwards.

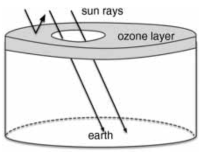
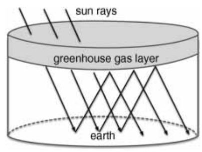
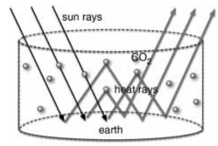
While working with the model, the students map the mesocosmic experiences with the model to their conceptions on signal conduction in microcosm in a set of conceptual metaphors: *Conduction Is Falling Dominoes, Straws Are Myelin, Dominoes Are Ion Channels*. In addition, they use these conceptual metaphors to express their newly developed conceptions: *Straw Is Bridge* and *Signal Is Jumping Agent*. These conceptual metaphors seem to be helpful for students to understand the process of signal conduction: When a signal jumps, it becomes faster; therefore they developed the idea *Conduction Speed Depends on Speed of Signal*.

At the end of the teaching experiment Ben mapped his newly developed conception to a situation from everyday life. He refers to the experience of giving and receiving a ball, i.e. in a game: Handing over the ball from one hand to another is slower than throwing a ball.

External Representations of the Greenhouse Effect

In a prior study, we analysed students' and scientists' conceptions of the greenhouse effect. Based on the conceptual metaphors they hold, we have shown that both students

Table 4. Thinking patterns on the causes of climate change

	(a) Ozone hole	(b) Greenhouse layer	(c) Greenhouse atmosphere
Quote	*CO_2 makes a hole into the ozone-layer. More sunrays enter the atmosphere and the earth warms up*	*More CO_2 thickens the greenhouse layer. The layer captures sunrays in the atmosphere and it warms up.*	*CO_2 is evenly distributed in the atmosphere. More CO_2 shifts the radiative equilibrium.*
Conceptual metaphors	 CO_2 Is Destroyer (of Boundary) Greenhouse Effect Is More Input	 CO_2 Is Boundary (of Container) Greenhouse Effect Is Less Output	 CO_2 Is Content (of Container) Greenhouse Effect Is Shifted Equilibrium

and scientists construct the greenhouse effect with different mappings of the image schemata of containers and balances in the atmosphere (Niebert & Gropengiesser, 2014).

The reanalysis of our results reveals the embodied conceptions guiding students' and scientists' understanding: The thinking patterns outlined in Table 4 show that students (a and b) and scientists (c) map different structures of the container to the structures of the atmosphere resulting in different conceptual metaphors: where *CO_2 Is Destroyer (of Boundary)* by attacking the atmosphere (a), or *CO_2 Is (thickening) Boundary (of Container)* (b) or *CO_2 Is Content (of Container)* (c). In addition, different mappings of the balance schema can be found: *Greenhouse Effect Is More Input* (a), *Greenhouse Effect Is Less Output* (b) or *Greenhouse Effect Is Shifted Equilibrium* (c).

In the study at hand, we defined the students' learning demand as follows: (1) Students need the experience of CO_2 interacting with radiation and (2) Students need to reflect on the mapping of the balance schema to the greenhouse effect. To address these learning demands we developed the external representation 'Greenhouse effect' that brought the principles of the greenhouse effect to the mesocosm. The greenhouse effect was simulated in two big (2 l) glass beakers: one of the beakers is filled with air, the other with CO_2. Both beakers were irradiated using a 200 W lamp and the development of temperature was measured in the beakers. As the beakers had no lid on them, there is no upper boundary, nothing can be attacked; thus, the warming has to be due to another mechanism. This setup addressed the students' conceptual metaphor that *CO_2 Is Destroyer of Boundary* of the container in a more indirect way of disclosing the employed schema and to ask for pondering on its selective use for understanding the role of CO_2 in climate change. To clarify the position of CO_2 in the container atmosphere, we additionally measured the concentration of CO_2 at the bottom, in the middle and at the top of the beaker. The students Ann and Tim worked with this external representation:

Ann: I thought that the ozone hole is responsible for warming. But it cannot be. I mean, we have no ozone layer here and it is warming anyway.

Tim: That's what I told you, it's not the ozone hole: CO_2 captures the sun rays. [. . .] I thought CO_2 forms a cloud. But this device shows that CO_2 is the same at the bottom and at the top. Does that mean this happens down here, where we live?

While working with the external representation of the greenhouse effect, the students discuss their conceptions in light of the evidence they found. Tim initially held the conception of the greenhouse effect using the conceptual metaphor *CO_2 Is Cloud* which is related to the conceptual metaphor *CO_2 Is Boundary* as both use the same spatial relations, even before working with the external representation. Ann initially stuck to the conceptual metaphor *CO_2 Is Destroyer* (*of Boundary*). The external representation led her into a cognitive conflict and made her reject her initial conceptual metaphor. The external representation in itself gave no explanation for how CO_2 leads to warming. This explanation is generated by Tim who sticks to his initial conception. Tim even goes a bit further after interpreting the results of measuring the concentration of CO_2. For him, it seems to be hard to believe that the greenhouse effect happens around him.

The idea of *Greenhouse Effect Is Shifted Equilibrium* is necessary to understand the role of CO_2 in climate change. But a dynamic equilibrium is hard to understand because it combines, even in its simplest implementation, two embodied image schemata: a container and a balance. To understand the combined schemata is the learning demand in this case. We disclosed the combination of schemata directly with the external representation 'visualised balance schema' consisting of a beaker with a valve at the bottom, fed and drained by water. If the valve at the bottom was medium open, the inflow and outflow of water were constant. Students were asked to manipulate the in- and outflow of water and compare it to the amount of heat in the atmosphere. From the perspective of conceptual metaphor theory, this external representation focused on helping students to consolidate the source domain and to map it onto the shifting radiative equilibrium of the atmosphere.

After working with the external representation 'dynamic equilibrium' we prepared cards with written conceptions of global warming (wording and diagrams as presented in Table 4) without tagging them as every day or scientific. The container image schema was explicitly used. The following students' conversation was typical when arguing about the different conceptions:

Max: The idea 'Warming By More Input' was what we initially thought. But it cannot be that way, because this would mean the ozone hole is involved—and it isn't. It's the CO_2 that stores the heat in the box, so it must be 'Warming By Less Output'.

Luke: But if it is less output, more and more heat is captured in the atmosphere. The temperature would rise to infinity. I think it must be this »New Equilibrium«.

Max: Yes, CO_2 stores heat and gives it away again. But the more CO_2 is in the atmosphere, the more heat is stored. [. . .] It is like my pocket money: Until my birthday, I got 10 € a week—and spent everything. Now, I get 15 € every week, and there is nothing left at the end of the week, too. But now I can afford to go to the cinema in every week.

In their argumentation, the students Max and Luke connected the experience they made during the experiments to the schemata they used to understand global warming: At first, they rejected the conception *Greenhouse Effect Is More Input* and switched to *Greenhouse Effect Is Less Output*. This mechanism of capturing heat rays is a conception that is also presented in some textbooks. It is an oversimplified idea of the energy budget, which is not appropriate to achieve an adequate understanding. The experience of a dynamic equilibrium helped the students to construct the scientific idea of global warming.

At the end of the teaching experiment, Max applied the scientific conception and the image schemata he used to the everyday experience of getting and spending pocket money. Obviously, the experience and his reflecting on the container and the balance image schemata enabled him to discuss not only the scientific conception but also his everyday experiences. We argue that this works for him because events are often construed in relation to a container (Lakoff & Johnson, 1980), and the incoming and outgoing money per week is also interpreted as an equilibrium. Therefore, the students can use the same resources to understand the energy budget of the atmosphere as their own 'fiscal budget'.

External Representations of the Carbon Cycle

In teaching experiments on the role of the carbon cycle in global warming we aimed to address a major problem reported by Sterman (2008). They probed students' ability to predict future CO_2 emissions and removal to mitigate global warming and informed students that today's CO_2 emissions are roughly twice the rate of net removal. Asked to predict the rate of CO_2 emissions and removal that is needed to stabilise the atmospheric CO_2 level, most students believed that stopping the growth of emissions stops the increase in CO_2 concentration. That vast majority of students (84%) asserted that the atmospheric CO_2 level would stabilise even though emissions exceed removal. This is in fact wrong—emissions and removal need to be the same to stabilise the CO_2 level.

To address this issue, we made use of a previous analysis of students' embodied conceptions of the carbon cycle (Niebert & Gropengiesser, 2013b). In this earlier study, we found that even if on a content level the conceptions of students differ widely from those of scientists, both draw on the same embodied conceptions: the image schemata of containers and balances form their conceptions which can be analysed from the conceptual metaphors they used: *CO_2 Is A Substance Stored*, *CO_2 Is A Substance Set Free*, *CO_2 Is A Substance Removed* (*from the Atmosphere*) (carbon pools are conceptualised as containers) or *CO_2 Is A Substance with Balanced Flow* or *CO_2 Is A Substance With Unbalanced Flow, Too Much CO_2 Disturbs Atmosphere* (carbon flows are conceptualised with the balance schema) (Niebert, 2007).

With these embodied conceptions in mind we used the setup of the external representation 'visualised balance schema' (see above) to foster students' understanding of the relation between the CO_2 emission/removal and the atmospheric CO_2 level. Before working with the external representation the students were asked to outline their conception in a graph: 'How do the CO_2 emissions and removals have to

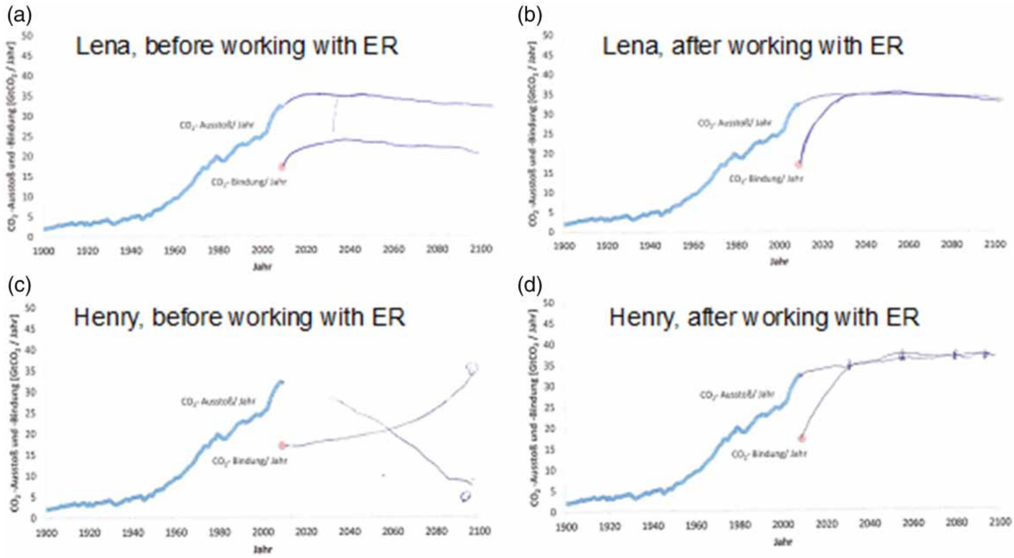


Figure 3. Lena's (a) and (b) and Henry's (c) and (d) graphs of CO_2 emissions and removal. Lena and Henry were asked to draw their conception on the development of CO_2 emission and removal to keep a constant concentration of CO_2 in the atmosphere; before (left) and after (right) working with the external representation 'dynamic equilibrium'

develop to keep a constant level of CO_2 in the atmosphere (i.e. limit global warming to 2°C).' This was the same task given by Sterman (2008).

The results (see Figure 3(a)) show that initially the student Lena had the same difficulties as reported by Sterman (2008): the emissions were stabilised but exceeded the removal. From the perspective of the balance image schema this conception is based on the idea *Constant CO_2 level Is Constant Input*. When working with the external representation Lena was asked to compare the amount of water in the beaker with the amount of CO_2 in the atmosphere:

Lena: In global warming more water flows into the beaker than leaving it.

Interviewer: Can you please map your findings to the atmosphere?

Lena: To keep the temperature at a certain level, the input and output of water must be the same. Then the same amount of CO_2 must go into the atmosphere and leave it again.

In working with the external representation of the atmospheric CO_2 level, Lena starts by implicitly switching between arguing on the mesocosmic level of the beaker and the macrocosmic level of the atmosphere. She refers to the balance image schema to construct a conceptual metaphor to explain global warming: *Warming Is More Inflow.* This conceptual metaphor brings together the mesocosmic level of the water flow and the macrocosmic level of warming. She uses a related conceptual metaphor to construct an idea of how to keep the atmospheric temperature constant: *Stopping Warming Is Balancing Flows.* Here again she refers to the mesocosmic water flow as a source for understanding. Finally, this understanding is mapped by her to the atmosphere when she exchanges the source domain water flow to CO_2 flow (*Stopping Warming Is Balancing CO_2 Flows*). From the perspective of the balance schema she argues now with the conceptual metaphor *Constant CO_2 level Is Balancing Input and Output*.

After working with the ER, we asked Lena if she wants to redraw her initial diagram. The results presented in Figure 3(b) show that she is able to transfer the conceptual development initiated in working with the external representation to draw a revised and correct diagram.

Figure 3(c) shows the conception Henry initially held. In his conception, the removal has to overshoot the emission of CO_2 to keep a constant CO_2 level. His use of the balance schema reveals the conceptual metaphor *Constant CO_2 level Is More Output than Input*. When working with the external representation he argues as follows:

> Henry: The CO2 emissions are the inflowing water, the outflowing water determines the removal. The beaker is the atmosphere. [...] We have a balance when input and output are the same. The less we emit, the less must be removed, to have a constant amount of CO2 in the atmosphere. [...] If I emit less CO2 than is removed, then at some point there is no CO2 in the atmosphere and we get the next ice age.

In working with the external representation Henry maps his mesocosmic experience with the beaker to the macrocosmic phenomena in the atmosphere. In his comparison, he explicitly constructs the conceptual metaphors *CO_2 Is Water, Emission Is Input, Removal Is Output*. He starts his explanations in working with the external representation in the mesocosm ('balance if input and output are the same') and then switches to macrocosm ('the less we emit, the less must be removed') to construct his idea of a balanced CO_2 emission and removal. In the last section, he reflects on his initial conception, which is presented in the graph in Figure 3(c): If removal exceeds emission the atmosphere would cool down. After working with the external representation he is asked to redraw his diagram. The result in Figure 3(d) shows that he too is able to transfer his insights from working with the external representation to the diagram.

Discussion

Our study was guided by the intention to find out how students' and scientists' embodied conceptions can serve as a framework to develop external representations of micro- and macrocosmic phenomena. In this section, we will discuss how conceptual metaphor theory can serve as a framework to identify the learning demand and to inform the design of external representations for teaching about micro- and macrocosmic phenomena.

Conceptual Metaphors as a Level to Reveal the Learning Demand

For the design of external representations that are informed by conceptual metaphor theory a teacher needs to know about the students' learning demand. Therefore, research into students' conceptions is required—and these conceptions need to be analysed to reveal embodied conceptions. In order to develop an evidence-based

Table 5. Conceptual metaphors of Students and Scientists: Central pre-instructional conceptual metaphors of scientists and students discussed in this paper[a]

Topic	Students' conceptual metaphors	Scientists' conceptual metaphors
Microbial growth	Dividing Is Becoming More Growth Is Division	Dividing Is Becoming More Dividing Is Becoming Smaller Growth Is Division and Enlargement
Signal conduction	Neuron Is Container, Myelin is Boundary, Neuron Is Path Conduction Speed Is Depending on Range of Path Signal Is Travelling Agent	Neuron Is Container, Myelin is Boundary Neuron Is Path, Myelin Is Barrier, Conduction Speed Is Depending on Range of Path Conduction Speed Is Depending on Speed of Signal Signal Is Jumping Agent
Greenhouse effect	Atmosphere Is Container CO_2 Is Boundary of Container/CO_2 Is Cloud, CO_2 Is Destroyer of Boundary Greenhouse Effect Is More Input Greenhouse Effect Is Less Output	Atmosphere Is Container CO_2 Is Content Greenhouse Effect Is Shifted Equilibrium
Carbon cycle	Carbon Pools Are Containers Constant CO_2 level Is Constant Input Constant CO_2 level Is Less Input than Output	Carbon Pools Are Containers Constant CO_2 level Is Balanced Input and Output

[a]A full list of the conceptual metaphors we analysed is presented in Appendix.

formulation of students' learning demand, we additionally analysed scientists' conceptions. Both conceptions are discussed at the level of conceptual metaphors to have a basis for comparison. A summary of the conceptual metaphors of scientists and students analysed in this paper is presented in Table 5.

An analysis of the conceptual metaphors students and scientists use to construe the selected phenomena reveals the mesocosmic experience they draw on. Contrasting students' and scientists' conceptual metaphors is fruitful insofar as it provides a systematic perspective to categorise students' conceptions. Our analysis of the conceptual metaphors revealed that only a limited number of image schematic structures were employed in construing the four very different phenomena. This finding fits with the compilation of Mathewson (2005) who analysed the visual core of scientific understanding at the level of *master images*. Mathewson describes master images as being a condensed structure of the visual content of science—patterns, structures, objects and phenomena. In his analyses, he stated that scientific understanding is based on a limited list of 36 master images. These master images like containers, cycles, flows, paths, boundaries and so on. are conceptually closely related to the image schemata described by Johnson (1987).

Moreover, our analysis has shown that the number of image schemata used to understand the discussed phenomena is not only limited; in all of the analysed

Table 6. Image schemata and sources of alternative conceptions to construe selected phenomena

Topic	Image schema	Source of alternative conception
Microbial growth	Division schema Part–whole schema	Just parts of the division schema are mapped to construe cell division
Signal conduction	Container schema Start-path-goal schema	Construct Myelin in container schema but not in start-path-goal schema Construe conduction speed by range of path but not by speed of agent
Greenhouse effect	Container schema Balance schema	Not adequate mapping of CO_2 in the container schema Solely focussing on input or output in balance schema to the atmosphere
Carbon cycle	Container schema Balance schema	Solely focussing on input or output in balance schema to the carbon budget

cases students and scientists referred to the *same* image schemata. However, although they draw on the same image schemata for understanding a phenomenon the constructed alternative conceptions are very different from the scientific ones. These can be traced back to selective mappings when constructing the conceptual metaphors (Table 6). Clearly, besides the selection of the source domain, the mapping of the different elements of an image schema is crucial for scientific understanding. This supports the hypothesis formulated by Amin (2009, p. 193) that 'learning the conventional mappings underlying the metaphoric expressions in scientific discourse constitutes an underappreciated obstacle to achieving conceptual change'.

The Literal and Metaphorical Use of Image Schematic Structures

In our analysis we interpreted conceptions related to the greenhouse effect or the carbon cycle based on the conceptual metaphor *Atmosphere Is Container*. But is this really a metaphorical construal of the atmosphere? The atmosphere is located in a spatial domain, so are not terms such as *emission*, *in the atmosphere*, *removal*, *incoming*, *outgoing*, *etc.* used literally? The examples Lakoff and Johnson (1980, 1999) cite are more obviously metaphorical: they found that conceptual domains like time, the mind or emotions are often understood in terms of very different domains such as space (*Time Is Space*), substances (*Mind Is a Machine*) or forces (*Love Is a Physical Force*). In the cognitive linguistics literature, conceptual metaphors like these are referred to as *ontological metaphors*. In these conceptual metaphors phenomena are conceived in terms of ontologically different types of phenomena. The conceptual metaphor *Atmosphere Is Container* of course does not change the ontological domain: The atmosphere and a container are both construed in a spatial domain. Elements of the container schema are: an inside, an outside and a bounding surface. Rooms and houses are obvious containers: The walls, ground and roof are the boundaries; through the doors, we can move from the inside to the outside of the container etc. But even where there is no natural physical boundary that can be viewed as defining a container, we can conceptually impose boundaries: A national territory has an inside, a borderline and neighbours outside the country. The same holds for the *atmosphere*. The atmosphere does not have discrete boundaries; it has no top (i.e. it is just a model), no sides and no bottom (i.e. the gaseous atmosphere reaches deep into the ground).

Imagination typically requires us to impose artificial boundaries that make physical phenomena discrete—just as we are, entities bounded by a surface (Lakoff & Johnson, 1980, p. 30). We use this imaginative thinking when we construct our understanding of the atmosphere based on the container schema. The atmosphere is thought of as having a top made of *ozone* or CO_2 and conceived with energy flows in and out of this container. The same holds for conceptual metaphors like *Neuron Is Container,* for example. A neuron is a cell and, therefore, conceptualised within a spatial domain. But as a neuron is an object of the microcosm it is not open for direct experience. Therefore, it is in line with conceptual metaphor theory and its epistemological foundations that we understand the spatial structure of a nerve cell metaphorically: Even the term 'cell' itself is metaphorical as it refers to a monk's cell in a monastery. What happens here is that a conceptual metaphor is constructed by drawing on mesocosmic experience conceptualised in terms of image schematic structures to understand spatial structures in micro- (neuron) and macrocosm (atmosphere).

By mapping all aspects of these image schemata, transfers may occur that hinder an adequate conceptual understanding. Students often compare phenomena within the same ontological domain in terms of surface similarity rather than in terms of deeper relational structure (Holyoak & Koh, 1987). This supports the finding of Halpern, Hansen, and Riefer (1990) who found that near domain analogies cause more obstacles to understand a scientific concept than distant domain analogies. When the similarity between two phenomena is more obscure students are required to put more effort into mapping the underlying relationships in order to render it meaningful.

We see the extensive use of image schemata, even from the same ontological domain as the target to be construed, as support for the hypotheses that understanding needs to be grounded in mesocosmic experience. To reveal the underlying image schemata for understanding micro- and macrocosmic phenomena, conceptual metaphors have worked as a fruitful grain size in our study. Relating the conceptual metaphors students and scientists construct to understand phenomena reveals the students' learning demand.

External Representations Informed by Conceptual Metaphor Theory

Based on the conceptual metaphors presented in Table 5, we developed external representations to address students' alternative conceptions. To do so, we formulated the learning demand based on the gap between the conceptual metaphors of students and those of scientists (Table 7).

The students' learning demand analysed in our study can be separated into two different types of requirements. First, some alternative conceptions occur as a result of students' repeated experiences with phenomena of their everyday world and an inadequate mapping of an image schematic structure. Second, other alternative conceptions can be traced back to missing experiences, which have to be made during

Table 7. Addressing students' experiential demand via external representations[a]

Topic	Learning demand	External representations
Microbial growth	Understand that cell division consists of division and enlargement: Reflect on how division schema is employed	External representation 'Tearing paper': Divide a sheet of paper as a representation of the division schema
Saltatory signal conduction	Understand that myelin makes the action potential jump from node to node: Reflect on how start-path-goal schema is employed	External representation 'Toppling Dominos': Domino-brick and straw model
Greenhouse effect	Understand the role of CO_2 in climate change: Experience the properties of CO_2 and reflect on how container schema is employed	External representation 'Greenhouse effect' to afford experience on the role of CO_2 in global warming, reflect on the absence of ozone
	Understand the energy flows in global warming: Reflect on how balance schema is employed	External representation 'Visualise balance schema' to disclose and work with an implementation of the combined container and balance schemata, reflect its mapping to the dynamic equilibrium within the greenhouse effect
Carbon cycle	Understand that a constant CO_2 level means a balance in emission and removal: Reflect on how balance schema is employed	External representation 'Visualise balance schema' to disclose and work with an implementation of the combined container and balance schemata, reflect its mapping to the dynamic equilibrium within the carbon cycle

[a]A full list of the external representations we analysed in our study is presented in Appendix.

science teaching. In the conceptual change framework these two approaches are discussed as 'misconceptions' and 'missing conceptions' (Aufschnaiter & Rogge, 2010).

With these requirements in mind the external representations presented in our study can be separated into two categories:

- External representations that address the experiential demand:

  The conceptual metaphors students used to construe the greenhouse effect showed that they lack an adequate idea of the role of CO_2 in global warming. In this case, no or inadequate conceptions can be traced back to a missing experience of the phenomenon; actually the learning demand reveals an experiential demand. To deal with this we provided a mesocosmic experience (simulate the greenhouse effect) to present the properties of CO_2.

  There are multiple representations that afford experiences of second-hand origin, such as photomicrographs, electromicrographs, chromatograms, recordings of action potentials and a view of a DNA sequencing gel. These representations, whether of first- or second-hand origin, can prepare the ground for the development of conceptions. Empirical methods in science are often means for students to experience beforehand imperceptible entities with the help of technical devices, for example, a microscope or a chromatograph. Representations that afford an experience of a phenomenon to be scientifically understood are of great importance for students. With an eye on the importance of experience, Johnstone (2007) demanded that every science lesson should start with the use of tangible experiences only. However, review studies indicate that making and interpreting scientific experiences in classrooms is a challenging task for students (Hofstein & Lunetta, 1982; Tobin, 1990). It seems that providing experiences to students does not always produce the intended motivation and understanding. In our approach, the analysis of students' conceptual metaphors was a prerequisite for the design of external representations that afford the essential experience.

- external representations that disclose the image schematic structure of concepts: In the cases of understanding microbial growth, saltatory signal conduction, the atmospheric energy budget and the CO_2 budget the students' conceptual metaphors reveal that they refer to the same image schemata as scientists. Divergences in the conceptions are due to a difference in mapping this image schematic structure to the target domains. Tearing paper, working with and reflecting on toppling dominoes and water flowing through a beaker are material representations of image schemata that students and scientists employ in understanding cell division, saltatory signal conduction, the carbon cycle or the greenhouse effect. These material representations of cognitive schemata helped students to re-experience the inherent structure of the schema, identify its essential elements and reflect on how they employ it in their effort to understand the phenomenon. This category of representation sheds light on the embodied conceptions that shape students' conceptual understanding. The external representations we developed realise the proposal of Amin (2009) that conceptual metaphor theory can inform the identification of a concept's image schematic grounding and reflecting on it. Models in classrooms often work in such a way that they provide new experiences students may use as a source for understanding. Representations that visualise an image schema and its mapping on a scientific concept work differently. They do not provide new experience; they induce an instance of a relived embodied experience. By working with these external representations students have the chance to analyse the structure of this specific experience and reflect on their embodied cognition.

In which category an external representation falls depends on how it is implemented in science teaching. The example of simulating the greenhouse effect shows how a single setting (affording experience on the properties of CO_2 in a glass container/ beaker) can, on the one hand, address a student's experiential demand and, on the other hand, helps him to reflect on the usage of an image schema. Therefore, the instructions given when working with the external representations are crucial. With a focus on addressing the experiential demand, tasks to observe and explain are helpful, while focussing on mapping often requires instructions to compare, to map or to analogise. For the latter case, the example of Lena on the carbon cycle is typical. Often students explicitly need to be asked to map their experience to the phenomenon to be understood. Therefore, not only the external representation itself is crucial, but also how it is implemented plays a major role for it to be fruitful.

Raising Metaconceptual Awareness by Reflecting on Image Schemata

When analysing the students' performance during the teaching experiments, our attention was drawn to the fact that after working with the external representations on the greenhouse effect and signal conduction, some students related the newly constructed conceptions to everyday life contexts—without being prompted to do so. In the case of signal conduction, a student saw saltatory signal conduction as passing the ball while playing handball; in the case of understanding the greenhouse effect, a student related the in- and outflow of energy in the atmosphere to his personal budget. These kinds of student-generated mappings are discussed in science education literature as self-generated analogies (Aubusson & Fogwill, 2006) or spontaneous analogies (Haglund & Jeppsson, 2012).

To us, the case where a student construes his weekly budget based on the same image schema of a balance like the atmospheric energy system is especially interesting as several authors report evidence that an adequate understanding of stock-and-flow relationships in science or everyday life is very rare (Cronin, Gonzalez, & Sterman, 2009; Sweeney & Sterman, 2000). As this analogical mapping of an image schema to both science and everyday life contexts was only an incidental finding, we are far from a sound generalisation of this finding, but we interpret it as an indicator of students' metaconceptual thinking. Mason (1994) has pointed out that successful analogical reasoning depends to a great extent on the metacognitive awareness of the nature and purpose of the mapping. She defines metacognitive competence as reflecting on what one knows and how new knowledge is developed by integrating it with the pre-existing conceptions.

We found other situations where working with the external representations that were developed based on the students' conceptual metaphors raised their awareness of their own conceptual status and progress: e.g. 'I thought that the ozone hole is responsible for warming. But it cannot be ... ' (Ann on the greenhouse effect); 'The idea "Warming By More Input" was what we initially thought ... ' (Max on the greenhouse effect). These different cases of metacognition can be interpreted by the kind of analysis used by Gilbert (2005) and Von Wright (1992), who discern two levels of metacognition in working with visualisations: At the lower level, an individual is capable of considering and comparing her conceptions to familiar contexts, whilst at the upper level she can reflect on her own knowledge. Adapted to our example of working with external representations, drawing analogical mappings to everyday life contexts is located on the lower level, while reflecting on the conceptual status (like the cases of Ann and Max above) indicates the higher level.

We draw back students' metaconceptual awareness to the type of external representations that encouraged them to reflect on their mapping of the image schemata to understand the incoming and outgoing radiation in the atmosphere or the processes in signal conduction. The external representation 'visualised balance schema' scrutinises the image schematic structure of understanding the energy flows in making the container image schema (beaker) and the balance schema (relation of inflow/outflow) explicit. This external representation is not only a representation of the phenomena of climate change but it is also an external representation of the container and the balance schema. The reflection on the structure of these image schemata seemed to support the students in understanding the atmospheric energy balance (often referred to as an energy *budget*), on the one hand. On the other hand, it seemed to make them aware of stock-and flow-relationships in their everyday life, too. Gilbert (2005) pointed out that becoming metacognitive is an important challenge to successfully deal with external representations like visualisations. The findings discussed above indicate that external representations that are designed to reflect on a concept's image schematic grounding supports students' metacognitive abilities.

Conclusions

Many decades ago, a tradition of research emerged that collected students' conceptions to *describe* how students understand certain science concepts. In recent years, several researchers in science education adapted the theoretical framework of embodied cognition to science education to *explain* why students think the way they think, i.e. to understand students' understanding; experience is the pivotal process for the development of understanding. This experience takes place in the world of medium dimensions, which Vollmer (1984) calls the mesocosm. We adapted the theoretical framework of conceptual metaphors along with Vollmer's epistemological distinction of micro-, meso- and macrocosm to science education and found that these frameworks can serve as *diagnostic tools to predict* the degrees of students' difficulties in understanding. Because understanding is firmly grounded in experience and, thus, in the mesocosm, understanding needs to be rooted in mesocosmic experience. We took this central claim of conceptual metaphor theory to elaborate the *prescriptive value* of this theoretical framework. We hope to have shown via evidence, and argued via theory, how external representations that help students reflect on their embodied conceptions from the mesocosm can improve the understanding of science. In our teaching experiments, we found the notion of conceptual metaphors to be useful for science education in two ways: it can serve as a theory to analyse conceptions and it is helpful for the design of external representations. Or, thinking metaphorically, uncovering how the hidden hand of our mesocosmic, embodied conceptions guide our understanding sheds light on the nature of understanding. In this way, offering this hidden hand to science educators enables them to use it as a guiding hand to enable a deeper understanding.

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Note

1. Note that the scale Johnstone proposed is different from the one Vollmer proposed (cf. Table 1). Johnstone calls the perceptible level *macroscopic*, while Vollmer points to the perceptible world as the *mesocosm*.

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Appendix. From Embodied Conceptions to External Representations

Full list of students' and scientists' embodied conceptions, the resulting learning demand, and the external representations we developed based on conceptual metaphor theory in our study.

Topic	Students' conceptual metaphors	Scientists' conceptual metaphors	Learning demand	External representations
Cell Biology	Dividing Is Becoming More	Dividing Is Becoming More Dividing Is Becoming Smaller	Understand that cell division consists of division and enlargement: Reflect the division schema	External representation 'Tearing paper': Divide a sheet of paper as a representation of the division schema
	Growth Is Division	Growth Is Division and Enlargement		
	Growth Is Becoming Mature	Growth Is a Cell Division	Understand the cellular principles of growth	External representation 'Onion roots', external representation 'Microscope' Observe the growth of onion roots with a naked eye (mesocosm) and microscope the root cells (microcosm)
	Cell Is Flat Structure	Cell Is Bodily Structure	Understand that a cell is a structure in three dimensions instead of two	External representation 'Soap bubbles': Comparing the 2D/3D relations of viewing a cell under a microscope with observing the structure of soap-bubbles in an aquarium via a glass wall (2D) or from top (3D)
	Gene Is Containing Information	Gene Is Information	Understand the ontology of a gene	External representation 'DNA sequence': Original data sheets with DNA sequences
	DNA Is Containing Code, Code Is Sequence of Numbers	DNA Is Code, Code Is Sequence of Bases	Reflect the conception codes	

(*Continued*)

Appendix. Continued

Topic	Students' conceptual metaphors	Scientists' conceptual metaphors	Learning demand	External representations
	Organism Is Containing Cells	Organism Is Made of Cells	Reflect on the ontology of cells	External representation 'Microscopy': Microscopy of root cells; reflection of part–whole image schema
	Division Is Cutting Information	Division Is Doubling Information	Understand the replication of a genome during mitotic cell division	External representation 'Tearing manual': Compare the tearing of a construction manual with genome division
Neurobiology	Conduction Speed Is Depending on Range of Path	Conduction Speed Is Depending on Range of Path	Understand that myelin makes the action potential jump from node to node: Reflect the travel schema	External representation 'Toppling Dominos': Domino-brick and straw model
	Signal Is Travelling Agent	Conduction Speed Is Depending on Speed of Agent	Understand the isolating role of myelin	External representation 'Myelin': Electromicroscopic photos of myelinated and demyelinated neurons
	Neuron Is Container	Signal Is Jumping Agent Neuron Is Container, Myelin Is Boundary of Container		
Greenhouse effect	Greenhouse Effect Is More Input, Greenhouse Effect Is Less Output	Greenhouse Effect Is Shifted Equilibrium	Understand the energy flows in global warming: Reflect the balance schema	External representation 'Reflect balance schema' to disclose and work with an implementation of the combined container and balance schemata, reflect its mapping to the dynamic equilibrium within the greenhouse effect
	CO_2 Is Detrimental, CO_2 Captures Heat	CO_2 Is Capturing and Releasing Heat Atmosphere Is Container	Understand the role of CO_2 in climate change: Experience the properties of CO_2 and reflect on the container schema	External representation 'Greenhouse effect' to afford experience on the role of CO_2 in global warming, and reflect on the absence of ozone

	Atmosphere Is Container CO_2 Is Top of Container, CO_2 Is Destroyer of Boundary	Atmosphere Is Container CO_2 Is Content	Understand the role of CO_2 in climate change: Reflect on the container schema	External representation 'Greenhouse effect' Measure the temperature on the bottom, in the middle and on top of a beaker in the greenhouse experiment
	CO_2 Is Reflecting Heat	CO_2 Is Opaque for Heat CO_2 Is Transparent for Light	Understand that CO_2 reacts differently with light and heat	External representation '(Im)permeable CO_2': Two plastic bags, one filled with air and the other filled with CO_2, are illuminated with a light bulb on one side. The brightness and temperature are measured on the other side
Carbon Cycle	Carbon Pools Are Containers	Carbon Pools Are Containers	Understand the nature of carbon containers	External representation 'Carbon pools' Present carbon containing materials (plants, air, sea water, molluscs, oil, etc.)
	CO_2 Is Man-Made, CO_2 is Man-Made or Natural	Carbon Flow Is Manmade or Natural	Understand CO_2 as a natural element of the atmosphere	External representation 'Track record' Historical track record with CO_2 in the atmosphere
	Climate Change by man-made CO_2	Climate Change By Imbalance in the carbon cycle	Relate climate change to manmade carbon flows instead of manmade CO_2 particles	External representation 'CO_2- Molecule': Molecular model of a CO_2- molecule and external representation 'Container-ball model' to model carbon flows
	Carbon Flows Are One Way Only	Carbon Flows Are Cyclic	Understand that in cyclic processes the start-path-goal schema is transferred into a cycle schema	External representation 'Container-ball model': Model carbon flows in a container-ball model to reflect on start-path-goal schema and cycle schema
	Constant CO_2 level Is Constant Input, Constant CO_2 level Is Constant Output	Carbon Pools Are Containers Constant CO_2 level By Balanced Input and Output	Understand that a constant CO_2 level means a balance in emission and removal: Reflect balance schema	External representation 'Reflect balance schema' to disclose and work with an implementation of the combined container- and balance schemata, reflect its mapping to the dynamic equilibrium within the cycle
	Carbon Flows Are Balanced	Carbon Flows Are Series of Imbalances	Understand that in the carbon cycle a series of imbalances creates a balanced carbon budget	External representation 'Container-ball model with multiple flows': Reflect the mapping of the balance schema in a set of multiple flows