International Journal of Science Education

ISSN: 0950-0693 (Print) 1464-5289 (Online) Journal homepage: https://www.tandfonline.com/loi/tsed20

Understanding the Greenhouse Effect by Embodiment – Analysing and Using Students' and Scientists' Conceptual Resources

Kai Niebert & Harald Gropengießer

To cite this article: Kai Niebert & Harald Gropengießer (2014) Understanding the Greenhouse Effect by Embodiment – Analysing and Using Students' and Scientists' Conceptual Resources, International Journal of Science Education, 36:2, 277-303, DOI: 10.1080/09500693.2013.763298

To link to this article: https://doi.org/10.1080/09500693.2013.763298

International Journal of Science Education, 2014
Vol. 36, No. 2, 277–303, http://dx.doi.org/10.1080/09500693.2013.763298

Understanding the Greenhouse Effect by Embodiment – Analysing and Using Students' and Scientists' Conceptual Resources

Kai Niebert[a*] and Harald Gropengießer[b]
[a]*Institute for Science Education, Leuphana Universität Lüneburg, Lüneburg, Germany;*
[b]*Institute for Science Education, Leibniz Universität Hannover, Hannover, Germany*

Over the last 20 years, science education studies have reported that there are very different understandings among students of science regarding the key aspects of climate change. We used the cognitive linguistic framework of experientialism to shed new light on this valuable pool of studies to identify the conceptual resources of understanding climate change. In our study, we interviewed 35 secondary school students on their understanding of the greenhouse effect and analysed the conceptions of climate scientists as drawn from textbooks and research reports. We analysed all data by metaphor analysis and qualitative content analysis to gain insight into students' and scientists' resources for understanding. In our analysis, we found that students and scientists refer to the same schemata to understand the greenhouse effect. We categorised their conceptions into three different principles the conceptions are based on: warming by more input, warming by less output, and warming by a new equilibrium. By interrelating students' and scientists' conceptions, we identified the students' learning demand: First, our students were afforded with experiences regarding the interactions of electromagnetic radiation and CO_2. Second, our students reflected about the experience-based schemata they use as source domains for metaphorical understanding of the greenhouse effect. By uncovering the—mostly unconscious—deployed schemata, we gave students access to their source domains. We implemented these teaching guidelines in interventions and evaluated them in teaching experiments to develop evidence-based and theory-guided learning activities on the greenhouse effect.

Keywords: *Climate change; Everyday conception; Conceptual change; Metaphor; Experience*

*Corresponding author. Science Education, Leuphana Universität Lüneburg, Lüneburg, Germany. Email: niebert@leuphana.de

Introduction

Climate change increasingly affects everyday life. For example, floods and hurricanes are believed to be the results of global warming, an increasing number of states levy carbon taxes to decrease CO_2 emissions, and a Nobel Peace Prize was awarded for actions implemented against global warming. However, everyday conceptions of global warming lag far behind even basic scientific knowledge. More than 24 science education studies have arrived at the well-documented, robust finding that students' conceptions, even after instruction, are often different from the scientific perspective. In the present study, we offer a new perspective on these findings by analysing the experience-based source of these conceptions. Based on this analysis and our own teaching experiments, we probed learning activities that address the students' perspectives by referring to their experiential sources.

An example of the conceptions about climate change commonly held by students is conveyed in the following statement:

> Greenhouse gases enter the atmosphere and bite a hole into the ozone layer. More sunrays come in through this hole and it warms up. [...] It is like in those movies at the dentist where little animals bite holes into the teeth. (Luke, 18 years)

Luke believes that climate change is caused by greenhouse gases. He analogises these gases to bacteria (which he imagines to be 'little animals') biting holes in people's teeth. In this anthropomorphic perspective, greenhouse gases cause (bite!) holes in the ozone layer, with the consequence of an increased insolation. In contrast, scientists relate global warming to an increased greenhouse effect caused by the tendency of greenhouse gases to trap heat.

Luke is not alone, however, in his scientifically incorrect beliefs. We analysed 24 studies published in refereed journals that address the conceptions of climate change (Niebert, 2010). The data are derived from a wide variety of people, ranging from primary school to university students and educated laypeople to scholars with science degrees from all over the world, including Europe, North America, Asia, and Australia. Despite the diversity of the studied populations, the results were similar everywhere. Most students and educated laypeople describe global warming according to one or more of the following perspectives:

- The thinking pattern *warming by the greenhouse effect* is framed by the idea that energy coming from the sun is trapped in the atmosphere. This entrapment results in a warming of the atmosphere due to a specific layer in the atmosphere (Andersson & Wallin, 2000; Hansen, 2010; Koulaidis & Christidou, 1999). The layer is usually described as being composed of greenhouse gases or exhaust fumes.
- Most students regard sunshine as a basic unit; that is, they *do not differentiate between UV rays, sunrays or heat rays* (Andersson & Wallin, 2000; Bord, Fisher, & O'Connor, 1998; Boyes & Stanisstreet, 1993; Dove, 1996; Jeffries, Boyes, & Stanisstreet, 2001; Khalid, 2003; Papadimitriou, 2004; Pruneau et al., 2001; Shepardson, Choi, Niyogi, & Charusombat, 2011).

- The thinking pattern *warming by the ozone hole* is based on the notion that greenhouse gases cause a hole in the ozone layer, increasing the amount of incoming solar radiation and thus warming the atmosphere. In addition, some students believe that sunrays entering the atmosphere through ozone holes become trapped under the ozone layer (Andersson & Wallin, 2000; Bord et al., 1998; Boyes & Stanisstreet, 1993; Dove, 1996; Hansen, 2010; Jeffries et al., 2001; Khalid, 2003; Papadimitriou, 2004; Pruneau et al., 2001; Rye, Rubba, & Wiesenmayer, 1997; Shepardson et al., 2011).
- Some—mostly younger—students describe the causes of global warming but offer no mechanism (Andersson & Wallin, 2000; Bostrom, Morgan, Fischhoff, & Read, 1994; Koulaidis & Christidou, 1999; Papadimitriou, 2004; Read, Bostrom, Morgan, Fischhoff, & Smuts, 1994; Shepardson et al., 2011). For these students, *increased pollution leads to global warming*. Pollution is either regarded as air pollution or, more specifically, pollution from acid rain, dirty water, nuclear energy, leaded petrol, etc.
- Some students blame the heat emitted by cities, factories, and/or volcanoes for global warming (Andersson & Wallin, 2000; Mason & Santi, 1998; Papadimitriou, 2004; Pruneau et al., 2001).
- In studies that ask open-ended questions, many students indicate they have 'no idea' of the causes of global warming (Andersson & Wallin, 2000; Papadimitriou, 2004; Pruneau et al., 2001).
- There is convincing evidence that many students have difficulty understanding the basic principles of the greenhouse effect, adhering to their everyday conceptions of global warming even after instruction. (Ekborg & Areskoug, 2006; Pruneau et al., 2001; Rye et al., 1997).

In our review, we were wondering why certain everyday conceptions are so prominent and resistant to conceptual change. This phenomenon is even more astonishing considering that the conception that 'global warming is caused by ozone holes' is not based on everyday experience, as neither the ozone layer nor ozone depletion is part of everyday life.

Experientialism as a Theory of Understanding

To analyse the source of the conceptions, we refer to theoretical considerations emerging from the fields of cognitive linguistics (Lakoff, 1990; Lakoff & Johnson, 1980), and philosophy (Johnson, 1987), as well as empirical findings from neurobiology (Gallese & Lakoff, 2005; Rohrer, 2001, 2005) and science education (Gropengießer, 2007; Niebert, Marsch, & Treagust, 2012). This theoretical framework is referred to as experientialism. It states that all knowledge is embodied, either direct or indirect. Abstract concepts—which include most concepts in science—are understood imaginatively, thereby drawing on directly meaningful concepts and schemata. These basic conceptual structures are embodied, that is, they arise from and are tied to our bodily experience (Lakoff, 1990). This perspective includes some of the central insights of the phenomenological tradition, such as the stress on the centrality of the body in structuring our experience.

Based on experientialism, we discern between two different types of conceptions: physical conceptions and abstract conceptions.

- *Physical conceptions* are embodied, that is, they are grounded in bodily experiences with our physical and social environments, i.e. perceptions, body movements, and social experiences. Physical conceptions are directly meaningful (Lakoff, 1990). Experiences such as up and down, centre and periphery, front and back, and inside and outside are conceptualised through schemata, which are conceptualisations of recurring, dynamic patterns of our perceptual interactions and motor programmes. The container schema, for instance, emerges from our experience that we are intimately aware of our bodies as three-dimensional containers into which we put certain things such as food, water, and air and out of which other things such as air, blood, and waste emerge (Johnson, 1987). Thus, we experience physical containment within our surroundings. We move in and out of rooms, clothes, vehicles, and numerous types of bounded spaces. Children experience containers by manipulating objects, placing them in cups, boxes, cans, bags, etc. A reality without boundaries is impossible to imagine. Thus, the container schema is a functional unit with an inside, an outside, a content and a boundary.
- *Abstract conceptions* get their meaning indirectly. They are not directly grounded in experience but draw on the structure of our experience. We imaginatively use our embodied schemata to understand abstract phenomena. Conceptions from a source domain (i.e. the container schema) are mapped onto an abstract target domain (i.e. atmosphere). Therefore schemata shape our conceptual understanding not only in everyday life but also in science. Accordingly, scientific understanding, as abstract as it may be, is ultimately grounded in embodied conceptions.

Obviously, conceptions of the enhanced greenhouse effect are abstract and thus indirectly embodied. We cannot experience the enhanced greenhouse effect. The only phenomena we can experience are the impacts of a warmer atmosphere. Thus, the principles of the greenhouse effect must be thought of in an imaginative way.

The theoretical framework of experientialism leads to the following research questions:

(1) What conceptions of the greenhouse effect do scientists and students hold?
(2) Which embodied conceptions are deployed as source domains for students' and scientists' conceptions of the greenhouse effect?
(3) How can educationally reconstructed learning activities foster an accurate understanding of the greenhouse effect?

Research Design: The Model of Educational Reconstruction

We adopted the model of educational reconstruction (MER) (Duit, Gropengiesser, & Kattmann, 2005; Duit, Gropengießer, Kattmann, & Komorek, 2012), as our research design. The MER is embedded within a constructivist epistemological framework (Duit & Treagust, 1998). According to the adaptation of the constructivist epistemology to science education, the conceptions and beliefs students bring into the classroom are not seen primarily as obstacles to learning but as starting points for guiding the learning of the science knowledge that is to be mastered. Additionally, science knowledge is also seen as a human construction (Longino, 1990; Solomon, 2008). We presume that there is no 'true' content structure of a particular content area. What is commonly called the science content structure is seen as the consensus of a particular scientific community. Every presentation of this consensus, be it in textbooks or research papers, are idiosyncratic reconstructions informed by the specific aims the authors explicitly or implicitly hold. Thus, academic textbooks are regarded as descriptions of concepts, principles and theories, not as accounts of reality itself.

For the design of learning activities, we draw on both—clarified science theories and students' resources—as equally important for the construction of instruction.

Within this model, the conceptions of scientists and students are set into relation to develop effective teaching and learning activities (Figure 1). We extracted scientists' conceptions (1) from various scientific university-level textbooks and the IPCC-Report (2007). Students' conceptions (2) of global warming were sampled in a reanalysis of 24 empirical studies on everyday concepts of global warming (for the complete list, see Niebert, 2010), our own interview study ($n = 11$; 18 years of age; 5 females, 6 males) and our 10 teaching experiments ($n = 24$, 18 years, 11 females, 13 males). All students attended secondary schools in Germany and had no prior instruction in climate change. In the course of the educational reconstruction of global warming, we developed teaching guidelines (3a) and learning activities (3b), which were evaluated in 10 teaching experiments (3c). Furthermore, we examined students' learning processes in our teaching experiments (Riemeier & Gropengiesser, 2008; Steffe, Thompson, & von Glaserfeld, 2000), which lasted approximately 65–90 min.

Following experientialism, we hold the view that language and thought are based on the same conceptual structures. Language is, therefore, a window into the

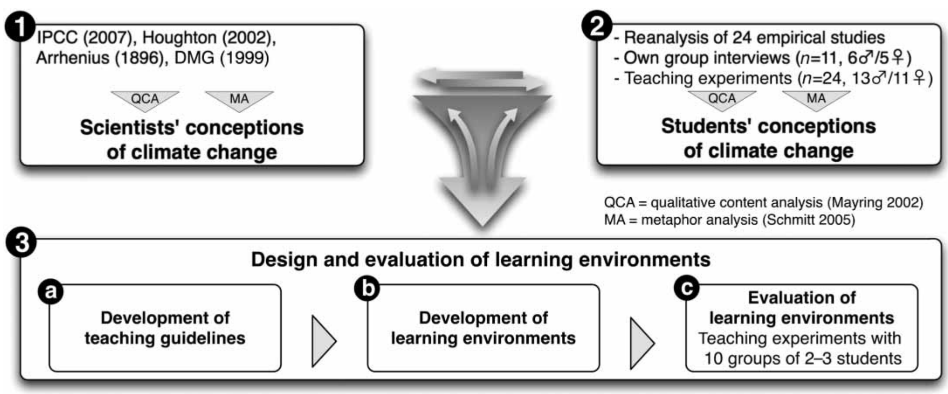


Figure 1. Research design: the MER

conceptions of students. Conceptions are expressed through various symbols of speech and/or drawings. Therefore, students' statements are regarded as representations of their conceptions. To analyse their conceptions, all data were audio-taped (interview study) or videotaped (teaching experiments), transcribed and investigated using qualitative content analysis (Mayring, 2002) and metaphor analysis (Schmitt, 2005).

In the course of qualitative content analysis, we developed categories by (1) transcribing the interviews and editing of the texts to improve readability, (2) rearranging statements by content, (3) interpreting the statements aimed at the underlying conceptions, and (4) revising and developing a final formulation of the categories.

The metaphor analysis provides the basis for our interpretation of the conceptions from the perspective of experientialism as follows: We identified a metaphor as a term or sequence that has, or may have, more than one meaning. First, (1) we identified all metaphors in the material and (2) chose the metaphors that were crucial for understanding the greenhouse effect. Subsequently, we arranged all metaphors with the same target and source domains and (3) described the metaphorical patterns used by students and scientists guided by experientialism. The basic schemata that act as source domains for understanding the greenhouse effect are presented in the following sections.

The results of the metaphor analysis guided the interpretation of the conceptions within the qualitative content analysis. To assure the quality of the analysis, all data were externally and consensually validated in our working group (Steinke, 2004) and cross-checked with other studies in the field. The teaching experiments and the interviews were conducted by this article's first author.

Results

We identified different conceptions regarding the causes of global warming in the references as well as in our own data. The summary of the review can be found in the first part of this paper; for a more extensive review, see Niebert (2010). In the following section, the various conceptions of students and scientists with a focus on the greenhouse effect are analysed. In a second step, the relevant learning activities are described and evaluated.

Scientists' Conception: Warming by a Greenhouse Atmosphere

In 1896, Arrhenius was the first to describe the effects of rising CO_2 concentrations on the climate. Since the Intergovernmental Panel on Climate Change (IPCC) began publishing its assessment reports, research on climate change has become a major field in climate research. Scientists relate global warming to a change in the earth's radiation budget due to an intensified greenhouse effect. To understand and explain the greenhouse effect, scientists refer to the container schema (cf. Figure 2):

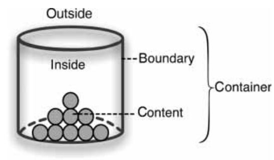


Figure 2. The container schema

> The solar radiation coming in is balanced by thermal radiation leaving the top of the atmosphere. (Houghton, 2002, p. 257; our underlining)

> Incoming solar radiation and outgoing infrared (thermal) radiation. (IPCC, 2007, p. 136; our underlining)

To interpret these statements, we identified the employed schemata by metaphor analysis (Schmitt, 2005) and analysed their structure to gain a deeper understanding of the scientists' perspective of the greenhouse effect. The container schema is based on the experience that our body is a container with a sharp border between the inside and the outside crossed by inputs and outputs (Johnson, 1987). Indicators for thinking in terms of a container are words like "into", "out", "coming in", "leaving", "incoming", "outgoing" or "contain".

Using the container schema, the atmosphere is conceptualised as a container to describe the flow of radiation between the inside and the outside. The conception that *the* atmosphere is a container uses the surface of the earth and a fictive top of the atmosphere as boundaries. The interior of the container consists of gases, while the outward boundary is drawn to describe and quantify the energy flows between the atmosphere and space. The surface of the earth is conceptualised as the lower boundary of the container, which is crossed by energy and gases.

> The atmosphere of a planet is a gaseous envelope [. . .] (Houghton, 2002, p. 1)

> [. . .] movements of carbon dioxide into and out of the atmosphere (Houghton, 2002, p. 252)

Greenhouse gases such as CO_2 are responsible for the warming of the atmosphere.

> The greenhouse effect [occurs in an] atmosphere that is more transparent to solar radiation than to infrared radiation. [IR-radiation] emitted by the planetary surface is absorbed by greenhouse gases. (Houghton, 2002, p. 3) [. . .] greenhouse gases are increasing, thus leading to an enhanced greenhouse effect. (Houghton, 2002, p. 255)

The conceptions of the greenhouse effect are based on two different entities interacting within the container atmosphere: radiation and CO_2. Radiation, according to scientists, is an electromagnetic energy characterised by wavelengths and related frequencies in a continuous spectrum. A relevant distinction in solar radiation is drawn between visible light (the short-wave section of the spectrum) and heat (infrared radiation). The visible light is absorbed by the earth's surface and re-emitted as infrared radiation. Visible light passes CO_2 unaffected, but infrared radiation interacts with CO_2, heating it. Rising CO_2 levels in the atmosphere raise the atmosphere's temperature and

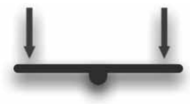


Figure 3. The balance schema

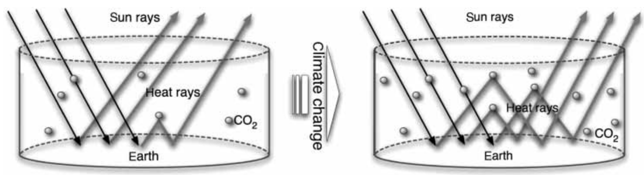


Figure 4. Warming by greenhouse atmosphere

enhance the thermal energy of the atmosphere. The more CO_2 in the atmosphere, the more thermal energy it encloses. In addition to the container schema, a balance schema is used to describe equilibrium between the in- and outflows (Figure 3). The balance schema (Lakoff, 1990) shapes our conceptual system with our first attempts at walking instead of crawling. This schema follows a logical sequence in which each change is followed by a counter-change. Indicators are words like "(im)balance", "equal" or "compensate".

In using the balance schema to describe the causes of global warming, scientists compare the incoming and outgoing radiation at the top of the atmosphere and describe both as equal. For scientists, an increasing amount of CO_2 leads to a *shift in radiation balance to a higher level*. We call this concept warming by the greenhouse atmosphere (Figure 4).

Thinking Pattern: Warming by Ozone Hole

In the introduction, we presented Luke's conception of a warming earth due to a hole in the ozone layer. For a broader understanding of this thinking pattern, we offer two more examples of students from our interview study who also adhere to this belief:

> CO_2 destroys the ozone layer. Radiation coming from the sun passes into the atmosphere through the layer and heats up the earth. (Ben, 18 years)

> The ozone hole is getting bigger, because CO_2 attacks the ozone layer and thus more sunrays enter the atmosphere. The sunrays are reflected between the earth and the ozone layer and warm the earth. (Lesley, 18 years)

Students adhering to this thinking pattern imagine a hole in the ozone layer as causing global warming. According to this idea, the ozone layer normally reflects some sunrays back into space. CO_2 causes a hole in the ozone layer, and sunrays penetrate the layer through the hole, thereby warming the earth (Figure 5(a)). This concept exists in a second variation (Figure 5(b)) in which the incoming radiation is additionally

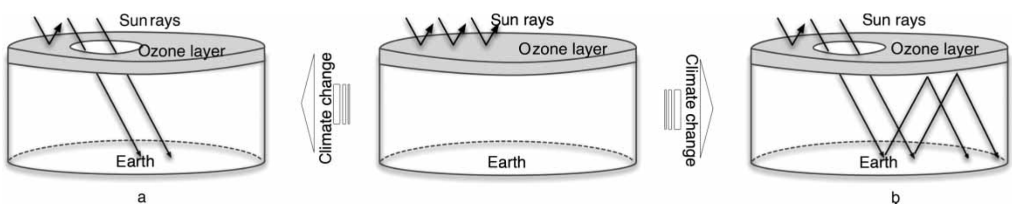


Figure 5. Warming by ozone hole. (a) More sun rays and (b) radiation trap

reflected between the ozone layer and the earth. In our study, 26 of 35 students expressed the notion that more sunrays pass through a hole in the atmospheric protection shield of the ozone layer. Metaphor analysis indicates the students' use of the container schema to describe the mechanisms of global warming. Expressions such as 'passes into the atmosphere', 'through the layer' or 'sunrays enter the atmosphere' indicate that the atmosphere is imagined as a container with the ozone layer as a shielding boundary. In the students' perspectives, devastating qualities are attributed to CO_2: it 'attacks', 'destroys' or 'bites'. With anthropomorphisms such as these, students strive to grasp the idea of how a hole can be made in the ozone layer's atmospheric protection shield.

Students using this conception do not distinguish between visible light (short-wave radiation) and heat (long-wave radiation). From an experientialist perspective, this finding is not surprising because we experience the sun shining as both bright and warming. What we recognise is that we feel warm if the sun shines down on us. Consequentially, the students hold the concept that the more sunrays there are, the warmer it is. Thus, the concept of a perforated atmospheric protection shield leads to the simple idea that *the atmosphere is warming because more heat gets in*.

Thinking Pattern: Warming by Greenhouse Effect

In our interviews, we identified another thinking pattern that seems quite similar to the concepts expressed by the scientists, *warming by greenhouse effect*. This concept is expressed in two variants that differ in the conceptualisation of sunrays and heat rays:

> A layer of CO_2 hinders the visible light coming to earth from going back into space again and reflects the light back to earth. So it gets warmer in the atmosphere. (Jason, 18 years)

> There is a layer of greenhouse gases on the top of the atmosphere. The CO_2 accumulates in this layer so it gets thicker. The sun's rays are transformed into heat rays on the earth's surface. These heat rays are trapped in the atmosphere under the layer. (Jacob, 18 years)

This thinking pattern is also based on the container schema ('into space', 'in the atmosphere'). The top of the container consists of a layer of greenhouse gases (mainly CO_2). This layer becomes thicker as more CO_2 accumulates on the top of the atmosphere. The layer causes global warming due to the special properties of CO_2, in that the layer is permeable for sunrays but nearly impermeable for the

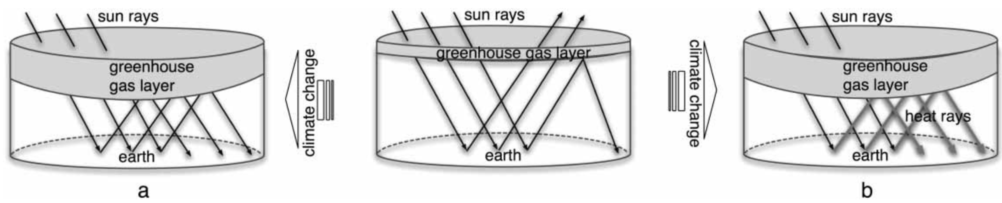


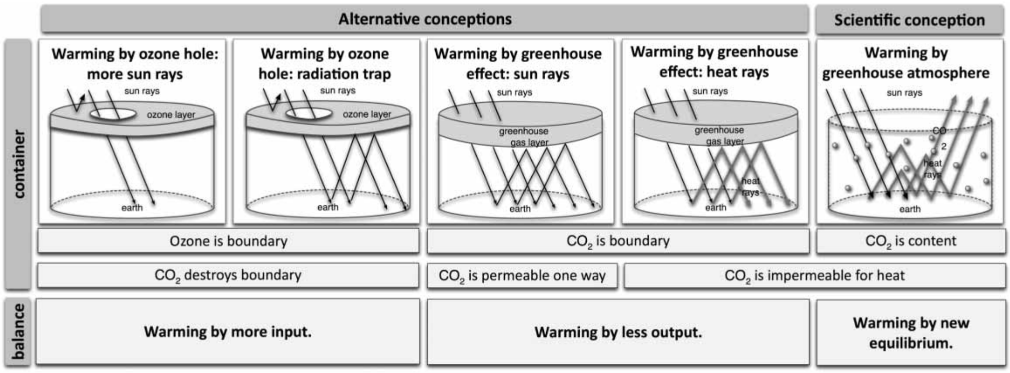
Figure 6. Warming by greenhouse effect. (a) Sun rays and (b) heat rays

radiation coming from the earth. This perspective is similar to the greenhouse effect as communicated in the media or in schoolbooks. The central element of this concept is a layer of greenhouse gases acting as a barrier that becomes thicker and thus less permeable. Therefore, the heat radiation is captured under the greenhouse gas layer in the atmosphere. The basic idea is that the earth warms up because less heat gets out or, even more simply, warming by less output. From the students' perspective, the CO_2 is not evenly distributed in the atmosphere but forms its upper layer. In contrast, scientists claim that evenly distributed CO_2 captures the heat in the atmosphere. The idea of a greenhouse bounded by a gas layer instead of containing a gas-atmosphere is traceable to cognitive systems' ecology insofar as it projects the events causing global warming to the mesocosmic level of the container's boundary, and it does not take into account the sub-microscopic level of molecules. The boundary of a container is easier to conceptualise as the continuum of the interior. Thus, the entity *boundary* is a well-experienced and embodied structure, while the entity *continuum* in the interior of a container is not a structure that can be grasped or experienced. Because the concept of a continuum is not experience-based but imaginative, it is easier to conceptualise the effect of global warming as a well-experienced structure similar to a boundary than to an imaginative structure such as a continuum. Furthermore, the greenhouse metaphor draws an analogy with a glasshouse as the atmosphere uses a structure with solid walls as a source. Within the thinking pattern as it is communicated by Jason, the layer of greenhouse gases is a one-way permeable boundary. That is, the radiation coming from the sun can permeate the layer, while the reflected radiation from the earth is trapped (Figure 6(a)). In contrast to Jason, Jacob holds a more sophisticated variant of this conception as Jacob discerns between sun radiation and heat radiation. He holds the perspective that the sun's radiation is transformed by the earth's surface into heat radiation, and this heat radiation is then captured by the CO_2 (Figure 6(b)). The students holding to the concept of a greenhouse effect describe global warming as a *warming by less output*.

Comparison of the Thinking Patterns

In Table 1, students' and scientists' conceptions are arranged according to the above analysis. In all cases, the atmosphere is conceptualised as a container, demonstrating that the same source domain was chosen for imaginative understanding. However,

Table 1. Conceptions of the processes of global warming



students and scientists map the container schema differently to the target domain of greenhouse effect depending on whether the atmosphere's boundary comprises CO_2 (greenhouse effect) or ozone (ozone hole) or merely a defined concept (scientists). CO_2 is conceptualised in different roles in relation to the container: an eradicator of the container's border (ozone hole), one-way permeable (greenhouse effect) or permeable for sunrays but impermeable for heat rays (scientists).

Table 1 shows a different use of the balance schema. While the concept of warming by a hole in the ozone is based on the idea of warming by more input, the students' idea of the greenhouse effect is based on the idea of warming by less output. Consequently, both concepts would lead to infinite warming as more and more heat is captured. It is analogous to sit in a bathtub and playing with the drain. When the inflow and outflow of water are the same, the water level does not change. If one closes the drain, the water level will rise until the bathtub overflows (warming by less output). If one opens the water-tap very wide while the drain is closed (warming by more input), more and more water will come in and the water will overflow. Sweeney and Sterman (2007) have shown that even highly educated subjects with extensive training in mathematics and science have a poor understanding of systems with inputs and outputs.

However, scientists posit the idea of a dynamic equilibrium to understand global warming. Using the analogy of the bathtub, this means that when the drain is closed and the inflow stays the same, the water level will rise to a new level until the drain is opened again. This analogy shows that the scientific idea of the greenhouse effect is based on principles similar to those of the students' ideas of global warming. However, the dynamic equilibrium, which is much more difficult to understand, can be explained by our experiences of balance and imbalance. Johnson (1987) found that we usually perceive a balance when we lose it. That is, we do not consider balance when we walk or ride a bike, but we perceive the imbalance when we stumble or fall. Thus, a dynamic equilibrium is nearly impossible to experience in everyday life. Our everyday life, however, is full of experiences where more energy (i.e. sunrays) results in stronger warming. It is warming when the sun begins to shine, when the heater is turned higher to bring more heat into a room, or when the stove burner is turned up to make water boil more quickly. While the dynamic aspects of these phenomena can be explained from a scientific position, they are usually not perceived in everyday life.

The stratospheric ozone as layers of greenhouse gases is presented in common textbooks for school and university science as atmospheric layers (Niebert, 2010). Thus, a common frame of understanding can be applied for both rather different phenomena. The greenhouse effect and the ozone depletion are presented as being connected to the atmosphere and the sun's rays and as being caused by emissions from industries and households. Both phenomena change the earth's radiation budget, and both phenomena are imperceptible. The same schemata and the same types of causes are used to explain both phenomena. As such, they form a common frame that is activated when thinking of *environmental problems of the atmosphere*.

From a science educator's perspective, the metaphor of the greenhouse effect that analogises the events in the atmosphere with those in a greenhouse is problematic because the atmosphere is warming due to a selective absorption of heat by climate-active gases. Instead, the greenhouse is, first and foremost, warming because the glass-windows suppress the circulation of air and, as a consequence, the convection of heat. This scientifically inadequate mapping of the source (greenhouse) to the target (atmosphere) is not recognised by the students. Indeed, the greenhouse effect is understood in terms of its impacts, not by its underlying mechanisms. The metaphor is convincing because the warmer inside of a greenhouse is open for direct experience, and this experience is mapped to the atmosphere. The mechanism of this warming, however, is not available for everyday experience and is thus not understood by the students. In other words, the greenhouse metaphor works because no student understands the mechanisms of a greenhouse.

Learning Activities for Meaningful Experiences

In the prior section, we analysed the experiential sources of students' conceptions on the greenhouse effect and showed that although students use the same schemata as scientists, they map them differently on the target domain of greenhouse effect. From an experientialist perspective, we developed learning activities based on the principle of 'reconstructing the container'. The learning activities followed the teaching guidelines as stated below:

(1) Students should explore and reflect on the boundary of the container. Is it an ozone layer, a CO_2 layer or is it just a defined boundary?
(2) Students should explore and reflect on the role of the CO_2. Does it form the boundary of the container or is it the content? Does it destroy the boundary or does it absorb heat?
(3) Students should re-experience and reflect on the use of the balance schema. Is it warming by more input, less output, or is it a new balance?

The next section shows how learning activities that address students' experiential resources can facilitate these reflections. To analyse whether and how learning activities influence students' conceptions, we evaluated the learning activities in teaching experiments. Teaching experiments provide empirical opportunities to combine investigational aspects of interviews with the interventional aspects of teaching (Riemeier & Gropengiesser, 2008; Steffe et al., 2000). The analysis of our teaching experiments provided information about the students' pre-instructional conceptions and their development throughout the course of the teaching process. The role of the researcher is twofold: to identify students' conceptions as an interviewer and to organise learning activities as a teacher based on students' conceptions. In the teaching experiments, students were challenged with learning activities that matched their conceptions. Therefore, not all students worked with all learning activities. The teaching experiments, which lasted 65–90 min, were videotaped for a process-based analysis of students' conceptual development. Evaluating the learning activities in the teaching experiments reflects the recursive aspects of the MER such that if a teaching experiment indicated that a learning activity required further interventions to be successful, these interventions were adapted. Furthermore, the process-based evaluation made it possible to evaluate the role of students' interactions or spontaneous interventions by the teacher and the planned learning activities.

As indicated herein, the understanding of the greenhouse effect is based on the container schema. Differences between a scientific understanding and everyday conceptions originate from different ways of mapping the structures of the container to the structures of the atmosphere. Thus, we developed learning activities that helped students reflect on the mapping of the container schema for climate change. Accordingly, we materialised the container schema as a glass box and asked students to analogise the box and the atmosphere (Figure 7). In contrast to very common versions of this experiment, we did not use closed bags or closed boxes but rather open-top boxes. This addresses the students' idea that CO_2 attacks the boundary of the container: We planned to lead students who adhere to this conception into a cognitive conflict by

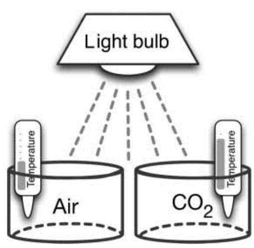


Figure 7. Reconstructing the container. Two glass boxes were filled with CO_2 (right box) and air (left box). Both boxes had open tops and black bottoms and were irradiated with a strong light bulb (200 W). The temperature was measured. It rose in the box filled with CO_2 approximately 2°C degrees centigrade higher than it did in the box filled with air. Students were asked to interpret the phenomenon.

experiencing a warming of the open box with CO_2. When there is no upper boundary, nothing can be attacked; so the warming has to be due to other mechanism.

Max was one of 18 students who worked in this learning activity of our teaching experiments. The following excerpt reveals his conceptual development:

> Max: Initially, we said that it gets warmer because CO_2 destroys the ozone layer. However, here, we have no ozone layer and no ozone hole. However, the container with the CO_2 heats up by two degrees anyway. How is the CO_2 doing this? I don't know.

In the beginning, Max adheres to the concept that climate change is due to an ozone hole caused by CO_2. During the experiment, he recognises a heating of the container with the CO_2 and notes that there is no ozone layer capping the container. Thus, the learning activity fostered learning. Max's observations led him to a cognitive conflict with his initial conception. He blames CO_2 for the heating, but he has no idea of the mechanism. Another student, Fred was also asked to explain his conceptions during the intervention:

> Fred: I thought that the ozone hole causes global warming. However, it is the CO_2 and not the ozone. You can see that the temperature in the box with CO_2 rises higher. [...] The CO_2 stores the heat. The heat gets into the CO_2 molecules.

Initially, Fred believed that climate change is the result of a hole in the ozone layer. While conducting the experiment, he realises that the temperature in the box with the CO_2 rises higher than it does in the other box even though there is no ozone involved, just CO_2. He explains the warming by conceptualising CO_2 as an aggregate of small containers (*into the molecules, molecules store heat*). The idea of storing heat in molecules may not be adequate from a thermodynamic perspective that conceptualises temperature as the vibration and thermal motion of molecules. However, from a phenomenological perspective, Fred's conception is comprehensible and sufficient to explain the causes of global warming. This particular example shows that the learning activity helps to express that CO_2 is the cause of global warming (see Table 2).

Table 2. Conceptual development while reconstructing the container

Statements (examples)	Students (*N*)	Concept in teaching experiment
'It is the CO_2 (and not the ozone)'	18	No ozone involved
'CO_2 stores the heat'	9	CO_2 stores heat
'CO_2 hinders the heat from leaving the box again'	5	CO_2 traps heat
'I don't know how CO_2 is doing this'	3	No mechanism
'There is no ozone in the box, but it must be ozone'	1	Warming by ozone hole

This learning activity was evaluated using 18 students. The first concept (no ozone involved) reflects the aim of the intervention. The other concepts (CO_2 stores heat, etc.) reflect the investigational aspects of this learning activity as they expose the students' further learning demands.

Students who adhere to the thinking pattern *warming by ozone hole* can reconstruct their conception by experiencing a warming caused solely by CO_2. In describing the experimental set-up, every student recognised that there is no ozone involved in this experiment and, consequently, in the warming. In our investigations, only one student held to the conception *warming by ozone hole* after the teaching experiment, despite realising that there is no ozone involved in the experiment. As all of our students explained that the warming must be caused by CO_2 because there is no ozone involved, the intervention fostered a conceptual development from *warming by ozone hole* to *warming by greenhouse effect*.

After the students successfully went into a cognitive conflict, we asked them how they think CO_2 leads to global warming. From the students' responses, we identified three different ideas to explain the causes of warming: *CO_2 stores heat, CO_2 traps heat (under a layer)* or *no idea of the causes*. The role of the radiation and its transformation from short-wave to long-wave radiation as well as the underlying processes as absorption and emission stay unrecognised by the students. This can be explained by the arrangement of the experiment, which shows the effect of CO_2 in global warming (absorbing heat) but provides no cues for an explanation. To engender an understanding of the mechanism of global warming, we prepared another learning activity that focused on the role of CO_2 in global warming (Figure 8).

Guided by this learning activity, a student who expressed a cognitive conflict reflects on the relevant properties of CO_2 in global warming.

> Max: The visible light goes through the bags. Behind the bag with the air it is warmer than behind the bag with CO_2. Thus, CO_2 will absorb the heat. The heat stays in the bag. [...] So my theory is the CO_2 in the atmosphere captures the heat and thus it gets warmer.

Max describes both bags as transparent for visible light. He also recognises that it is warmer behind the bag filled with air than behind the bag filled with CO_2. He interprets his observations in the intended way: CO_2 is transparent for light and not transparent for heat, while air is transparent for both. After interpreting the results of the experiment, he relates his hypotheses to the atmosphere and relates global warming to the capturing of heat due to CO_2.

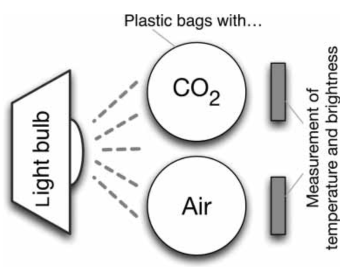


Figure 8. (Im-)permeable CO_2. Two plastic bags, one filled with air and the other filled with CO_2, were illuminated with a light bulb on one side. The brightness and temperature were measured on the other side. While the brightness was the same behind both bags, the temperature behind the bag filled with CO_2 was 1.5 °C lower than that behind the plastic bag because CO_2 absorbs the heat.

Inspired by both experiments, Max reconstructs his mapping of the container schema to the atmosphere. While a hole in the container's boundary is initially blamed for allowing heat into the container, the first experiment leads to a cognitive conflict; therefore, Max subsequently rejects this theory. The second experiment allows Max to experience the effect of CO_2 in global warming on a small scale. Inspired by this experiment, he develops the idea that CO_2 as the container's content causes global warming by trapping the heat. Thus, he reconstructs not only the role of the container's boundary but also the role of the content from disrupting (causing the hole) to capturing (trapping the heat).

Two other students were asked to predict the results of the experiment:

> Nina: The light and the heat will pass easier through the bag with the air than through the bag with CO_2. It will be colder and darker behind the bag with CO_2.
>
> Ernest: Yes. CO_2 will block the heat and the light.
>
> Nina: [While conducting the experiment] The light passes both bags very well. Light comes in and leaves the bags again. However, the heat does not leave the bag with CO_2. I remember heat rays have a longer wavelength. They cannot pass the CO_2. They stay in the CO_2 bag.
>
> Ernest: We were wrong. CO_2 does not block the light, it just blocks the heat. [...] That explains why the sun's rays can enter the atmosphere. However, after the sun's rays are transformed into heat rays by the earth, the heat rays cannot leave the atmosphere again.

Nina and Ernest both distinguish between light and heat radiation. Initially, both predict a higher temperature and brightness behind the bag with air. As the results of the experiment conflict with their predictions, they reconstruct their conceptions to *air is permeable for heat and light* and *CO_2 is permeable for light but impermeable for heat*. As the learning activity provides experience but no explanation of the phenomenon, Nina reverts, correctly, to the formerly learned concept of wavelength.

Ernest projects his experience onto the atmosphere and explains the selective permeability of the atmosphere for sun's rays and heat rays as responsible for global warming. While the sun's rays can pass through the atmosphere, the heat rays cannot escape the atmosphere. Furthermore, he describes the absorption and emission of radiation as a transformation. The experience of the CO_2's properties of selective permeability helped students to reconstruct their conceptions towards a more scientific perspective.

This learning activity focuses on providing experience with the selective permeability of CO_2 for light, not for heat. Furthermore, the experimental set-up helps to discern between light and heat radiation as it directs the students' attention to the two entities. Guided by the experience provided in this experiment, all of our students formulated the following two concepts: *CO_2 is permeable for light and impermeable for heat* and *air is permeable for light and heat*. Thus, this learning activity proved to be successful in furthering students' understanding of the basic but hard-to-grasp principles of the greenhouse effect. However, the cause for this selective permeability is explained differently. Two students explained their observations of a chemical

Table 3. Conceptual development while experiencing (im-)permeable CO_2

Statements (examples)	Students (N)	Concept in teaching experiment
'The light easily passes both bags, but it is colder behind the bag with CO_2'	24	CO_2 is permeable for light, but impermeable for heat
'CO_2 stores/captures the heat in the bag'	16	CO_2 stores heat
'CO_2 absorbs the heat rays'	6	CO_2 absorbs heat
'It might be that heat splits CO_2 into C and O_2'	2	Heat splits CO_2

The learning activity was evaluated with 24 students. The first concept reflects the aim of the intervention. The concepts explaining the cause of this permeability reflect the investigational aspect of this learning activity as they expose the students' further learning demand.

reaction induced by heat rays ('Perhaps the rays split CO_2 into C and O_2'), while the majority discuss a storage or absorption of heat rays by CO_2. Our learning activity stopped at this point, as the latter explanations are sufficient to explain the causes of global warming. Accordingly, the experience of a selective permeability or—more appropriately—selective absorption could be used to initiate a discussion about the molecular properties of gases and explain why some gases act as climate-active gases and others do not. The conceptual developments the students revealed while working with this learning activity are summarised in Table 3.

In the first versions of this experiment, the students just measured the temperature behind the bags. Our analysis showed that some students tried to explain the mechanism of global warming by a chemical reaction ('CO_2 is split into C and O.'). This statement reveals the limits of the experiment: It affords experiences with CO_2 as selectively transparent for short-wave radiation, but it does not explain the causes of this phenomenon.

Some students analogise the light bulb with the sun, which has some conceptual traps. For example, the light bulb emits both light rays and heat rays, while the sun's output intensity is highest in the visible part of the spectrum. The heat rays in the atmosphere are mainly earth-rays. That is, the sun's rays are absorbed by the earth, and the energy is emitted again mainly as heat rays. The heat rays are then absorbed by the CO_2 and re-emitted. This concept should be discussed with students while critically analysing the model.

A second limitation of the experiment is the aspect of time: In our teaching experiments, this learning activity took about 15–20 min. In this time, the temperature behind the bag with air rose about 1.5–2 degree higher than behind the bag filled with CO_2. After a longer time period (approximately 40 min), the temperature behind the bag with CO_2 rises to that behind the bag filled with air, as a new (higher!) equilibrium arises and both bags emit an equal amount of radiation. As we interrupted the experiment before the new equilibrium arose, we did not discuss this with our students.

Thus far, we have shown how interventions affording experience on the role of CO_2 in global warming can engender an adequate mapping of different elements of the

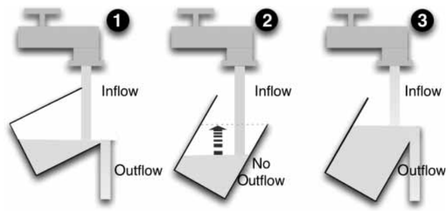


Figure 9. Modelling a dynamic equilibrium. A tilted beaker is fixed on a stand under a water tap. In- and outflow are the same. Students are asked to analogise the amount of water in the beaker with the amount of heat in the atmosphere. The learning activity provided students with experience regarding a container-flow system in action and change: (1) dynamic balance, (2) imbalance, and a new (3) dynamic balance at a higher content level.

container schema to the atmosphere. In a last example, we show how an analogical experience can foster an understanding of the aspects of a dynamic equilibrium (see Figure 9).

While working with the learning activity, Raphael commented as follows:

> Raphael: When inflow and outflow are equal, we have a balance. If more CO_2 enters the atmosphere, it gets warmer. That is like the beaker filling up. Then, we have no balance [Raphael puts the beaker in a more vertical position (2)]. When the beaker is more vertical, more water stays in the beaker. And anytime inflow and outflow are equal again, we have a new balance. [. . .] If there is more CO_2 in the atmosphere, the beaker is more vertical. An atmosphere without CO_2 is like a horizontal beaker. That is a balance, too. However, it is cold then. And when it is nearly vertical, the earth is very warm, but it is a balance, too.

Raphael creates an analogy between the atmosphere and the experiment. More CO_2 means to him that the beaker is filling up. His experience of equal inflow and outflow results in the description of a balanced situation. For him, the position of the beaker and the water level is not relevant to perceiving something as balanced as balance is reached when inflow and outflow are identical. An imbalance exists when the position of the beaker is changed, that is, once the beaker is filled to the new water level and there is a new balance on the higher content level. In analysing the learning activity, we found that all of our students were able to analogise the model with the mechanisms in the atmosphere (Table 4). The start of the experiment is analogised with a constant CO_2 concentration, while the increasing amount of CO_2 is considered equivalent to changing the position of the beaker to a more vertical position, thus resulting in a higher water level in the beaker (higher temperature in the atmosphere). In working with the model, some students even discuss a horizontal beaker as being analogous to an atmosphere without CO_2. The modelling may lead to questioning the meaning of the natural greenhouse effect of the atmosphere. Working with the learning activity, all of our students were able to describe the scientifically adequate concept that *more CO_2 stores more heat*.

After the first two teaching experiments, we found that some students needed to be asked explicitly to discuss their observations from the perspective of balances and imbalances in the stock-flow system. Reflecting on their experiences of dynamic

Table 4. Conceptual development while modelling a dynamic equilibrium

Statements (examples)	Students (N)	Concept in teaching experiment
'When we have more CO_2, more heat is stored'	12	More CO_2 stores more heat
'Storing more and more heat is an imbalance'	8	Imbalance by rising CO_2 level
'When there is more CO_2, we have an imbalance'	3	Higher CO_2 level equates to imbalance
'When the beaker is vertical, a new balance arises'	5	Higher CO_2 level equates to new balance

This learning activity was evaluated in teaching experiments with 12 students.

balance and imbalance in the water stock in the beaker fostered the students' understanding of the balance schema to the earth's radiation budget. All of our students recognised that an increased amount of CO_2 causes an imbalance. Two students incorrectly described a further imbalance even when a new CO_2 level is reached, thus reflecting robust findings that even well-educated adults have difficulties in understanding balances in stock-flow systems (Cronin, Gonzalez, & Sterman, 2009; Sterman & Sweeney, 2007): However, some students, such as Raphael, were able to discern a balance, an imbalance and a new balance at a higher level. By experiencing the balance and imbalance in the model, Raphael constructs the scientific concept of a new balance in the radiation budget at a higher level.

Discussion

In our study, we used the MER for a structured analysis of conceptions on the greenhouse effect as well as a comprehensible design of learning activities by coordinating three closely interrelated aspects of research: (1) investigations into students' perspectives, (2) clarification and analysis of subject matter content and (3) design of learning activities. In the following discussion, we want to reflect on the role experientialism played within these analyses. For a deeper discussion on the role of the MER as research design in science education see Duit et al. (2005), Duit et al. (2012), and Duschl, Maeng, and Sezen (2011).

Understandings of the Greenhouse Effect: A Content-Oriented Theory

Guided by experientialism, we analysed students' and scientists' conceptions of the greenhouse effect (cf. Table 1) and formulated content-oriented theories (Andersson & Wallin, 2006) regarding students' resources for understanding of the greenhouse effect. We have shown that, as different as the conceptions of scientists and students may be, both perspectives are embodied indirectly by ways of systematic links to embodied concepts (cf. Lakoff, 1990, p. 154). To analyse the conceptions means to look for the directly embodied concepts to which they are tied and from which they arise (Niebert et al., 2012). The various conceptions of the greenhouse effect make sense because they are linked to the core of our conceptual system with its embodied image schemata. Remarkably, students and scientists link their understanding of the greenhouse effect to the same three schemata, i.e. *container*, *flow* and *balance*. The schemata are bound together by imagination in an attempt to understand the greenhouse effect. According to the individual applications of semantic composition, the three schemata form quite different variants of cognitive models that we call thinking patterns (see Table 1), which are considerably more complex than the schemata of which they are composed. The contingencies of different thinking patterns emerge through the individual construction. Both, selective use of the internal structure of the schemata and their idiosyncratic structuring relative to one another, leads to different thinking patterns. Comparing the conceptions from global warming caused by a hole in the ozone layer via warming by a greenhouse gas layer to warming by a greenhouse atmosphere, the mapping of the embodied schemata to the abstract phenomenon of global warming becomes more complex.

By adopting the view of experientialism, we analysed and categorised students' and scientists' thinking. Based on the theoretical view of experientialism, we could interpret and explain the thinking of both students and scientists.

In our approach, we neither judged the thinking patterns *warming by ozone hole* and *warming by the greenhouse effect* as misconceptions nor looked for their external sources, such as newspapers or textbooks. We also did not allege that the students were confused. Rather, we grasped how students and scientists employ their conceptual resources in an attempt to understand the greenhouse effect. The resources were mainly the schemata of a *container*, *flow* and *balance*, all of which are used to make imaginative sense of the greenhouse effect. Imagination may lead to different thinking patterns, all of which differ on how the boundary of the container and the in- and outflow are conceptualised. The thinking pattern *warming by the ozone hole* is based on the idea of 'warming by more inflow', while the thinking pattern *warming by the greenhouse effect* is based on the notion of 'warming by less outflow'. Accordingly, the patterns differ in the properties that are ascribed to CO_2, that is, from *devastative* over *permeable one-way only* to *permeable for light and impermeable for heat*.

The conceptions that we found in our interviews were similar to those described in the references, which were from very different samples (i.e. Andersson & Wallin, 2000; Ekborg & Areskoug, 2006; Koulaidis & Christidou, 1999; Shepardson et al., 2011). Furthermore, the metaphor analysis (Schmitt, 2005) allowed us to open a window into students' and scientists' conceptual resources for understanding the greenhouse effect.

However, in our interviews, we did not find the conceptions that global warming was the result of *warming by volcanic eruptions, warming by factories* or *warming by cities* which have been described by Andersson and Wallin (2000) and Mason and Santi (1998). This may be due to the higher age of our students (18-years-old), or else to the increased media coverage after the IPCC published its Fourth Assessment Report in 2007. However, these conceptions could be interpreted as akin to the notion *it gets warmer because heat is emitted*. This interpretation can be regarded as a variation of the thinking pattern ‘warming by more inflow’. In these cases, the energy does not come from the sun but is, instead, emitted by the earth itself through either natural (volcanic) or man-made causes (factories, cities). Thus, students blame urban heat emissions that they experience (i.e. from metro stations, chimneys, open fires, heaters, etc.) as a cause of the warming of the atmosphere.

Climate change is an abstract concept held by scientists regarding a phenomenon that is not a part of everyday life. Additionally, the causes and mechanisms of climate change are not open for everyday experience. The time scale in which climate change occurs is too great to be experienced in human terms. Our interactions with our environment and therefore our basic experiences are restricted to mesocosmic dimensions (Vollmer, 1984). Therefore, we are confined to comprehend macrocosmic (as well as microcosmic) phenomena in terms of mesocosmic concepts and schemata. This issue is one of the reasons that the enhanced greenhouse effect—and, often, science in general—is difficult to grasp. Scientific understanding depends, to a large degree, on technologically extended perception, which enables us to gain insight into the macrocosm (and microcosm). Thus, scientific understanding depends largely on imagination. This fact explains why even scientists refer to basic schemata, such as the container schema or the balance schema, to understand climate change. The schemata are easily used to help make sense without paying much attention to the finite details. To reflect on how an understanding is achieved is far more challenging. This insight bears important consequences for instructional interventions.

Understanding by Embodiment: Meaningful Experience on the Greenhouse Effect

To help students understand the greenhouse effect, scientific experiences necessary for an adequate understanding must be provided, especially those that originate from the macrocosm. This finding is consistent with Vosniadou and Ioannides (1998), who demand ‘meaningful experience’. We organised meaningful experiences for our students that aimed at provoking thoughts and doubts on their specific conceptions. The preceding analysis led by experientialism enabled us to design learning activities that take scientists’ and students’ conceptions as starting points for further learning. This was appropriate because students and scientists refer to the same schemata to understand the greenhouse effect. The students reflected on their domain specific use of the schemata as resources of these conceptions: (1) Students reflect on their conceptions of the borders of the container atmosphere. In other words, is it an ozone layer, a CO_2 layer or just a defined layer? (2) Students reflect on the role of CO_2. That is, does it form the border of the container or is it the content? Does it destroy the border or trap heat? (3) Students reflect on the use of the balance schema. That is, is it the warming due to more inflow, less outflow or a new balance?

By evaluating the respective process-oriented learning activities in the teaching experiments, we were able to track the students’ conceptual development and describe the strength and weaknesses of our learning activities:

- Learning activity *reconstructing the container* (cf. Figure 7): This learning activity helps students to recognise that CO_2 is a cause of global warming. Furthermore, upon reflection of the experimental setting, the students realise that an ozone hole is not a cause of global warming because there is no ozone involved in this experiment.

  This experiment provides experience that engenders a cognitive conflict for those students who adhere to the perspective that global warming is the result of an increasing hole in the ozone. To best solve this conflict, further learning activities incorporating a more explanatory character are needed. Therefore, we constructed the following activity focusing on the interplay of radiation and climate-active gases like CO_2.
- Learning activity *(im-)permeable CO_2* (cf. Figure 8): This experiment provides experience regarding the selective permeability of CO_2 for light and heat, which was observed and discussed by all of our students during the teaching experiments. The students were able to create analogies between their experiences with the experiment and the atmospheric processes. This leads to the idea that CO_2 is transparent for radiation in the visible part of the spectrum and opaque for long-wave radiation. Accordingly, this experience helped students to formulate adequate scientific conceptions on a phenomenological level that sufficiently explain the causes of global warming. This learning activity addresses what Koulaidis and Christidou (1999) ask for, that is to focus on clarifying the conceptual distinction between short- and long-wave radiation when teaching the greenhouse effect. To enable an understanding of the molecular properties of CO_2 that enable the absorption and emission of radiation (i.e. vibrational transitions), further interventions are needed. From the perspective of experientialism, the strategy of Aubusson and Fogwill (2006) of using an analogical role play for modelling the vibrational states of CO_2 might be a promising intervention.
- Learning activity *dynamic equilibrium* (cf. Figure 9): This learning activity addresses the students' conception of a continuous imbalance in the radiation budget. By experiencing the change between *balance* and *imbalance* and a *balance on a new level* in a beaker with water, students can draw analogies to the atmosphere and reflect on the idea of balance and imbalance in the radiation budget. Constructing the scientific idea related to the shifted balance in the radiation budget seems to be a difficult concept for students to grasp (cf. Table 4). To enable another experience of a shifted equilibrium, the limitations of the experiment *(im)permeable CO_2* which we discussed above could be used: After a longer time period of radiative disequilibrium in the bag filled with $CO_{2,}$ a new equilibrium would be reached and both bags would emit the same amount of heat radiation—with the difference that the temperature in the bag with CO_2 would be higher than in the bag with air. This could be measured and discussed upon additional thermometers in the bags.

By working with the learning activities, students re-experience the inherent structure of the schemata employed in understanding the greenhouse effect, and they reflect on how they employ this inherent structure in their effort to understand the phenomenon. The learning activities, however, inspired the students to use their conceptual resources and employ those resources as they re-experienced and reflected on their learning, thus helping students to better understand the complex and abstract phenomenon of climate change.

Conclusions

In our study, we used the MER combined with the theoretical framework of experientialism that provide a fruitful means to analyse students' conceptions on climate change and to design learning activities that address their learning needs. In this last section, we reflect on the role this approach can play in science education (research).

From Analysing Misconceptions to Analysing Resources for Understanding

Research on students' conceptions is an important topic in science education research since the 1970s. By today, this research provides a vast body of evidence on conceptions of learners that differ from the contemporary accepted scientific theory. These variant or alternative conceptions are often classified as misconceptions. In disputes between scientists, this indeed may be an appropriate term. As science educators with a constructivist perspective, we avoid this term with respect to students' conceptions, as it could belittle the efforts of the learners to understand the scientific view. We hold that learners do their best to make sense of a phenomenon. Guided by experientialism as a theory of understanding, we are primarily interested in how and why students understand as they understand. Analysing the conceptions based on experientialism gives us access to the conceptualisation capacity of students and scientists alike. It results in the theory-guided and evidence-based development of (1) a content-oriented theory of variant conceptions in a small number of thinking patterns (cf. Table 1), and (2) learning activities that adequately and effectively address student's learning needs.

How Experientialism Can Reveal Our Conceptual Resources for Understanding

Our analysis of students' and scientists' experiential resources for understanding the greenhouse effect revealed basic conceptual structures like the container or the balance schema. These schemata are basic but they come with a structure. This structure that is grounded in experience forms our understanding of the schema as an embodied conceptual resource (cf. Figures 2 and 3). When we use a schema as a source to understand an abstract science concept, we draw links between the elements of these schemata and the science concept to be understood. Therefore, the schemata cannot be used as unstructured building blocks put together to form a conception. Instead, the structure of a schema together with its basic logic is used to make sense in an abstract domain. This is accomplished by projection of the very structure of a schema to the target domain. However, mapping the image-schematic structure to an abstract scientific target domain is an intricate task. The conceptions analysed in our study show that students and scientists use the same schema but map them differently on the greenhouse effect, resulting in very different conceptions: Combining differently structured schemata and using its structure selectively to understand a scientific concept yields quite different meanings.

In a separate study (Niebert et al., 2012), we connected experientialism as a theory of understanding to different approaches of science education research on conceptual change. We found that analysing the experience conceptions are based on seems to be an appropriate grain size for an analysis to (a) relate different theoretical approaches to each other and (b) explain students' and scientists' understanding of a phenomenon.

How Experientialism Can Inform Science Teaching

When drawing conclusions from experientialism for teaching and learning on the greenhouse effect or science in general it should be clear that experientialism is an epistemology and not a theory of learning. It provides explanations as to how phenomena and concepts are understood. But it provides no direction on how these explanations can be implemented in science classrooms. With these limitations in mind, the approach presented in our study offers three options for content specific teaching (Niebert, Riemeier, & Gropengiesser, 2013). For teaching climate change as well as other topics one can

(1) denote a scientific conception, i.e. by an information text, an equation for radiative equilibrium or a figure of the greenhouse effect. Núñez, Edwards, and Matos (1999) noted that the insistence on the rigorous, abstract characterisation of concepts omits the reality of their grounding in experiential intuitions. For a scientist, abstract representations might be adequate and understandable because they refer to common scientific experience. The challenge for students is to relate these representations to the scientific phenomena that they are meant to represent.
(2) afford experiences, i.e. by the experiment on (im-)permeable CO_2 as shown in Figure 8. From the perspective of experientialism, providing an experience and developing the scientific topic to be taught by reflecting this experience is probably the most effective teaching strategy. This requires an analysis of students' prior conceptions *and* prior experience to decide on the needed experience. These experiences, whether of first- or second-hand origin, prepare the basis for the development of conceptions through experiences.

The two strategies for teaching climate change discussed above are not new: Providing experience via experiments and denoting the scientific conceptions behind the phenomena to be shown is, or at least should be, a very typical approach in science classrooms. In our study, we found and evaluated a third approach deduced from experientialism that aims at a metacognitive level:

(3) For teaching science, one can depict an embodied schema or help the students to re-experience their schemata. Modelling a dynamic equilibrium as shown in Figure 9 or reflecting on the boundaries of a container picks up the schemata

students use to conceptualise these phenomena and helps them to rethink the mapping of these schemata. By working with a schema-based model, students re-experience the inherent structure of a schema and reflect on how they employ it in their effort to understand the radiative equilibrium. Awareness of the schemata can be deliberately deployed to understand the scientific conception of the phenomena. The experiment on the dynamic equilibrium reveals that the mapping process requires reflection on highlighting and hiding of a schema. This third perspective opens opportunities to provide *meaningful experience* and *metaconceptual strategies* for our students, as it is demanded by Vosniadou and Ioannides (1998) among others.

With our analysis, we would like to put forward experientialism as a helpful theory for explaining why students hold certain conceptions on the greenhouse effect and what role experience plays in reconstructing and developing new conceptions. Our analysis substantiates Lakoff's argument that understanding is embodied: We have shown how an analysis of the experiential background of everyday and scientific conceptions can provide a fruitful basis for understanding them and how understanding students' conceptual resources can help science educators initiating a conceptual development.

References

Andersson, B., & Wallin, A. (2000). Students' understanding of the greenhouse effect, the social consequences of reducing CO_2 emissions and the problem of ozone layer depletion. *Journal of Research in Science Teaching*, *37*(10), 1096–1111.

Andersson, B., & Wallin, A. (2006). On developing content-oriented theories taking biological evolution as an example. *International Journal of Science Education*, *28*(6), 673–695.

Arrhenius, S. (1896). On the influence of carbonic acid in the air upon the temperature of the ground. *Philosophical Magazine and Journal of Science*, *41*(5), 237–276.

Aubusson, P.J., & Fogwill, S. (2006). Role play as analogical modelling in science. In P.J. Aubusson, A.G. Harrison, & S.M. Ritchie (Eds.), *Metaphor and analogy in science education* (pp. 93–104). Dordrecht: Springer.

Bord, R.J., Fisher, A., & O'Connor, R.E. (1998). Public perceptions of global warming: United States and internationational perspectives. *Climate Research*, *11,* 75–84.

Bostrom, A., Morgan, M.G., Fischhoff, B., & Read, D. (1994). What do people know about global climate change? 1. Metal models. *Risk Analysis*, *14*(6), 959–970.

Boyes, E., & Stanisstreet, M. (1993). The greenhouse-effect—childrens perceptions of causes, consequences and cures. *International Journal of Science Education*, *15*(5), 531–552.

Cronin, M., Gonzalez, C., & Sterman, J. (2009). Why don't well-educated adults understand accumulation? A challenge to researchers, educators, and citizens. *Organizational Behavior and Human Decision Processes*, *108*(1), 116–130.

Deutsche Meteorologische Gesellschaft (German Society for Meteorology [DMG]). (1999). *Grundlagen des Treibhauseffektes* [Principles of the greenhouse effect], Report of the German Association for Meteorology, Berlin, pp. 1–4.

Dove, J. (1996). Student teacher understanding of the greenhouse effect, ozone layer depletion and acid rain. *Environmental Education Research*, *2*(1), 89–100.

Duit, R., Gropengiesser, H., & Kattmann, U. (2005). Towards science education research that is relevant for improving practice: The model of educational reconstruction. In H. Fischer

(Ed.), *Developing standards in research on science education, the ESERA Summer School 2004* (pp. 1–9). London: Taylor & Francis Group.

Duit, R., Gropengießer, H., Kattmann, U., & Komorek, M. (2012). The model of educational reconstruction—a framework for improving teaching and learning science. In D. Jorde & J. Dillon (Eds.), *Science education research and practice in Europe* (pp. 13–38). Rotterdam: Sense Publishers.

Duit, R., & Treagust, D. (1998). Learning in science—from behaviourism towards social constructivism and beyond. In B. Fraser & K. Tobin (Eds.), *International handbook of science education* (Vol. 1, Part 1, pp. 3–25). Dordrecht: Kluwer Academic Publishers.

Duschl, R., Maeng, S., & Sezen, A. (2011). Learning progressions and teaching sequences: A review and analysis. *Studies in Science Education*, *47*(2), 123–182.

Ekborg, M., & Areskoug, M. (2006). How student teacher's understanding of the greenhouse effect develops during a teacher education programme. *NorDiNa*, *1*(5), 17–29.

Gallese, V., & Lakoff, G. (2005). The brain's concepts: The role of the sensory-motor system in conceptual knowledge. *Cognitive Neuropsychology*, *21,* 1–26.

Gropengießer, H. (2007). Theorie des erfahrungsbasierten Verstehens [Experientialism]. In D. Krüger & H. Vogt (Eds.), *Theorien in der biologiedidaktischen Forschung* (pp. 105–116). Berlin/Heidelberg: Springer.

Hansen, P.J.K. (2010). Knowledge about the greenhouse effect and the effects of the ozone layer among Norwegian pupils finishing compulsory education in 1989, 1993, and 2005—what now? *International Journal of Science Education*, *32*(3), 397–419.

Houghton, J. (2002). *Physics of the atmospheres*. Cambridge: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (2007). *Climate change 2007: The physical science basis*. Cambridge: Cambridge University Press.

Jeffries, H., Boyes, E., & Stanisstreet, M. (2001). Knowledge about the greenhouse effect: Have college students improved? *Research in Science & Technological Education*, *19*(2), 205–221.

Johnson, M. (1987). *The body in the mind—the bodily basis of meaning, imagination, and reason*. Chicago: The University of Chicago Press.

Khalid, T. (2003). Pre-service high school teachers' perceptions of three environmental phenomena. *Environmental Education Research*, *9*(1), 35–50.

Koulaidis, V., & Christidou, V. (1999). Models of students' thinking concerning the greenhouse effect and teaching implications. *Science Education*, *83*(5), 559–576.

Lakoff, G. (1990). *Women, fire, and dangerous things: What categories reveal about the mind* (Vol. 64). Chicago: The University of Chicago Press.

Lakoff, G., & Johnson, M. (1980). *Metaphors we live by* (Vol. 56). Chicago: The University of Chicago Press.

Longino, H. (1990). *Science as social knowledge*. Princeton: Princeton University Press.

Mason, L., & Santi, M. (1998). Discussing the greenhouse effect: Children's collaborative discourse reasoning and conceptual change. *Environmental Education Research*, *4*(1), 67–85.

Mayring, P. (2002). Qualitative content analysis—research instrument or mode of interpretation? In M. Kiegelmann (Ed.), *The role of the researcher in qualitative psychology* (pp. 139–148). Tuebingen: UTB.

Niebert, K. (2010). *Den Klimawandel verstehen. Eine Didaktische Rekonstruktion der globalen Erwärmung* [Understanding climate change. An educational reconstruction of global warming]. Oldenburg: Didaktisches Zentrum Oldenburg (diz).

Niebert, K., Marsch, S., & Treagust, D. (2012). Understanding needs embodiment: A theory-guided reanalysis of the role of metaphors and analogies in understanding science. *Science Education*, *96*(5), 849–877.

Niebert, K., Riemeier, T., & Gropengiesser, H. (2013). The hidden hand that shapes conceptual understanding: Choosing effective representations for teaching cell division and climate change. In C.Y. Tsui & D. Treagust (Eds.), Multiple representations in biological education, Models and Modeling in Science Education (Vol. 7, pp. 210–229). New York: Springer. doi: 10.1007/978-94-007-4192-8_16.

Núñez, R.E., Edwards, L.D., & Matos, F.J. (1999). Embodied cognition as grounding for situatedness and context in mathematics education. *Educational Studies in Mathematics*, *39*(1), 45–65.

Papadimitriou, V. (2004). Prospective primary teachers' understanding of climate change, greenhouse effect, and ozone layer depletion. *Journal of Science Education and Technology*, *13*(2), 299–307.

Pruneau, D., Liboiron, L., Vrain, E., Biosphère, L., Gravel, H., Bourque, W., & Langis, J. (2001). People's ideas about climate change: A source of inspiration for the creation of educational programs. *Canadian Journal of Environmental Education (CJEE)*, *6*(1), 121–138.

Read, D., Bostrom, A., Morgan, M.G., Fischhoff, B., & Smuts, T. (1994). What do people know about global climate change? 2. Survey studies of educated laypeople. *Risk Analysis*, *14*(6), 971–982.

Riemeier, T., & Gropengiesser, H. (2008). On the roots of difficulties in learning about cell division: Process-based analysis of students' conceptual development in teaching experiments. *International Journal of Science Education*, *30*(7), 923–939.

Rohrer, T. (2001, July). *Understanding through the body: fMRI and ERP investigations into the neurophysiology of cognitive semantics*. Paper presented at the 7th International Cognitive Linguistics Association, University of Carlifornia at Santa Barbara, CA.

Rohrer, T. (2005). Image schemata in the brain. In B. Hampe & J. Grady (Eds.), *From perception to meaning: Images schemas in cognitive linguistics* (pp. 165–196). Berlin: Mouton de Gruyter.

Rye, J.A., Rubba, P.A., & Wiesenmayer, R.L. (1997). An investigation of middle school students' alternative conceptions of global warming. *International Journal of Science Education*, *19*(5), 527–551.

Schmitt, R. (2005). Systematic metaphor analysis as a method of qualitative research. *The Qualitative Report*, *10*(2), 358–394.

Shepardson, D., Choi, S., Niyogi, D., & Charusombat, U. (2011). Seventh grade students' mental models of the greenhouse effect. *Environmental Education Research*, *17*(1), 1–17.

Solomon, M. (2008). Social epistemology of science. In R.A. Duschl & R.E. Grandy (Eds.), *Establishing a consensus agenda for K-12 science inquiry* (pp. 86–94). Rotterdam, NL: Sense.

Steffe, L., Thompson, P., & von Glaserfeld, E. (2000). Teaching experiment methodology: Underlying principles and essential elements. In A. Kelly & R. Lesh (Eds.), *Handbook of research design in mathematics and science education* (pp. 277–309). London: Lawrence Erlbaum Associates.

Steinke, I. (2004). Quality criteria in qualitative research. In U. Flick, E. Kardorff, & I. Steinke (Eds.), *A companion to qualitative research* (pp. 184–191). London: Sage.

Sterman, J., & Sweeney, L.B. (2007). Understanding public complacency about climate change: Adults' mental models of climate change violate conservation of matter. *Climatic Change*, *80*(3), 213–238.

Sweeney, L.B., & Sterman, J.D. (2007). Thinking about systems: Student and teacher conceptions of natural and social systems. *System Dynamics Review*, *23*(2–3), 285–311.

Vollmer, G. (1984). Mesocosm and objective knowledge. In F. Wuketits (Ed.), *Concepts and approaches in evolutionary epistemology* (pp. 69–121). Dordrecht: Reidel.

Vosniadou, S., & Ioannides, C. (1998). From conceptual development to science education: A psychological point of view. *International Journal of Science Education*, *20*(10), 1213–1230.