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The Impact of Secondary School Students' Preconceptions on the Evolution of their Mental Models of the Greenhouse effect and Global Warming

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The Impact of Secondary School Students' Preconceptions on the Evolution of their Mental Models of the Greenhouse effect and Global Warming

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This paper provides a video-based learning process study that investigates the kinds of mental models of the atmospheric greenhouse effect 13-year-old learners have and how these mental models change with a learning environment, which is optimised in regard to instructional psychology. The objective of this explorative study was to observe and analyse the learners' learning pathways according to their previous knowledge in detail and to understand the mental model formation processes associated with them more precisely. For the analysis of the learning pathways, drawings, texts, video and interview transcripts from 12 students were studied using qualitative methods. The learning pathways pursued by the learners significantly depend on their domain-specific previous knowledge. The learners' preconceptions could be typified based on specific characteristics, whereby three preconception types could be formed. The 'isolated pieces of knowledge' type of learners, who have very little or no previous knowledge about the greenhouse effect, build new mental models that are close to the target model. 'Reduced heat output' type of learners, who have previous knowledge that indicates compliances with central ideas of the normative model, reconstruct their knowledge by reorganising and interpreting their existing knowledge structures. 'Increasing heat input' type of learners, whose previous knowledge consists of subjective worldly knowledge, which has a greater personal explanatory value than the information from the learning environment, have more difficulties changing their mental models. They have to fundamentally reconstruct their mental models.

Keywords: *Greenhouse effect; Preconception types; Conceptual development; Learning process analysis; Mental model evolution*

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Introduction

The issue of global climate change is considered to have potentially serious consequences for human welfare and the natural environment (IPCC, 2012). In order to understand climate change, its impacts and options for mitigation, a basic understanding of the process of the atmospheric greenhouse effect is required of all citizens even of those who had only little science education during their compulsory schooling. By greenhouse effect, we mean the natural physical processes by which thermal radiation from the Earth surface is absorbed by greenhouse gases, particularly CO_2, and reradiated in all directions thus slowing down the radiation energy loss of the atmosphere resulting in a higher average surface temperature. This study is concerned with 13-year-old lower secondary-school students' understanding of these basic processes from which the enhanced greenhouse effect, i.e. the strengthening of the natural greenhouse effect through human activities, can be inferred.

Various studies were able to verify that the greenhouse effect is difficult to convey because it is very complex and can only be described to laypeople in a relatively abstract manner (Aeschbacher, Calò, & Wehrli, 2001; Kempton, 1993; Kirkeby Hansen, 2010; Klosterman & Sadler, 2010; Österlind, 2005). This difficulty is further complicated by the fact that the basic mechanisms which the greenhouse effect involve, such as the conversion of the short-wave percentage of the solar radiation into long-wave infrared radiation and the characteristic of the selective transparency of CO_2 compared with the radiation of different wavelengths, cannot be or are difficult to be perceived through the senses. Reinfried, Schuler, Aeschbacher, and Huber (2008) developed a learning environment for the greenhouse effect optimised in regard to instructional psychology, which helps overcome the special learning difficulties related to the greenhouse effect, and induce a relatively lasting conceptual change. The verification of the effectiveness of the learning environment was carried out with quantitative methods in line with an explorative intervention study, called GeoConcepts I, and revealed a significant and relatively consistent increase of knowledge, combined with a better understanding of the greenhouse effect phenomenon (Reinfried, Aeschbacher, & Rottermann, 2012). However, only the participants' previous knowledge and their knowledge output were recorded over time in GeoConcepts I. The learning-dependent changes of their personal mental models could not be diagnosed with the quantitative design of the study. The qualitative part of the study described here, called GeoConcepts II, pursued the objective of recording the learning-dependent conceptual changes of 13-year-old learners more precisely to observe and analyse their learning pathways and mental model evolution according to their previous knowledge in detail.

Background

Numerous studies on students' understanding of the greenhouse effect and global warming report poor results indicating that common sense ideas tend to dominate students' reasoning even after teaching (e.g. Andersson & Wallin, 2000; Boyes &

Stanisstreet, 1993; Dove, 1996; Kirkeby Hansen, 2010). An often-observed mental model involves the idea that global warming is the result of heat accumulation in the atmosphere due to an invisible barrier of greenhouse gases that prevent the heat from escaping (Andersson & Wallin, 2000). Another common mental model involves the explanation that a hole in the ozone layer is held accountable for more energy reaching the earth surface, causing global warming (e.g. Aeschbacher & Huber, 1996; Aeschbacher et al., 2001; Boyes & Stanisstreet, 1993; Dove, 1996; Koulaidis & Christidou, 1999; Reinfried et al., 2012; Rye, Rubba, & Wiesenmayer, 1997). These examples show that mental models are based on sets of assumptions that can subjectively be perceived as consistent, even if they are incomplete or contradict scientific models. As a result of their plausibility, they are extremely stable and durable (Vosniadou & Brewer, 1994). Mental models are constructed by an individual's cognitive system. They represent simplifications, illustrations, analogies and simulations of real objects, events or imaginary simulations (Gentner & Stevens, 1983; Johnson-Laird, 1983; Stachowiak, 1973). In the attempt to grasp new knowledge or a certain phenomenon, mental models are constructed that refer to previous knowledge, with which the presented information allows itself to be interpreted. Therefore, the construction of mental models by novices inevitably differs from experts' scientific models in content, structure and semiotics. The learning-dependent modification of mental models is called conceptual change (Seel, 2003).

Mental Models as constructions of knowledge and understanding play a central role in the theory of learning of cognitive constructivism, which represents the epistemological position this study is based on. Cognitive constructivists argue that all knowledge is actively constructed by learners and that any account of knowledge makes essential references to cognitive structures. Therefore, understanding the learner's existing intellectual framework is central to understanding the learning process (Aebli, 1983; Piaget, 1968; Seel, 2003, p. 25). According to cognitive constructivism, the construction of mental models can be considered as a process of knowledge assimilation and accommodation. New information is assimilated into one's previous existing internal cognitive structures and the knowledge structure is accommodated to the new knowledge. As long as the information to be processed can be assimilated, no need arises for a change of conceptions, and there is therefore no reason to change a mental model. Seel (1991, p. 44) argues that a conceptual change process begins if the cognitive system is forced to modify its knowledge. Specifically, if new information cannot be inserted into existing knowledge structures, a cognitive conflict arises, which triggers a process of change, i.e. of accommodation of existing mental models.

The question of what changes in conceptual change has generated considerable controversy in the literature. Some authors view conceptual change as a restructuring of a mental model in the sense of a reorganisation and reinterpretation of area-specific larger knowledge structures (knowledge-as-a-theory approach), and not just simply as an expansion and differentiation of knowledge (Chi, 2008, p. 66f; Rumelhart & Norman, 1978; Vosniadou & Brewer, 1987, p. 52). Accordingly, conceptual change means not just the different interpretation of a concept, but its conscious modification

(Dole & Sinatra, 1998). diSessa (1988) views conceptual change as a restructuring of existing, fine-grained, mostly intuitive knowledge components and structures (phenomenological primitives or p-prims) involving a gradual increase of coherence and consistency (knowledge-in-pieces approach).

There are different possibilities for inducing a conceptual change of persistent misconceptions through instruction (Clement, 2008, p. 421). Various authors assume that a conceptual change is preceded by a subjective dissatisfaction with an existing concept (Dole & Sinatra, 1998; Hewson & A'Becket Hewson, 1884; Nussbaum & Novick, 1983; Posner, Strike, Hewson, & Gertzog, 1982; Strike & Posner, 1992). This occurs, for example, if a person experiences an anomaly between a conception and a new viewpoint. Although cognitive conflicts do not necessarily lead to a conceptual change (diSessa, 2008; Wiser & Amin, 2001), the moderate use of teaching strategies that trigger a cognitive conflict can be sensible in order to help change conceptions (Keil & Newman, 2008, p. 84; Vosniadou, Vamvakoussi, & Skopeliti, 2008, p. 26).

Internal, dynamic processes of knowledge construction cannot, however, be observed directly; rather, they must be inferred via the externalisation of mental models, e.g. in texts, drawings and interviews, and interpreted from an educational point of view. Since every phase of teaching triggers different learning processes in every learner, qualitative analyses based on individual cases can be used to gain key information on the process of construction of mental models, and processes of learning and understanding can be at least partially clarified. This research approach remains still rare in conceptual-change research (diSessa, 2008). To give an idea of the different methodologies employed in the context of qualitative social research to trace the knowledge construction of the greenhouse effect phenomenon and global warming the studies of Niebert (2010) and Schuler (2011) are briefly reviewed. Niebert (2010) developed learning opportunities aimed at fostering the knowledge development of 18-year-old high-school students who had formal science knowledge. He evaluated the effect of these learning opportunities through qualitative content analysis applied on transcripts of interviews and videotapes recorded during the students' work. He mapped the students' learning paths over time with regard to the scientific adequacy of their newly constructed or reconstructed conceptions. Niebert observed that students who believed that global warming is a result of less heat loss due to a layer of greenhouse gases in the upper atmosphere further developed their understanding of global warming, while some students who believed that global warming occurred due to more heat input because of the ozone hole had difficulties to change this conception. Schuler (2011) reconstructed the existing mental models of 25 students in grade 12 concerning global climate change. The students had studied the issue in class a year earlier. Schuler used a qualitative approach that relates to the method of systemic structuring which consisted of a combination of interviews and concept maps drawn by the students displaying their personal theories about global warming. The results show that a majority of the students related global warming to the ozone hole or the depletion of the ozone layer and see emissions from traffic and industries as being responsible for the warming.

In contrast to Niebert (2010), our learning-process study presented here used a learning environment, the efficacy of which has been proven by quantitative research (Reinfried et al., 2012). The focus of our study is on the diagnosis of *learning-dependent changes* of individual model constructions when learning the greenhouse effect under particular consideration of the previous knowledge of learners who had yet not had any instruction in physics or chemistry. Of particular interest in this study is the question of whether similar previous knowledge leads to similar learning pathways; whether, that is, there are typical initial mental models that evolve according to typical development profiles.

Research Questions

The overall aim of this learning process study was to explore students' mental model evolution and conceptual change processes concerning the greenhouse effect when working with a psychologically optimised learning environment (cf. Reinfried et al., 2008). Learning always begins with the activation of prior knowledge. New knowledge must be related to relevant existing concepts in that learner's cognitive structure for meaningful learning to occur (Ausubel, 1968). Therefore, the students' area-specific previous knowledge was of great importance in the context of this study. The students' conceptions before and after the entire work phase with the learning environment are of interest as well as the learners' intermediate mental models, which are formed during the learning process. At the same time, it must be considered that mental models cannot be directly observed. In order to be able to study them, they must be externalised. The possibilities of recording them using indirect methods, such as by thinking aloud, writing texts, creating concept maps, sketches and drawings, are limited. For the study of mental models, this means that the mental model itself cannot be studied but merely its externalised form (cf. Al-Diban, 2002, p. 109). Therefore, this research is centred on the diagnosis of the externalised changes of the mental models of 13-year-old learners according to their previous knowledge. To find out more about learning-dependent changes of individual mental models of the greenhouse effect, the following research questions were examined:

- How does the knowledge-construction process work with the learning environment?
- What role does previous knowledge play in the construction of the mental models?
- Are there typical development profiles in the evolution of mental models and what do they depend on?

Methodology

The type of research appropriate for this kind of learning-process analysis is that of qualitative social research (Cohen, Manion, & Morrison, 2011). Its purpose was to obtain a more complete picture of how young learners construct their mental models of the greenhouse effect and what role their preconceptions do play thereby. To attain a kind of in-depth description of the mental model evolution processes, the learners need to externalise as much ideas as possible during their learning. Accordingly, the research design was set up in a manner to provide frequent opportunities for the learners to express their thoughts and understanding, e.g. in written texts, drawings, small group discussions and one-on-one interviews. To monitor the students' mental model evolution process whilst working with the learning environment (Work phase in Table 1), the technique of the teaching experiment was appropriate (Steffe, 1983; Steffe, Thompson, & von Glasersfeld, 2000). The teaching experiment is an interview technique, which is based on Piaget's clinical interview (Steffe et al., 2000); however, it contains methodical elements, as are known from Socratic dialogue. Unlike the clinical interview, the teaching experiment is organised to a great extent as a teach−learn situation involving the participating learners and a teacher or tutor (Table 1, t2–t6). It is designed so that the learners are confronted with experiments and/or phenomena in need of explanation and are asked to verbalise approaches for solving specific problems. The tutor can change the teaching situation to an interview situation to discuss the ideas the learners' developed, their tentative explanations or learning difficulties in more detail. The tutor is to encourage the test persons to think aloud, to give feedback and to provide causes for thought and support in situations in which the learners cannot come up with any useful ideas. The interlocking of the elements 'interview' and 'teaching' is an essential part of the strategy of the teaching experiment and makes it an effective evaluation instrument for learning-process studies. To ensure that the aspect of interaction and co-construction with other learners is given the advanced teaching experiment in which the students work in pairs was applied (Komorek & Duit, 2004; Wilbers & Duit, 2001).

To interpret the data gained from the students' written and drawn work and the transcript of the interviews, content analysis, a methodology in the social sciences for studying the content of recorded human communication, was used. The qualitative and interpretative analysis of the data sources forms the empirical foundation for the depiction of the knowledge constructions and learning paths. From a holistic point of view of the specific contents of these data sources, we expected that new hypotheses regarding the preconception-dependent course of the learning pathways were able to be generated, which are to be validated later by means of further research (Krippendorf, 2004; Mayring, 2002, 2007).

Participants

The sample involved 14 test persons (6 girls and 8 boys) of a secondary class (class 7, track A) from the Swiss canton of Lucerne, who were an average of 13.14 ($\pm$0.5) years old. The selection criteria for the inclusion of students in the study were a sufficiently good grade point average of at least 4.5 or higher[1] in Mathematics, the languages German and French and the subjects Geography and History. These criteria were aimed at selecting test persons with sufficient school performances, who would generate analysable input in the work phase with the learning environment

Table 1. Course of the study

Phases	Times of assessment	Brief description	Approx. duration (min)	Instrument/ learning material	Data
Preliminary evaluation	t1	Students draw and describe their personal mental models	15		Student drawings and texts
Work phase (working with the learning	t2	Students study the worksheet individually	10	Worksheet (Appendix 1)	
environment)	t3	Students reproduce individually the contents of the worksheet from memory	10		Student drawings and texts
	t4	Students explain their understanding of the contents of the worksheet to each other and the tutor	15		Transcripts of the video recordings of t4, t5, t6
	t5	Implementation of the MED	15	MED	
	t6	Students and tutor discuss the MED	5	Discussion guideline (Appendix 2)	
Post evaluation	t7	Students draw and describe their personal mental models individually	10		Student drawings and texts
Interviews	t8	Focussed individual interview referring to the students' learning processes	7	Interview guideline (Appendix 3)	Transcripts of t8, t9
	t9	Individual interview with probing questions	7	Interview guideline (Appendix 4)	

and who would also be qualified to externalise their thoughts. From this group, those students were selected whose parents gave their permission to record the learning process on video and who displayed distinct communicative behaviour, i.e. an extroverted, outgoing attitude and pleasure in interacting in social groups. This behaviour was significant for the data collection, in which discussions and asking and answering questions played an important role. Given that there is no binding, cantonal curriculum with regard to content in Switzerland, the effect of previous knowledge conveyed in the secondary school had to be controlled by selecting all test persons from one and the same class. This ensured that (1) all test persons did not participate in any noteworthy physics or chemistry lessons in class 7 up to the conclusion of the data collection and (2) that no knowledge of the greenhouse effect was acquired at school. In each case, the students participated in the study in groups of two. The intervention happened outside the hours fixed for school attendance. For their willingness to collaborate, the students received a voucher for books or CDs worth 10 Swiss Francs. The students were able to decide themselves who wanted to work together with whom. Consequently, this resulted in seven test groups, which each consisted homogeneously of boys or girls. Due to the fact that there were technical problems in recording the data in one of the groups, only the data from 12 test persons were able to be analysed.

Learning Environment and Learning Materials

The learning environment used for the knowledge construction is virtually identical to the one applied in GeoConcepts I (Reinfried et al., 2008, 2012). It consists of a worksheet and a model-based experimental demonstration (MED). They trace back to the psychological didactics from Aebli[2] (1983) and include elements of the model of conceptual change teaching from Driver and Oldham (1986). The learning material provides information in various formats of representation. It is to convey new knowledge and contribute to a restructuring of the learners' conceptions of the greenhouse effect. The theoretical model of the greenhouse effect, which is to be conveyed using the learning material, depicts the scientific model in a hypothetical and level-appropriate manner, with the objective of making the basic principles of the greenhouse effect comprehensible to scientific laypersons.

The learning environment consists of the learning material that is imbedded in a methodical framework aimed at the activation of various learning strategies, which promote cognitive, socio-cognitive and metacognitive processes. Specifically, these are the use of analogies; the challenge to explain own assumptions and considerations; the confrontation of the learners' conceptions with scientific information (staging of discrepant events), the use of the MED by the tutor and a subsequent attempt to run it by the students; various questioning techniques (authentic questions, probing questions); the clarification of uncertainties; the drawing of conclusions; the encouraging of reflective discussions; the identification, clarification and contesting of everyday conceptions with the objective of supporting mental model formation and the application of elements of scaffolding.

The worksheet. The worksheet (Appendix 1) was developed on the basis of Aebli's didactics on a psychological basis (Aebli, 1983) which emphasises deep cognitive learning aimed at comprehension-oriented knowledge development as well as flexible and problem-solving thinking. The consequence of Aebli's approach is that an abstract concept must be broken down into its basic knowledge components and processes that are comprehensible and consistent with general assimilation schemata (Reinfried et al., 2012). To make the fundamental processes comprehensible, we focused only on one greenhouse gas, CO_2, which is the second most-important greenhouse gas after water vapour by its percentage contribution (Kiehl & Trenberth, 1997). The restriction on CO_2 is justified if we consider that CO_2 represents at 77% by far the greatest share of man-made worldwide greenhouse gas emissions (Baumert, Herzog & Pershigh, 2005, p. 5). The worksheet consists of four explicit and simple diagrams with explanatory texts, which contain the basic elements and processes of the greenhouse effect. The image–text units are designed in such a manner that a learner can comprehend, mentally connect and subsequently mentally stimulate the individual key concepts step by step, so that the greenhouse effect is perceived as a dynamic process. The worksheet is designed to first stimulate the learner's previous knowledge, then introduce the new concept with its essential mechanisms and create a reference of application for the concept (cf. Driver & Oldham, 1986). The first image–text combination is intended to trigger a cognitive conflict by bringing up the widely spread everyday conception that damage to the ozone layer is the cause for the greenhouse effect, but is immediately dismissed again.[3]

The MED. Infrared radiation can be experienced with a simple analogue MED, which physically displays the greenhouse effect (DemoEx, 2011) (Figure 1).[4] One can feel the thermal radiation and read it on a radiometer. Furthermore, it was also intended to trigger a cognitive conflict with the MED by visualising the opacity of carbon dioxide to infrared radiation compared to air (Aeschbacher & Huber, 1996). The MED is used to improve the learners' understanding and increase their motivation for the subject. Venville and Treagust (1996) described that analogue models can have a positive impact on conceptual changes due to their motivating effect.

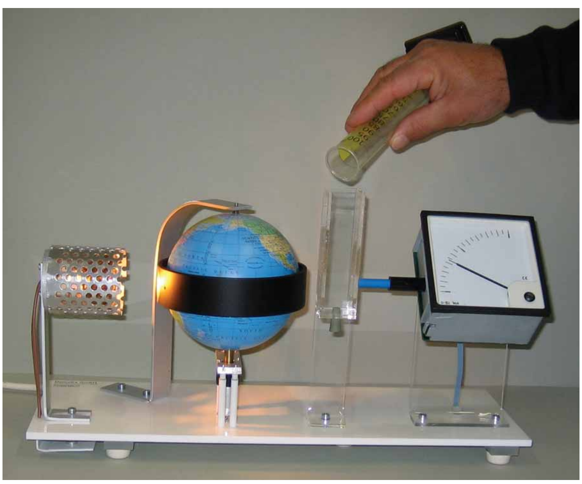


Figure 1. The model-based experimental demonstration.

Research Design and Instruments

Design. To obtain an accurate specification of the processes of knowledge construction and a precise diagnosis of the change of the mental models, a research design was chosen, which consists of four phases, which were divided into nine times of assessment (t1–t9) and took approx. 90 minutes (see Table 1). This division enabled specifying the knowledge construction of each person in cognitive phases, which are definable with regard to contents and which are linked and interdependent through or in their genesis. Images and sound were recorded with an unmanned camera and an external microphone on the worktable. The video recordings were necessary for the analysis of the students' interaction with the learning material in order to retrace the connections between the students' actions and speech which was documented in the transcripts. Both the authors participated, the first author in the role of the tutor in the teaching experiment and both authors in the role of the interviewers in phases 8 and 9. Their activities and comments in the work phase and in the interviews were also documented on video, to be able to analyse their effect on the learners' formation of concepts.

The data collection began with a preliminary evaluation with which data on previous knowledge were collected. After a brief getting-to-know-you interview, the learners were asked to draw their conception of the greenhouse effect and to provide written comments for the drawings (t1). In the following work phase (t2–t6), the learners worked with the learning environment in groups of two for approx. 60 minutes.

The work phase with the learning environment began with the learners studying the worksheet (t2, Appendix 1), which was then placed aside. Then, each student drew and described the knowledge he/she had gained from the worksheet on his or her own from memory (t3). In the following step, the students explained what they had drawn and written to one another (t4). If it seemed reasonable for the purpose of clarifying issues, the tutor prompted a discussion between the test persons or asked questions regarding uncertainties or misunderstandings. The tutor answered specific questions; however, she avoided articulating compact contents of knowledge herself. Instead, she followed up on apparent misinterpretations, let the ideas be explained to her and encouraged taking another and closer look at certain aspects in the worksheet. After that, the tutor implemented the MED. Then she asked the learners to hypothesise what happens when CO_2 gas is filled into the 'atmosphere' of the model. While the tutor conducted the experiment, the learners observed what was happening (t5). The students were then given the opportunity to conduct the experiment themselves. A semi-structured group discussion between the tutor and the group of students about the MED and its connections to the actual greenhouse effect followed (t6, Appendix 2). Post-evaluation followed the work phase, in which the learners drew on and described their conceptions again (t7). Then, each student in the learning group was questioned individually by one of the two authors in separate rooms to make sure that the students felt less exposed and gave their opinions freely. In this guideline-oriented, semi-structured interview each student was questioned on his/her learning process and possible learning difficulties (t8;

Appendix 3) followed by eight probing questions on the contents addressed in the learning environment (t9; Appendix 4).

The research material from the times of assessment t1, t3 and t7 included a total of three texts and annotated student drawings per test person, which were created at three different points in time. These data are images of the test persons' mental models. There is also the video material from the group work and interview phases (t4, t6, t8, t9), which contains the verbalisation of the individual cognitive processes. All these data provided insight into the learning-dependent changes of their mental models.

Discussion and interview guidelines. During and after the work phase with the learning material (t2–t6), various instruments were used. After the application of the MED, a semi-structured discussion guideline (t6, Appendix 2) was used, so that it would be possible to cover depth and breadth during questioning and also be able to pose spontaneous questions, which would supply further information about the learners' conceptions in the situation. For the interview phases at t8, and t9 on the other hand, we selected structured interview guidelines. Using the guideline in Appendix 3, the learners were individually asked about their learning process while working with the learning environment. After that, there were questions regarding the conditions 'intelligibility', 'plausibility', 'dissatisfaction' and 'fruitfulness', which are of importance for a conceptual change according to Posner et al. (1982) and Strike and Posner (1992). It was specifically asked whether these conditions were consciously perceived. Subsequently, a structured individual interview followed (Appendix 4) with questions, which refer to the difficult aspects of the greenhouse effect, which often contain misconceptions. The interview was intended to show how the students can deal with the new knowledge and how reliable the new knowledge is in a logical and factual sense. We call the questions here in the text probing questions.

Data Analysis

To begin with, the analysis took place for each person individually. Using a polynominal deductive-inductive method based on the structuring content analysis according to Mayring (2002, 2007), the analysis of each student's drawings and texts and all video transcripts was then conducted. The deductive aspect of the analysis is that all data were initially classified into four categories, which reasonably describe the basics of the greenhouse effect. The categories are (1) hole conception, (2) radiation conversion, (3) knowledge of CO_2 and (4) concurrence of several factors/general information on the greenhouse effect. The categories are based on constructs, which represent the prevalent subjective mental models of the greenhouse effect as well as on scientific concepts, which are essential in understanding the greenhouse effect. The category 'hole conception' is aimed at the everyday conceptions in the area of the ozone hole model, i.e. the conception that damage to the ozone layer is responsible for the greenhouse effect; the category 'radiation conversion' deals with the absorption of solar radiation by the Earth's surface and the radiation of infrared radiation; the category 'knowledge of CO_2' describes the characteristic of selective transparency of the molecule CO_2, in particular its effect as an infrared radiation absorber and emitter. The category 'concurrence of several factors/general information on the greenhouse effect' refers to the concurrence of the stated categories as well as the impact on global warming, which results from it. The material, which was categorised in this manner, was then inductively searched for other categories, whereby a fifth category called 'layer conception' was detected.

The categorised, oral, graphic and written statements of each student were listed in their chronological order. The order began with the previous knowledge expressed by each student being summarised from the complete body of data material. Then the listing of the written, categorised data from the work phase and the interview phases (t3–t9) followed in chronological order. The next step entailed comparing the previous knowledge of all test persons. It became clear that the learning pathway the learners took significantly depended on their domain-specific pre-knowledge, which is why a typification of the learners' preconceptions seemed appropriate. The typification served the structuring of the data as well as the generation of hypotheses on the evolution of the conceptual changes in the course of the learning process, which are discussed in the discussion section. According to the preconception types, which were formed in this manner, the type-specific learning pathways were then analysed. The test persons' learning pathways were compared within each preconception type and between the preconception types.

The analytical procedure was conducted several times for the complete data. The data quality assurance took place by means of communicative validation by two independent researchers (Jacobs, Kawanaka, & Stigler, 1999). The adequacy of the deductively formed categories was ensured by means of content validation.[5]

Results

The analysis of the data resulted in finding that none of the learners had scientifically rooted previous knowledge in terms of the two significant concepts for the greenhouse effect, the radiation conversion and the radiatively active effect of the greenhouse gas CO_2 compared with the radiation of different wavelengths. Very similar experience-based schemata can be determined in all learners, such as solar radiation is warm, a finding also described by Kesidou (1990) and Wiser (1986), or that solar radiation is reflected off of the Earth's surface; exhaust fumes, which CO_2 is also considered to be, can form a layer in the atmosphere; heat is a substance-kind entity, which can be contained and transferred (cf. Chi, 2008, p. 67ff; Wiser & Amin, 2001). And yet, despite such shared commonalities, crucial differences between the learners are apparent regarding the overall view of the greenhouse effect concept.

The individual cases included in this study, which, at first glance, all externalised very distinct pre-knowledge and had taken different learning pathways, were able to be grouped into three preconception types by case comparison and case contrasting (Kelle & Kluge, 1999). Type 1 is transcribed with the designation 'isolated pieces of knowledge', type 2 with 'reduced heat output' and type 3 with 'increasing heat input'. These designations specify the main differences of the types. We do not claim to represent all possibly occurring types with this analysis. Furthermore, the preconception types formed by means of this typification and the type-specific learning pathways in regard to a generalisation are of hypothetical nature.

In the following section, we outline the characteristics of each preconception type. We then explain the type-specific mental model evolution using a typical case as an example.

Depiction of the Preconception Types

Preconception type 1 'isolated pieces of knowledge'. Five test persons fit the type 'isolated pieces of knowledge' (students A2, A3, A6, B2, B3). Their conceptions of the greenhouse effect consist of single ideas or facts which are consequently extremely different. For example, they think that the greenhouse effect has something to do with a glass greenhouse; or that the ozone layer protects the Earth against UV radiation, that exhaust fumes and incineration lead to more CO_2 in the air and that there is less shade because of deforestation. One of the students associates the greenhouse effect with 'tectonic plates', which float on magma. However, none of the learners show any references to any kind of thermal effect of the atmosphere whatsoever. Their common denominator is that in the beginning, their conceptions more or less consist of incoherent facts. In their interviews, the learners of this group later stated that they did not know what the greenhouse effect is and that they spontaneously speculated in the preliminary evaluation what the greenhouse effect could be. In the graphic and written representation of their preconceptions, the learners tried to combine various ideas, which they in part associated ad hoc with the term greenhouse effect and presumably in part had already once heard in connection with environmental problems. However, their representations included no information that could explain the warming of the Earth's atmosphere.

Preconception type 2 'reduced heat output'. Three test persons belong to this type (students A5, B7; B5). Students with this preconception show a layer model, in which radiation penetrates the Earth's atmosphere through a layer (ozone layer); however, it does not get out again. The initial mental models already contain concrete factual knowledge and knowledge about interrelations, such as the concept of the emission of radiation from the Earth's surface and the retention of radiation in the Earth's atmosphere, for instance. However, knowledge of radiation conversion and the selective penetrability of CO_2 is lacking.

Preconception type 3 'increasing heat input'. Four test persons were able to be allocated to this type (students A1, A7, B1, B6). Their initial mental models are also characterised by a differentiated factual knowledge and knowledge about interrelations. However, they associate the term greenhouse effect with a warming of the atmosphere due to a more severe incident or increased solar radiation. Two subtypes can be distinguished: (1) the *layer conception* according to which a layer confines the atmosphere and becomes more penetrable for radiation (=ozone hole model) or a layer which ‘increases’ the radiation like a pane of glass or a burning glass (=glasshouse model); (2) the *increasing irradiation conception*: the sun shines more intensely than in the past.

Description of the Type-Specific Learning Pathways and Mental Model Evolution

In this section, a brief outline of the characteristics of the learning pathways typical for each preconception type is given in general terms followed by the detailed description of a representative case, which represents the type well. Three students were selected (A2, A5 and B1, all male, 13 years old), whose drawn and described conceptions appeared to be similar at first glance. They all express a layer conception, which is characterised by the Earth being surrounded by the ozone layer, which carries out various protective functions. One could assume that these students would all take the same learning pathway as a result of their similar previous knowledge. However, our detailed analysis showed that their preconceptions indicated fundamental differences, which changed in regard to the specific type. Student A2 is exemplarily represented as the example for the ‘isolated pieces of knowledge’ type, student A5 for the ‘reduced heat output’ type and student B1 for the ‘increasing heat input’ type.

Preconception type 1 ‘isolated pieces of knowledge’. The students’ who were allocated to this type develop their mental model by following the steps provided in the learning environment: After working with the worksheet (Appendix 1; t3 in Table 1), the students’ externalised statements indicate a partial understanding of the emission of infrared radiation from the Earth’s surface. At the end of working with the learning environment (t6), the energy exchange between the Earth’s surface and the atmosphere is described by most of the learners in the way it is conveyed in the learning material. However, in regard to understanding the selectivity of CO_2, i.e. the characteristic of CO_2 to allow solar radiation to pass through but not infrared radiation, they achieve different levels of understanding. The differences range from conceptions that CO_2 forms a *barrier* absorbing and emitting thermal radiation to the understanding that CO_2 *molecules* act as infrared radiation absorber and emitter, as described in the worksheet and amplified by the MED.

Student A2’s learning path. In the preliminary evaluation, student A2 assumes that the greenhouse effect meant that the ozone layer protects the Earth against UV radiation. He does not express any further knowledge thereof. After working with the worksheet, he gives a correct account of the conversion of solar radiation into infrared radiation in his second drawing (t3). It is also correctly described that the CO_2 molecules, drawn as small dots, hold infrared radiation back in the atmosphere by absorbing and re-emitting heat rays, which are emitted from the Earth. In the legend to this drawing he writes: *The sunlight hits the ground, where it is converted into heat rays. A few of* *them* [*heat rays*][6] *should leave the atmosphere again but the excess CO_2* [*CO_2 produced by mankind*] *prevents the heat rays from doing this = global warming*. However, he does not make any explicit statements regarding the selective penetrability of CO_2, which, however, does not have to implicate that he is not aware of this issue. After studying the worksheets, A2 has, in our opinion, a coherent concept, which can explain the greenhouse effect. As witnessed over the course of the learning process, A2 appears to have deduced the absorption and emission of infrared radiation by the CO_2 during the demonstration of the MED and during the discussion about it (t5, t6) in more detail. In the legend in the third drawing (t7), he writes: *The heat rays are absorbed by the CO_2 and are then re-emitted.* In the individual interview (t8), he explicitly expresses his thoughts regarding these circumstances:

Interviewer: Do you think it is a contradiction that solar radiation penetrates CO_2 but infrared radiation does not?
A2: Yes, a little bit.
Interviewer: How could that be explained?
A2: Somehow, the *sunlight* is not interesting for the molecule. It [the molecule] attracts the heat.

The interview also shows how he comprehended the complex effect of the absorption and emission of infrared radiation by CO_2. A2's response to the question on how he would explain the mechanism of CO_2 to someone younger, e.g. a sibling, is:

A2: . . . , that the sunlight, which enters, is turned into heat rays on the ground, is then caught by a CO_2 molecule and—just like a radiator—the molecule is like a radiator and it heats.

A2 describes the greenhouse effect as it is conveyed in the learning material, as comprehensible and plausible. A2 liked that the worksheet first broached the issue of a misconception and that was then corrected. He was impressed with how the MED showed the effect of CO_2. He thinks it important to understand the greenhouse effect so that one is willing to produce less CO_2 and switch to using public transportation. In response to the interviewer's question of whether it was a surprise to him that the greenhouse effect is different than he had originally imagined, he shrugs his shoulders, smiles and says with a bit of embarrassment:

A2: Yes, but it was just learning. I recognised that my conception is wrong and then learned the right one. I would not have thought [at the beginning of the work phase] that the ozone layer has almost nothing to do with it [with the greenhouse effect].

From his response the conclusion can be made that his expectations regarding the explanation of what the greenhouse effect is were not met and a cognitive dissonance developed. In the final interview with the probing questions (t9), his knowledge proves to be very reliable.

Preconception type 2 'reduced heat output'. Students who externalised mental models of the 'reduced heat output'-type follow the gradual learning pathway as conveyed in the learning material. They understand the concepts of radiation conversion and the selectivity of CO_2 already well with the worksheet (t2), including detailed knowledge about the absorption and emission of infrared radiation through CO_2. They use the work with the MED for processing and deepening the knowledge assimilated with the worksheet (t5, t6). Compared to type 1, they understand the concepts underlying the greenhouse effect more rapidly and are able to construct a more comprehensive mental model.

Student A5's learning path. In his drawing produced in the preliminary evaluation, student A5 depicts a layer, which restrains the atmosphere outwardly and refers to it as an ozone layer. He does not distinguish between solar and infrared radiation but uses both types of radiation synonymously like all students in this study. This is reflected in the legend of the drawing: *Sunlight (heat) cannot escape*. He assumes that the warming of the Earth's atmosphere can be attributed to the warm radiation, which has entered, not being able to leave the atmosphere and return back to space*: The sunlight can penetrate the ozone layer but the heat cannot get back out, like in a greenhouse.* A5 knows that the solar radiation that reaches the Earth's surface is re-emitted but he is not yet familiar with radiation conversion and thinks it has to do with reflection. A layer of ozone is seen as an accumulator of the outgoing sunlight but the incoming solar radiation can penetrate without hindrance. This leads to a type of heat accumulation, in which the sunlight, i.e. the heat, remains trapped between the Earth's surface and the ozone layer. He gives no explanation for why this is the case. The second drawing, which A5 made directly after working on the worksheet (t3), shows that he assimilated and adapted the concept of radiation conversion. He draws sunlight, which reaches the Earth's surface through a layer—still labelled as ozone layer—is absorbed at the Earth's surface and then emitted as thermal radiation. However, as to the selectivity of CO_2, he devised an interesting synthetic model. He does not mention CO_2 in his drawing or his text, but writes that the ozone layer prevents the emission of thermal radiation from the atmosphere: *The sunlight penetrates the ozone layer without any resistance. Then it reaches the Earth. The Earth converts the sunlight into heat rays and the heat rays can no longer escape through the ozone layer. Therefore, there is a warming of the Earth's atmosphere*. He also sticks to this conclusion when asked by the interviewer to explain how he understood the explanations in the worksheet (t4).

> A5: ... that the sunlight can enter through the ozone layer and is converted into heat rays in the Earth and that these can no longer escape through the ozone layer and therefore, it gets warmer.

In response to the interviewer's question on how he got the idea that the ozone layer is the reason for the accumulation of the thermal radiation, he says:

> A5: ... because of the CO_2, that absorbs heat and re-emits it into the environment.

Therefore, he does not distinguish between CO_2 and the ozone layer, but it has become clear to him that CO_2 does not simply block heat but absorbs and re-emits it. After the interviewer encourages him to take another look at the worksheet, he notices that the heat is not retained by the ozone layer but the CO_2 molecules.

Before the MED begins, it becomes evident that A5 understands the analogies used in the MED and their reference to the normative model of the greenhouse effect. He can hypothetically deduce the results of the MED beforehand based on his knowledge of the effect of CO_2. In his 3rd drawing, which he made after working with the MED (t7), he expresses that CO_2 has nothing to do with the ozone layer and that CO_2 has a heat-retaining effect because of its selectivity. He draws CO_2 molecules in the form of small dots, which are distributed in the Earth's atmosphere and writes: *The sunlight can penetrate the CO_2 and it is converted into heat rays in the Earth. It* [*the heat rays*] *cannot escape and is absorbed by the CO_2.* A5 understood the most important principles of the greenhouse effect early on in the learning process. His knowledge proves to be reliable. In response to the question of whether the Earth's atmosphere is warmed by solar radiation, he says:

> A5: Sun rays, I don't think so. Not until it [the sun rays] reaches the Earth and it then turns into thermal radiation.

In the final interview, he also knows that the CO_2 has nothing to do with the ozone layer and that CO_2 is responsible for the natural and anthropogenic greenhouse effect because it absorbs thermal radiation. The greenhouse effect, as it is explained in the learning material, is comprehensible and plausible to him. In view of the referendum common in Switzerland, he thinks it is important to understand the greenhouse effect, so that one can understand the reports on it in the media and what it has to do with, when it is about fighting the anthropogenically induced climate change. He indicates having experienced a cognitive conflict:

> Interviewer: We looked [in his drawings] at how you imagined the greenhouse effect and the warming of the atmosphere at the beginning of the session. Was it a surprise to you that that was different?
> A5: Yes, it was a little bit.

Preconception type 3 'increasing heat input'. Type 3 learners apparently struggle with the contradictions resulting during the learning process between their preconception of the increasing heat input into the atmosphere and the scientifically rooted explanation of the greenhouse effect presented in the worksheet. Although the learners have a conception of radiation being emitted from the Earth's surface after working with the worksheet (t3), they have problems understanding the concept of radiation conversion. It is difficult for them to question their schema 'thermal radiation equals solar radiation'. They have to fundamentally change their belief of increasing heat input being responsible for the atmospheric warming to the science-based concept that it is reduced heat output. Only after that learning step are they able to assimilate the concept of radiation conversion into their newly constructed intermediate mental model. They do not achieve an understanding of the selective effect of CO_2, until the end of their work with the learning environment, as is explained in the teaching aids. Basically, they understand that CO_2 allows something in but does not allow it back out and it first begins by devising a CO_2 layer, which has the effect of a one-way street impediment, whereby solar radiation is able to enter and radiation emitted from the Earth is retained. The selectivity of CO_2 is only understood in the function of a barrier. The special characteristic about this type is that a learning pathway was taken, which runs in the opposite direction of the path advised by the learning environment: first, a container model of the earth's atmosphere using CO_2 as a barrier retaining the heat is constructed and then follows an attempt to understand the radiation conversion.

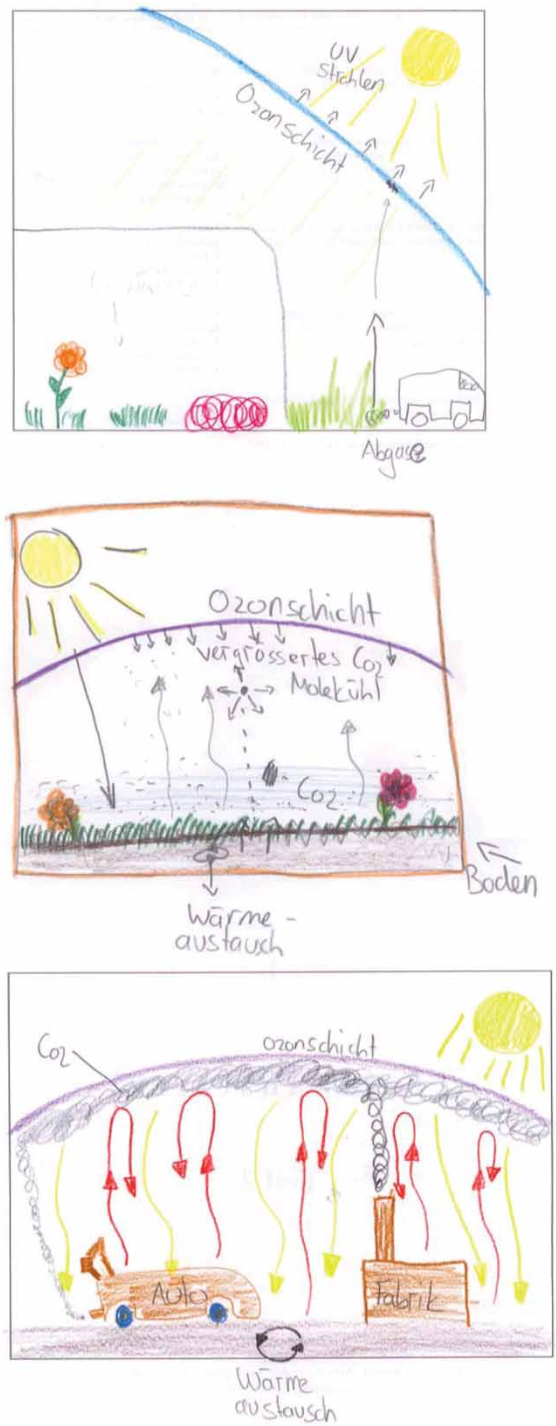
Student B1's learning path. At the time of the preliminary evaluation (t1), B1 has the ozone hole model: The Earth's atmosphere is surrounded by an ozone layer, which is being damaged by exhaust fumes (automobile exhaust emissions, CO_2) and is therefore becoming more penetrable for radiation, which leads to a warming of the Earth's atmosphere (Figure 2). He writes: *Exhaust fumes are destroying the ozone layer, which enables ultraviolet rays to reach the Earth = it gets warmer!* After studying the worksheet (t3), B1 understands that CO_2 allows something to enter the atmosphere but not back out and even absorbs heat: *CO_2 works like a blanket. It stores the heat.* His statement suggests that he has grasped one of the significant concepts for the greenhouse effect and has changed his mental model form 'increasing heat input' to 'reduced heat output'. However, the student does not understand the relevant concept of the conversion of light into thermal heat or only understands it in part. Although the worksheet shows him that something happens with the solar radiation, he has problems with the new information that solar radiation and thermal radiation are two different kinds of radiation and that light can be converted into heat. This becomes very evident upon closer examination of the student's written statements: *The sun rays reach the Earth. The ground stores the rays and a heat exchange takes place and the warm rays* [*emitted from the Earth's surface*] *can no longer leave, back into space.* He obviously assumes that a heat exchange or a mixing takes place between the sunlight and the ground and that the rays that are 'heat exchanged' in this manner, which he calls warm rays, are reflected off the ground. However, in the case of B1, it is not evident how he imagines this process and if he thinks that the solar radiation changes its characteristics by means of the 'heat exchange with the ground', for instance.

Through the work with the worksheet (t2), he explicitly understands the principle that the warming of the Earth's atmosphere is based on a reduced energy radiation and not on increased energy irradiation and that CO_2 plays a role in the process. However, he cannot overcome the idea that sunlight does not carry heat for the benefit of radiation conversion. His conception of the selective effect of CO_2 remains non-specific. He remains with the blanket analogy but now emphasises the hindering nature of CO_2. Contrary to the incoming rays, the heat rays 'exchanged' in the ground are hindered by CO_2:

B1's drawing at t1:

B1's drawing at t3:

B1's drawing at t7:



Legend:

- UV Strahlen = UV rays
- Ozonschicht = Ozone layer
- Abgase = exhaust fumes
- vergrössertes CO_2 Molekül = enlarged CO_2 molecule
- Wärmeaustausch = heat exchange
- Boden = soil
- Auto = car
- Fabrik = factory

Figure 2. Student B1's conceptions of the greenhouse effect at three different times of assessment.

> B1: ... then the sunlight goes in and back out of the ground and the CO_2 works like a blanket, i.e. holds the sunlight back and then it cannot escape. And that means that the more CO_2 we produce, the warmer it gets in the world because the CO_2 then becomes so dense that absolutely no sunlight can escape anymore.

Even after the application of the MED (t6), his conceptions regarding the conversion of solar radiation into thermal radiation are basically the same as at t3:

> B1: The sunlight enters the ground. Yeah, and then a heat exchange takes place in the ground.
> Interviewer: What do you mean by 'heat exchange'?
> B1: The sunlight enters the ground and there, it somehow becomes a mixture and then the heat comes back up out of the ground.

Not until the end of the work phase does it become clear to him that sunlight and thermal radiation are different. In his written work at t7 he explicitly writes that heat rays are generated in and emitted from the ground and also sticks to this knowledge all the way up to the final interview (t9). However, despite persistent enquiries, it cannot be precisely determined what the term 'heat exchange' means to him.

Regarding the selective effect of CO_2, B1's conceptions experience further distinction through the MED and the subsequent discussion. However, he cannot distance himself from the layer conception. It reappears in his 3rd drawing (t7; Figure 2) in the form of the ozone layer, which he maintained throughout the entire learning process. The layer conception apparently corresponds to a familiar schema, which is spontaneously activated because it is most likely to lead to a plausible explanation. At the end of the work phase, he has a synthetic model with the accumulation of the anthropogenically induced CO_2 as a thick, additional layer underneath the ozone layer, which was thickened in this (t7). Sunlight reaches the atmosphere through the layer, collides with the ground, is converted into heat rays in the ground through 'heat exchange' and is re-emitted. The heat rays are reflected back to the Earth's surface from this CO_2 layer. In the interview (t8), B1 explains that he understands the greenhouse effect, as it is presented in the learning material and that it is plausible to him. He thinks knowledge of the greenhouse effect is important to become aware of what it means for the climate if mankind continues in this manner. He did not consciously sense a cognitive conflict. The final interview with the probing questions shows that B1's knowledge is not very reliable in all aspects:

> Interviewer: Does CO_2 affect the ozone layer, i.e. does it make it thinner, e.g. or does it create a hole?
> B1: No, I don't believe that CO_2 creates holes but it does make it thinner.
> Interviewer: Can sunlight heat up the Earth's atmosphere?
> B1: I don't know, I don't know.

The fact that student B1 enhanced his knowledge can be clearly seen in his third drawing (t7). The heat no longer enters the atmosphere through the ozone layer but is the result of a 'heat exchange' between solar radiation and the Earth's surface. However, the hole conception was not truly done away with but merely suppressed and reappears in the interview in the form of the layer-thinning effect of CO_2. B1 also resists the idea of CO_2 gas absorbing and emitting thermal radiation. On the contrary, he assimilates the CO_2 with his existing layer conception, in which the CO_2 becomes a layer intensifier (Figure 2).

Discussion

This research is aimed at shedding some light on the inner knowledge construction of the greenhouse effect phenomenon in 13-year-old students who had no prior science instruction. The case-based analysis and the mutual comparison of the students' learning pathways confirm that their prior knowledge has a significant influence on their way of knowledge construction. Moreover, the analysis of the students' learning paths, in relation to the preconception type they were allocated to, suggests that their mental models evolve in a type-specific way. The preconception type can therefore be seen as a reliable predictor of the subsequent learning process. What makes this research so special is the rare view it provides on *how* specific preconception types impact knowledge development concerning the greenhouse effect. Furthermore, the study gives an answer to the question why some learners, even though they are greatly interested in the topic and work hard to understand its fundamentals, do not reach the target.

Three preconception types could be formed based on the characteristics and structures of the previous knowledge, which were designated 'isolated pieces of knowledge' (type 1), 'reduced heat output' (type 2) and 'increasing heat input' (type 3) according to their characteristics. The preconception types can be divided into two levels of complexity: type 1 is distinguished by a lack of knowledge or very limited knowledge, which was expressed *ad hoc* in the problem-solving situation. The types 2 and 3 are distinguished by complex mental models of the greenhouse effect, which differ in subjective plausibility and coherence. The mental models of type 2 are closer to the scientific view of the greenhouse effect than those of the other preconception types; however, they are not coherent because it remains unclear why solar radiation assumed to carry heat can penetrate the 'ozone layer', but remains trapped underneath it after the radiation reflection from the Earth's surface. Those of type 3 virtually completely consist of everyday conceptions, which are however, subjectively coherent. The mental models of all learners become more complex in the course of the work phase through the integration of new facts and features. However, the students achieve different levels of understanding in the course of their mental model-evolution process.

Conceptual development was achieved, in regard to

(1) radiation conversion, by all type 1 and type 2 learners. Type 3 students integrate radiation conversion into their mental model without accommodating their previous idea that sunlight carries heat. Their knowledge remains inconsistent and proves to be less reliable compared with that of the other two groups.
(2) the selectivity of CO_2 in terms of its description in the worksheet, by most of the type 1 and all type 2 students. Type 3 learners only understand the effect of CO_2 in terms of a barrier for the thermal radiation emitted by the Earth's surface.

Type 1 learners, who only have a very limited previous knowledge relevant to the greenhouse effect, construct their mental models by assimilating new information into their existing small knowledge bases, extending and enriching them. Their knowledge gain is remarkable. Most of their mental models come quite close to the explanatory we conveyed. Their mental model constructions correspond to the learning pathway suggested in the learning material, even if the newly acquired knowledge does not always immediately lead to completely accurate mental models. The type 1 profile of knowledge construction would not be regarded as conceptual change by some conceptual change theorists, but as knowledge building and enhancement (Chi, 2008, p. 66f; Rumelhart & Norman, 1978). This assessment most likely applies to the superordinate concept of the greenhouse effect, but not on the level of the mechanisms, which constitute the greenhouse effect. Our research suggests that a conceptual change most certainly took place for type 1 learners on the level of their false conceptions underlying the greenhouse effect, e.g. that sunlight is warm or that gases (here, CO_2) just block outgoing thermal radiation.

The type 2 test persons have vast topic-oriented and relational previous knowledge of the greenhouse effect, which comes close to that in the explanatory model. Their elaborate, initial mental models change when confronted with the normative knowledge as suggested in the learning material because their cognitive schemata are in line with the facts presented in our teaching aids and merely have to be specified using the science-based knowledge (Schnotz, 1995, 88f). The preconception of the 'reduced heat output' literally 'screams' for explanations, which gives it coherence. Therefore, radiation conversion and the selectivity of CO_2 can be built into the initial mental model by readjusting the overall preconception of the greenhouse effect. Thus, type 2 learners change their mental models gradually to clear away inconsistencies between the new information and their previous knowledge. We consider this modification of knowledge structures as conceptual change, which is based on a weak knowledge reconstruction.

Type 3 learners have considerable difficulties in processing the conveyed information. Their learning difficulties lie in the fact that they have to construct those cognitive structures in the same work step and these form the basis of being able to understand the conveyed contents in the first place (Aeschbacher et al., 2001, p. 237). Their personal theory that the warming of the Earth's atmosphere is attributed to an increased supply of heat hinders their learning process. A similar observation describes Niebert (2010). The differences of their conceptions to the presented information are so profound that they must construct a radically different mental model, in order to understand the greenhouse effect. This change is difficult to perform because it involves, in the first learning step, their subjective coherent preconceptions to be transformed into a non-coherent mental model, namely that of the 'reduced heat output', which cannot explain why solar radiation is able to enter the atmosphere through a layer, but can then no longer get out.

The example of student B1 shows that it is not easy to get a cognitive system to take on a new world outlook if it contradicts its previous everyday theory. The difficulties type 3 learners have with the concept of radiation conversion in the learning process show that self-generated explanations and those based on own observations, such as the feeling of warmth when sitting in the sun, are often more plausible than predetermined scientific theories for phenomena in the world of objects and events due to their coherence with everyday knowledge (Seel, 1991, p. 47). Without a 'severe restructuring', i.e. the construction of a radically new perception of the greenhouse effect, the meaning of new information is changed under the influence of the 'old' knowledge and distorted in the direction of the inaccurate explanation. This is shown by how student B1 conceptualises the energy conversion and the effect of CO_2: He transformed the meaning of the conveyed information by explicitly changing the sunlight, which for him, is implicitly warm, to *warm sunlight* through 'heat exchange' with the Earth, which, in doing so, remained a factor in line with his established everyday theories. The warm sunlight is emitted by the Earth's surface and trapped in the atmosphere, the top of which is limited by a layer (e.g. the ozone layer). The naturally and above all anthropogenically produced CO_2 intensifies the protective layer, so that even less heat can be emitted. The 'increasing heat input' conception has the effect of an inaccurate assimilation schema during the processing of information, which is why only those elements are accepted from the presented information, which are in line with the factually inaccurate mental model. The target model cannot be constructed for biased information selection and a cognitive dissonance also cannot develop. This would explain why student B1 apparently did not sense a cognitive conflict.

The results of this research indicate that the model of the 'reduced heat output' seems to be the higher-order concept in understanding the greenhouse effect for 13-year-old learners. It is the prerequisite for the assimilation of the knowledge on radiation conversion, whereby the everyday theory of the increasing heat input into the atmosphere lapses. If this concept is clear, the effect of CO_2 in the atmosphere can be looked at in the next learning step.

Implications

This study exemplarily demonstrates that learning processes must be conceived as constructivist and therefore as individual, and that individual preconceptions play a significant role in knowledge construction. Although all students learn under the same conditions with a psychologically and educationally as well as didactically well-conceived learning environment, the principle effectiveness of which is empirically substantiated (Reinfried et al., 2012), some of the students are led astray while others have virtually no problems in correctly processing the new findings. So what does this mean in regard to teaching practice? It would of course be ideal if the students' specific conceptions could be responded to individually. However, this is not feasible in day-to-day school life. But the learning processes presented here, which are dependent on preconception, show similarities in the individual learning pathways and therefore offer teachers the possibility of anticipating and understanding problems resulting from previous knowledge.

Therefore, the great significance of this study lies in the knowledge of preconception-dependent, prototypical processes of knowledge construction making teachers more aware of their students' possible learning pathways and learning difficulties. With the knowledge of the students' misunderstandings, teachers can anticipate the most common misconceptions and are prepared for learning difficulties, which arise in the course of the lesson. They succeed in recognising which everyday theories mislead the students in the course of the lesson—often simply by listening—and are more flexible in reacting to them without embarrassing the student. They can use the everyday conceptions as productive ties for the revision of existing knowledge structures and the development of a scientific understanding, by going into the everyday conceptions and deliberating on these with the learners from a different perspective (Van Dijk & Kattmann, 2010).

Using the knowledge of the prototypical processes, teachers can deliberately steer the discussion with the learners during the lesson so that the coherence of the scientific concept is compared with misconceptions, which have become apparent. They can pay attention to starting points of student conceptions, which could be made productive for a conceptual reconstruction by adding subject-specific conceptions to them. In the case of student B1's layer conception, that would be tying in with the ozone layer, for instance, which according to his mental model surrounds the atmosphere and prevents heat from leaving the atmosphere. It is okay to imagine a layer when thinking about the atmosphere however, not in the form of an outer casing around the atmosphere like the casing of a balloon. In fact, the entire atmosphere can be seen as a layer with the CO_2 molecules contained within it and each individual one prevents the emission of thermal radiation. It therefore follows that the more CO_2 is in the air the less heat can leave the atmosphere. An increasing heat input, for whatever reason, is simply not necessary to explain the greenhouse effect and global warming. This rethinking of the processes, which account for the greenhouse effect, provides the learners with another opportunity to ponder, evaluate, assess and reassess the validity of their conceptions and in doing so possibly come across inconsistencies, which were not realised before, which also still enables inducing a cognitive conflict retrospectively.

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Notes

1. In Switzerland, a grading scale of 1–6 is used, in which 6 is the best grade.
2. Hans Aebli, a well-known psychologist and educator in Switzerland, was a student of Piaget and further developed Piaget's cognitive-constructivist theory, to make it applicable in a didactic manner.

3. We slightly altered the diagram in the first image – text unit of the worksheet compared to the one used in GeoConcepts I (cf. Reinfried et al., 2012). Instead of graphically portraying a hole in the atmosphere, we only addressed it in the form of a question. This was necessary because several students did not immediately recognise the hole in the worksheet for GeoConcepts I as an illustration of a widespread misconception. In GeoConcepts I we used the hole conception as a starting point in the worksheet, assuming that in doing so, we are addressing the initial mental models of many learners.
4. The MED (www.demoex.ch) is set up as follows: A rotating desktop globe, heated by lighting, serves as an infrared radiation source. The Earth's atmosphere is shown as a section in the form of a plexiglass cuvette, which is open on top. The CO_2 is poured into the previously air-filled cuvette from the top on the unlit side—the night side. A measuring device, positioned outside of this 'piece of atmosphere', measures the intensity of infrared radiation, which enters into space from the heated surface of the globe through the 'piece of atmosphere'. The measuring device immediately indicates a decrease in this intensity, when the CO_2 is poured in. Therefore, it is not a matter of a precise measurement but rather of the qualitative immediate effect of the falling needle. A video demonstration of the MED is available in German on www.demoex.ch/?Produkte → Schülervideo.
5. The content validity of the categories resulted from the analysis of specialist literature (IPCC, 2007; Schönwiese, 2003; Weischet & Endlicher, 2008), from the analysis of several studies which discuss cognitive constructs based on misconceptions (Aeschbacher et al., 2001; Andersson & Wallin, 2000; Bord, O'Connor, & Fisher, 2000; Boyes & Stanisstreet, 1993; Dieckmann & Meyer, 2007; Dove, 1996; Kempton, 1993; Koulaidis & Christidou, 1999; Löfstedt, 1992; Read, Bostrum, Morgan, Fischhoff, & Smuts, 1994; Rye et al., 1997; Schuler, 2011), from the analysis of 61 teaching materials (textbooks and instructional texts) and 37 web pages in which the misconceptions were also found (as at May 2009), from the discussions of the categories with three experts (a climatologist, a physicist and a psychologist) and from the previous success with the categories in the quantification of the knowledge gain of the learners in GeoConcepts I (cf. Reinfried et al., 2008, 2012).
6. Omissions in the following transcript excerpts are marked with ... The language in the transcripts is slightly improved. The information in square brackets designates comments added by the authors.

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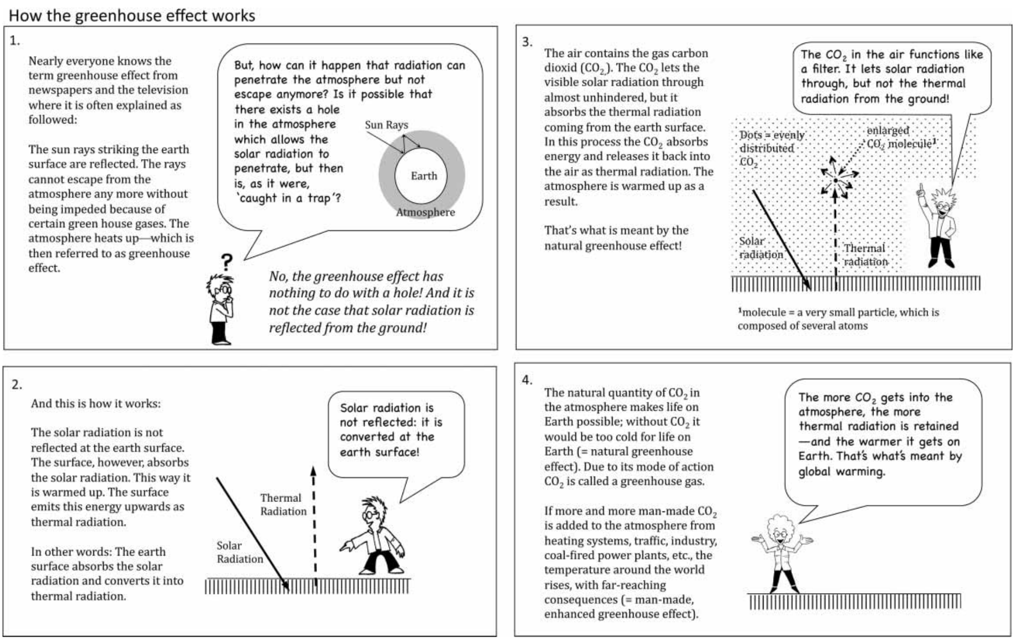
Appendix 1. The worksheet



Source: The worksheet was previously presented in Reinfried et al. (2012) in a slightly different manner.

Appendix 2. Discussion guideline

Questions posed after the MED (t6):

(1) What did you observe when the demonstration was being applied?
(2) How do you explain your observations?
(3) The demonstration is merely a reproduction of the actual circumstances in the Earth's atmosphere. In which way is the demonstration consistent with reality? What limitations does the demonstration have?
(4) CO_2 is released by burning wood, crude oil, natural gas and coal. What happens if more and more CO_2 is released into the atmosphere?
(5) Take another look at your drawing and description of the greenhouse effect, which you made at the beginning of the lesson. Can you determine any differences to the knowledge you have now? How do your conceptions differ?

Appendix 3. Interview guideline

Direct questions regarding students' learning process and their learning difficulties in working with the learning environment:

(1) In all, what did you like most about the work/what didn't you like?
(2) What didn't you understand in the worksheet, what wasn't comprehensible? (Is the concept intelligible?)
(3) Did the experiment convince you (in the terms of that you are now sure that CO_2 leads to the warming of the atmosphere)? (Is the concept plausible?)
(4) Does the principle of how the greenhouse effect works (which you have now learned) convince you? (Is the concept plausible?)
(5) Do you still remember how you imagined the greenhouse effect worked at the beginning of today's lesson? Was it a surprise for you that it was different? (Was a cognitive conflict experienced?)
(6) Do you think it is a contradiction that solar radiation penetrates CO_2 but infrared radiation does not? (Was a cognitive conflict experienced?).
(7) Why is it important to understand the greenhouse effect? How do you benefit from understanding it? (Is the concept fruitful?)

Appendix 4. Interview guideline

Questions to test the reliability of the knowledge on the greenhouse effect:

Hole conception

- What does the ozone hole have to do with the greenhouse effect?
- Is it true that the greenhouse gases form a layer in the atmosphere? If so, which gases?
- Does CO_2 affect the ozone layer, i.e. make it thinner, e.g. or create a hole in it or are these possibly other gases, which cause this?

Radiation conversion and greenhouse gases as a radiation trap

- Do exhaust fumes from cars and chimneys have anything to do with the greenhouse effect?
- Sometimes you can read on the Internet: The sun's rays enter the Earth's atmosphere and are reflected off of the Earth's surface. Is that correct?
- Can the sun's rays heat up the Earth's atmosphere?
- Do we even need CO_2 in the atmosphere or would it be better to remove the gas if that were possible?

Anthropogenic versus natural greenhouse effect

- Given that natural CO_2 warms the atmosphere, CO_2 caused by human activity would have to increase the warming. Would you agree?