

Understanding needs embodiment

A theory-guided reanalysis of the role of metaphors and analogies in understanding science

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Abstract

Many authors stress the importance of basing teaching on students' prior knowledge. To build a bridge between students' everyday knowledge and scientific concepts, the role of metaphors and analogies came into the focus of the science education community during the last two decades. Approaches using metaphor-based teaching strategies often regard metaphors and analogies as teaching tools that can be adopted by a teacher. On the basis of the theoretical framework of experientialism, we argue that not only teaching but also thinking about and understanding science without metaphors and analogies is not possible.

An analysis of studies dealing with metaphors and analogies in science education shows that instructional analogies and metaphors are often not understood as intended or not used by students in their own explanations. By reanalysing 199 instructional metaphors and analogies on the basis of a metaphor analysis, we show that it takes more than making a connection to everyday life to communicate science fruitfully. We show that good instructional metaphors and analogies need embodied sources. These embodied sources are everyday experiences conceptualised in, for example, schemata such as containers, paths, balances, and up-and-down. For the analysis, we introduce the concept of conceptual metaphors for analysing metaphors as well as analogies.

Introduction

Our everyday lives are full of metaphors: "This idea will save you hours" or "I've invested a lot of time in this article" are very common ways of expressing the idea that "Time Is Money". Theories are often understood metaphorically as buildings: "That's the foundation for my theory", "He constructed a strong argument", or "The theory stands on the strength of that argument". Similarly, many everyday expressions such as "That's a clear argument", "I

see your point”, and “I’ve got the picture” constitute metaphorical interpretations of understanding and knowing as seeing.

Research has shown that we do not just employ metaphors in everyday thinking but also use metaphors to understand scientific topics (Niebert & Gropengießer, 2011; Riemeier & Gropengießer, 2007). Metaphors not only pervade everyday life but science relies strongly on metaphor, too: atoms are imagined as being like a solar system, waves, or clouds. Textbook writers use metaphors, for example to explain the immune defence as war: “Although the body *responds* to HIV with an *aggressive* immune response sufficient to *eliminate* most viral infections, some HIV invariably *escapes*” (Campbell, et al., 2008). Also, scientists use similar metaphors in their research papers: “CD4+ cells did not *participate* in the *active killing* of bladder tumour *target* cells” (Thanhäuser, et al., 1995). The history of science provides examples in which metaphors and analogies were used to develop new theories:

- Arrhenius was the first to describe the greenhouse effect by describing the atmosphere as being like a hotpot,
- Kepler developed his concept of planetary motion with the comparison to a clock,
- Watson and Crick arrived at the double helix structure of DNA by making analogical models of a twisted ladder,
- Kekulé derived his idea for a benzene ring from an image of a snake biting its tail, and
- Huygens used water waves to theorise that light is wavelike.

Theoretical framework of this study

Most of the studies dealing with the relevance of metaphors and analogies in science education conceptualise metaphors and analogies as tools for teaching science (Duit, 1991; Harrison & Treagust, 2006; Ritchie, 1994). However, since the mid-twentieth century, philosophers have shown that metaphors and analogies are not simply teaching tools but permeate all discourse, are fundamental to human thought, and provide a basis for mental

leaps (Johnson, 1987; Lakoff & Johnson, 1980). Similarly, the potential contribution of metaphors and analogies to cognitive learning has attracted the attention of the science education community. One of the most important revelations is that metaphor is not merely a linguistic phenomenon but also a fundamental principle of thought and action. To provide a basis for an analysis of students', scientists' and teachers' metaphors and analogies, we will introduce experientialism as a framework in science education that can help to explain students' and scientists' conceptual understanding of a scientific idea and illustrate how experientialism can help in the design of learning environments.

Metaphors and analogies in science education

During the past 25 years, many studies have evaluated the use of metaphors and analogies in science classrooms and various theories of the use of metaphors and analogies have been developed. Gentner's structure mapping approach (Gentner, 1989) and Holyoak's pragmatic approach (Holyoak, 1985) are the most prominent ones. Both approaches share the view that mental representations of source and target domains are crucial for analogical reasoning. The process of drawing conclusions from source to target is essentially based on the logical equivalence of features at the source and target (Gentner, 1989, p.210). This perspective implies that there are logical similarities between the source and the target, and the teacher simply has to emphasise them when using an analogy. However, Wilbers and Duit (2001) argue that from a constructivist point of view, this similarity is constructed and dependent on prior experience with source and target: if a teacher generates a metaphor or analogy, the target domain is as well known to him or her as is the source domain. The student is instead totally ignorant of the scientific concepts that are communicated. Therefore, the teacher's use of the metaphor or analogy is presumably different from the student's: while the teachers construct the similarities, the students have to search for them.

Analogies and metaphors are promoted by scientists as successful conceptualizations, but are often seen as problematic by the science education research community (Dagher, 1995; Duit, 1991). Those who study analogy offer frequent reminders that the useful applicability of an analogy is limited: only some aspects of a source domain can be mapped to a target domain. For example, an important aspect of the target domain that has no counterpart in the source domain or a salient characteristic of the source domain that has no analogue in the topic domain is nevertheless exported to the topic. Students are particularly vulnerable to the formation of inadequate conceptions derived from mapping errors (Harrison & Treagust, 2006; Vosniadou & Brewer, 1987). Lakoff and Johnson (1980) call this characteristic “highlighting and hiding”: the systematicity that allows the comprehension of one aspect of a concept in terms of a special source that will necessarily hide other aspects of the concept. In allowing the focus on one aspect of a concept, a metaphor or analogy keeps one from focusing on other aspects of the concept that are inconsistent with that metaphor or analogy.

Experientialism as a theory of metaphors and analogies

Most actual debates about conceptions in science education see knowledge as a personal construct of an individual. This claim refers to the epistemological position of constructivism (Matthews, 2000). Commonly, constructivism is interpreted as a learning theory that emphasises the role of prior knowledge in learning: students interpret new concepts that are taught in terms of prior knowledge. However, first and foremost, constructivism is not a theory of learning but an epistemology dealing with the question: What is knowledge and how can it be acquired? Within constructivism, knowledge is seen as a personal construction of meaning. Knowledge is not passively received either through the senses or by way of communication but is actively built up by the cognising subject (v. Glasersfeld, 1989). This perspective—which is also supported by findings of neurobiology (i.e., Karmiloff-Smith,

2009)—is rooted in Kant’s synthesis of rationalism and empiricism, in which it is noted that the subject has no direct access to external reality.

However, the insight that all meaning is a construct of the individual itself based on prior knowledge creates a start-up-problem: if our conceptions are personal constructions based on prior knowledge, how did we create the foundational knowledge acting as the basis for the development of further knowledge? Furthermore, constructivism does not make a statement regarding how knowledge is achieved.

This epistemological problem can be solved with the help of empirical findings emerging from the fields of linguistics (Lakoff, 1990; Lakoff & Johnson, 1980; Lakoff & Johnson, 1999), philosophy (Johnson, 1987), science education (Gropengießer, 2007), and neurobiology (Gallese & Lakoff, 2005; Rohrer, 2001, 2005). These findings, summarised as the theory of experientialism, show that abstract concepts—this refers to most concepts in science—are not understood directly but in terms of other domains of knowledge; that is, understanding is ultimately grounded in embodied experience. The relational structure of abstract domains derives from the relational structure constituting experientially based notions of force, space, and motion (Lakoff, 1990): our basic conceptions emerge from bodily experience with our physical and social environment. 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 programs. Schemata give coherence and structure to our experiences. The verticality schema, for instance, emerges from our tendency to employ an up-down orientation in picking out meaningful structures of our experience. We grasp this structure of verticality repeatedly in thousands of perceptions and activities every day, such as standing upright, climbing stairs, or experiencing the rising of the water level in the bathtub. The

verticality schema is the abstract structure of these up-down experiences, images, and perceptions (Johnson, 1987).

Several other schemata, such as the container schema or the source-path-goal schema, are conceptual structures grounded in bodily experience and can be understood directly. These schemata shape our conceptual understanding not only in everyday life but also in science. We will describe the schemata employed in this analysis in the results. A description of further basic schemata that shape our conceptual system can be found in Johnson (1987).

In contrast to direct conceptions, most scientific concepts are based on models and generalisations derived from scientific inquiry guided by methods such as experiments, in which variables are controlled, or instruments such as a microscope, which enables observation of previously imperceptible entities. Concepts derived from an often very intelligent but complex inquiry cannot be embodied in the same way as the above-mentioned schemata. Thus, they must be thought of in an imaginative way (Niebert, Riemeier, & Gropengießer, 2011). Imaginative thinking is accomplished primarily by using metaphors and analogies.

Therefore, we distinguish between embodied conceptions and imaginative conceptions. The latter are not directly grounded in experience but draw on the structure of our experience; we use our embodied schemata to explain abstract phenomena. Imagination can be seen as bridging the gap between experience and abstract phenomena. We employ conceptions from a source domain (i.e., the container schema) and map them onto an abstract target domain (i.e., atmosphere) to understand abstract phenomena. Thus, the use of imagination requires a source-target mapping. The structure of a source domain is projected onto a target domain via metaphors or analogies. The distinction between embodied and imaginative conceptions shows that schemata and metaphors are different concepts: when one works with a container like a cup or a box, the experiences are conceptualised. These conceptualisations are denoted

as “container schema”. When this schema is used to think of a container like a box or cup, it is not a metaphor or analogy but the use of a direct conception to understand a direct experience. However, if one uses the container schema to understand the cell or the atmosphere, it becomes the source domain of a metaphor or analogy. Then, one uses a direct conception to understand an abstract concept.

Rohrer analysed the neurobiological processing of the mapping process between a source and a target by carrying out fMRI and ERP investigations. His studies (Rohrer, 2001, 2005) and Gallese and Lakoff’s (2005) findings provide evidence that understanding a phenomenon in an imaginative way activates the same neural structures as thinking about the source domain or physically experiencing the source domain. In other words, imagining a cell to be like a container activates the same neurons as thinking about containers or exploring the structure of containers such as cups or boxes.

Differences and commonalities between metaphors and analogies

In many science education publications, the term “analogy” is used in the same way as the term “metaphor” (Glynn, 2007). However, some authors distinguish between the two terms (Aubusson, Harrison, & Ritchie, 2006), others use them as synonyms (Ritchie, et al., 2006) and some authors use the term “metaphor” to describe the same type of explanation of scientific issues often described by analogies (Gropengießer, 2007). Some authors describe analogies as an explicit correspondence of the structure of two domains, while metaphors compare the features that match in two domains implicitly (Duit, 1991).

A very common distinction is that in a metaphor, A is B (i.e., Immune Defence Is War) and in an analogy, A is *like* B (i.e., An Atom Is Like The Solar System). Another distinction is that the comparisons in a metaphor are implicit, whereas in an analogy, comparisons are explicit and often planned (Aubusson, et al., 2006). A more content specific finding of a

literature review shows that often, the term “analogy” is used to describe the teaching and learning of a specific concept, while the term “metaphor” is used to describe students’ and teachers’ perspectives of teaching and learning.

Based on their findings, Lakoff and Johnson (1980) define a metaphor as a statement that characterises one thing in terms of another. This definition encompasses metaphors as well as analogies and similarities. Therefore the term metaphor can be applied to all comparisons that construct a similarity between two objects or phenomena. The term analogy often is used when the comparison explicitly highlights similarities and differences between two objects (Aubusson et al, 2006). Thus, all analogies are metaphors but not all metaphors are extended into analogies.

An additional aspect we found while analysing the literature on metaphors and analogies is that often comparisons which work both ways (“An Atom Is Like The Solar System” and “A Solar System Is Like An Atom” both make sense) are called analogies (Gentner, 1989). Comparisons that work only in one way (“Immune Defence Is War” makes sense but “War Is Immune Defence” does not) are often termed as metaphors (i.e. Amin, 2009; Niebert & Gropengießer 2011).

Gentner, Bowdle, Wolff, and Boronat (2001) describe processes of mapping an analogy as structural alignment, inference projection, progressive abstraction, and representation. Furthermore, these authors explain that the processes of understanding a metaphor are the same as the processes of understanding an analogy.

A consequence of the findings of Gentner et al. and Lakoff and Johnson is that the distinction between metaphors and analogies is not theoretical but technical in nature and is based upon the number and quality of explicit mappings between the source and target. For the purpose of the argument developed in this article that understanding requires embodiment, we will adopt the position of Gentner et al. and Lakoff and Johnson of not differentiating

between analogy and metaphor. According to the experientialist's perspective in this article, we refer to conceptual metaphors (Lakoff & Johnson 1980) to analyse metaphors, analogies, and experiences on the same grain size. Conceptual metaphors categorise the metaphors and analogies employed in understanding a certain topic at the level of the used source and target domain as Target Is Source (e.g., a Cell Is a Container, Immune Defense Is War, etc.). Recent research has shown that while the variety of metaphors and analogies describing an aspect is nearly unlimited, the metaphors and analogies can be categorised into a limited number of conceptual metaphors (Schmitt, 2005).

Conceptual metaphors consist of a set of correspondences that can be factored into two types: ontological and epistemic (Lakoff, 1990). Ontological correspondences are correspondences between the entities in the source domain and the corresponding entities in the target domain. For example, the container is often used as a source for understanding the body in the target domain (for example, "uptake of food" or "bacteria pervade the skin"). Epistemic correspondences are correspondences between knowledge about the source domain and corresponding knowledge about the target domain. For example, the source domain container has a boundary that can be pervaded and an interior that can be filled with content. The target domain, one's body, can be filled with food, or the skin can be invaded by a bacteria and create a wound.

Experientialism, metaphors and analogies in science education research

As a theory of understanding, Lakoff and Johnson's theory of conceptual metaphors has served as a framework for the investigation of understanding in a variety of domains. In recent years, the theoretical approach of experientialism has been used not only to analyse the structure of scientific theories but also as an interpretational framework for understanding everyday conceptions of scientific topics.

When taking experientialism as a theory of understanding into account and adapting it to science education, there are two major demands for teaching science. The first is to enable students to develop direct, embodied conceptions: as direct conceptions require direct experience, a teacher should provide experience of the phenomenon to be taught to the students (i.e., via explorations or experiments). The second is to enable students to develop imaginative conceptions: metaphors and analogies help students to bridge the gap between their embodied conceptions and the phenomenon to be taught. This aspect seems to be appropriate for phenomena that are not able to be experienced directly.

A review of literature shows that there are studies in which metaphors and analogies are very fruitful in teaching scientific topics such as cell division (Riemeier & Gropengießer, 2008), seeing (Gropengießer, 1997), climate change (Niebert & Gropengießer, 2011), the concept of heat (Wiser & Amin, 2001), or the concepts of force and electricity (Reiner, et al., 2000). Concurrently the review shows that instructional analogies and metaphors are often not understood as intended or are not used as intended by the students for their own explanations (Harrison & Jong, 2005; Harrison & Treagust, 2006; Treagust, Harrison, & Venville, 1996).

Research question

With regard to the perspective of experientialism, we can assume that for scientific phenomena that are outside direct experience, we need to employ imaginative thinking via metaphors or analogies to base understanding on embodied conceptions. As shown above, some studies foster this assumption. Nevertheless, there are studies that show that some metaphors and analogies are often not understood or adopted in the intended way. To analyse this ambivalence, we deal with the following research question:

- Why are some metaphors and analogies effective in engendering an understanding of certain scientific issues, whereas others are not effective?

Connected to this research question is our explanation of how the choice of a metaphor's or analogy's source domain is connected to the engendering of conceptual understanding. Essentially, the focus of the article is the analysis of the experience that students, teachers, and scientists use to understand specific scientific issues by employing certain conceptual metaphors (namely, metaphors or analogies). We want to find out if there is a connection between the selection of a certain source domain and its success in teaching a certain scientific topic using metaphors or analogies.

Research design and methodology

The primary focus of this study is the correspondence between the source domain of an instructional metaphor or analogy and students' experience. For the reanalysis, studies dealing with analogies and metaphors for teaching science were chosen that (a) were published with peer review and (b) have data that can be interpreted by metaphor analysis (i.e., interviews; classroom observations; teaching experiments, lessons, and transcripts; and written texts from students). The last premise limited the number of selectable studies because we needed sufficient parts of transcripts with published student interaction to analyse students' source domains for understanding. But this limitation had no effect as we found a saturation (Glaser & Strauss, 1967) of factors determining the effectiveness of metaphors and analogies in these 17 articles. Consequently, we analysed 199 conceptual metaphors (metaphors and analogies) published in 17 articles, summarised in Appendix 1.

This article summarises our findings on how conceptual metaphors are used in learning guided by a systematic metaphor analysis (Schmitt, 2005). We followed the example of Schmitt and identified a metaphor as a term or sequence that has or can have more than one meaning, having a literal meaning with origins in a domain of physical or social experience (source domain) and being capable of transfer to an abstract area – the target domain. Our

adaption of the systematic metaphor analysis is presented in the following five steps by way of an example of the analogy of the greenhouse effect in which the atmosphere is conceptualised as a container:

1. Extraction of all relevant metaphors from the material. In the first step, we identified all metaphors and analogies in the material dealing with the topic, the greenhouse effect, to be communicated to the students: *The greenhouse effect occurs in an atmosphere that is more transparent to solar radiation than to infrared radiation. The solar radiation coming in is balanced by thermal radiation leaving the top of the atmosphere.* (Houghton, 2002, p. 255)

2. Categorising the level of conceptual metaphors. In the next step, we arranged all metaphors and analogies with the same target and source domain to describe the imaginative principles behind the analogy or metaphor. We refer to this principle as a conceptual metaphor. To structure the findings, we categorised the conceptual metaphors as Target Is Source: *The Atmosphere Is a Container: in an atmosphere, radiation coming in, leaving the atmosphere, top of the atmosphere...*

Further conceptual metaphors are found in the example (e.g., *The Atmosphere Is a Greenhouse, The Atmosphere Is Transparent*) but are not analysed in this section.

3. Reconstruction of the complete metaphor. In the third step, the images transported via the metaphors and analogies are completed: often only parts of a conceptual metaphor communicated in the selection of a certain source domain are explicitly stated in the material. In this step, the logic behind the use of a specific experience as the source of understanding is reconstructed. Therefore, we use the logic behind a schema described by Johnson (1987) and Niebert (2010) to analyse the conceptual metaphor itself: *The Atmosphere Is a Container: The*

greenhouse-gas layer is the upper boundary; the earth is the lower boundary; air is the content; space is the outside

4. Interpretation of a metaphor's deficits and resources. The deficits and resources of a conceptual metaphor are reconstructed by analysing the highlighting and hiding of the metaphor or analogy: *The conceptual metaphor Atmosphere Is a Container, reifies the atmosphere as a container. The container-schema is used to describe the energy flow between an imaginative upper boundary of the atmosphere and space. [...] It highlights the energy flows between the atmosphere and the space but hides the lack of a clear boundary between the atmosphere and the space.*

5. Comparison and interpretation of students' and teachers' source domains. We analysed the student data presented in the selected studies with exactly the same methods that we used to analyse the metaphors and analogies used to teach a scientific concept. To interrelate the students' and teachers' metaphors and find similarities and differences, we compared both at the level of conceptual metaphors. Thus, we analysed, on the one hand, the instructional metaphor or analogy itself, and on the other hand, the students' response to it. To improve readability, the examples discussed in this article are edited transcripts.

In addition to the systematic metaphor analysis, we interpreted the scientific content (target domain) to be communicated by qualitative content analysis (Mayring, 2002) to comprise the scientific content to be taught. To ensure the quality and validity of the analysis, all data were gathered from peer-reviewed studies and reanalysed independently by two experienced researchers. Cases of doubt were interpreted on the basis of a consensual validation. To give a more solid foundation to our analysis of students' understanding of the

concept to be taught via a metaphor or analogy, we triangulated our interpretations with the results of published studies on students' conceptions of the concept to be taught (such as genetics, chemical equilibrium, cell division, etc.).

Results: Why some metaphors and analogies go wrong

Our results are presented in two sections. In the first section, we exemplarily analyse instructional metaphors and analogies that fail in their aim to communicate scientific knowledge. In the latter section, we analyse metaphorical and analogical learning environments that engender an adequate scientific understanding. The examples we have chosen from the peer-reviewed studies reflect the various aspects we found in the analysed 199 conceptual metaphors (metaphors and analogies) that foster or hinder conceptual understanding.

Equilibrium Is A Dance—When a Metaphor's Source Is Not Embodied

Harrison and de Jong (2005) observed three lessons in which the concept of chemical equilibrium was taught on the basis of analogies. Interviews with students after the lessons showed that many of the students a) still had conceptions that were not scientifically adequate, b) did not refer to the teacher's analogies in their explanations, and c) had problems transferring meaning from the analogies to equilibrium phenomena. What went wrong with these analogies? We will try to provide an answer by using a reanalysis guided by experientialism. The teacher introduced the principles of a chemical reaction and conditions of chemical equilibrium using a school-dance metaphor:

Table 1: The school-dance metaphor for chemical equilibrium

Target	Source
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Chemical reaction:	School dance: 500 boys and 500 girls are blindfolded in
reaction rate depends on collision rate	a hall. However, there is only room for 250 couples to
incomplete reaction	commit in a separate room that is only open to couples.
Conditions for chemical equilibrium:	Committing and breaking up is continuous, and the rate
	of committing is equal to the rate of breaking up;
Closed system:	The hall is sealed.

The metaphor Equilibrium Is A Dance presented in table 1 is very sophisticated: many aspects from the source domain can be mapped to the target domain. The metaphor is not only used to highlight chemical reactions but also includes several factors that influence reaction rate, concentration, temperature, and surface area. However, the sophistication makes it a very complex metaphor. The student has to gain a deep awareness of the metaphor to understand the construction of the school dance setting with the blindfolded students who sometimes appear and sometimes do not appear as couples, the building, the separation of couples, and the students being either in the dancehall or in the commitment room. The intelligence with which the metaphor is constructed reveals the problem—it is constructed and not embodied. Students do not have an embodied experience with the metaphor's source domain but need imaginative skills to understand it. The many factors that are mapped from the target domain back into the source, which require more and more details in the source, makes the metaphor too complex to be embodied. A classroom conversation that took place just after the introduction of the metaphor provides further evidence of the insufficiency of this metaphor. After introducing the metaphor, the teacher interacts with his students to describe the concept of a dynamic equilibrium:

Teacher: A plus B results in AB, but at exactly the same time, AB is breaking up, resulting in A plus B. Can that happen?

Student: It's a cycle.

Teacher: Can A and B combine to form AB, at the same time another AB is breaks up to form A plus B?

Student: But only in theory, right? It would not happen in real life.

The transcript reveals the student's difficulty in understanding the equilibrium situation. Even though the interaction took place just after the teacher's introduction of the school-dance analogy, the student does not refer to it. As argued above, this could be due to the complexity of the metaphor which might—under very constructed conditions—be possible to experience but is not experience-based or embodied at all. However, the classroom conversation shows more: the student and the teacher refer to different experiences to understand the equilibrium situation. In his metaphor, the teacher refers to the balance schema. Something is perceived as balanced when it is symmetrical, that is, when the same elements have identical weights on each side relative to an axis or when there is an identical distribution of weight and forces relative to an axis (Johnson, 1987, p. 81). The idea of a dynamic equilibrium composes a logic in which each change is followed by a counter-change. The student instead refers to the cycle schema (Johnson, 1987). This schema composes a logic in which an object starts at one point, proceeds through a series of events or places and ends where it began. Using this schema, the student focuses on the products of the reaction, namely, the continuous occurrence of either the educts (A+B) or the product (AB).

In a particular way, the teacher also uses a cycle schema when imagining the parallel occurrence of educts and products. However, while the student focuses on the occurrence of products and educts, and thus, on the matter, the teacher focuses on parallel contrariwise processes and their identical rate, which substantiates equilibrium. For the student, the parallel occurrence of educts and products is not imaginable and is just "theory".

An analysis of students' conceptions as reported in other studies (i.e., Van Driel, et al., 1998) show that it is very common for students to understand dynamic equilibrium as a cycle instead of a balance. One reason why students and teachers reason with different schemata might be that the balance schema is difficult to grasp: the experience of balance is so common that we don't conceptualise the appearance of balance in everyday life. Generally, we are only aware of balance when we lose balance and not when we gain balance. The principle of balance is based on a steep status quo with no changes because every change violates the balance. The principle of a dynamic equilibrium instead contains the idea of a continuous interchange of matter with steady rates. However, for the student, this continuous interchange is imagined as being circular, like the continuous occurrence of certain locations or objects commonly experienced when moving in a cycle or experiencing the recurrent occurrence of certain events such as night-day-cycles (Johnson 1987).

The teacher introduced the properties of chemical equilibrium with other analogies, such as *planning an air flight including route details*, to explain that many steps produce an overall effect as a property of the reaction mechanism and *being normal or insane* as a metaphor for physical equilibrium being similar to mental stability. These examples are possible to experience and are also imaginable, but they contain one problem—they are not common, and thus, not embodied experiences for the students (i.e., flying an aircraft, perceiving insanity as imbalance). To understand the sources of these analogies, the students have to employ imagination because they cannot refer to embodied conceptions.

The Gene Is A Code—When a source for understanding is ambiguous

The following section highlights a student's metaphorical reasoning in a biology class in which the concept of the gene was taught (Venville & Treagust, 1999). The teacher introduced the structure of genes with the popular metaphor DNA Is a Code. This metaphor is

very common in scientific textbooks: “All forms of life employ essentially the same genetic code.” (Campbell, et al., 2008, p. 9); “The dictionary of the genetic code” (Campbell, et al., 2008, p. 330), or “cells replicate their DNA [... and] decode the instructions represented in the DNA” (Alberts, et al., 2008, p. 25). In a survey, Venville and Treagust investigated students’ understanding of genes during a biology course. After the lesson, a student named Phillipa explained her understanding of the metaphor as follows:

Interviewer: Do you have any ideas about DNA being a code?

Phillipa: It’s a code because it gets mapped out somehow.

Interviewer: What gets mapped out?

Phillipa: The DNA, or the chromosomes or something like that. It has little numbers underneath and that’s the code.

Interviewer: The code, what for?

Phillipa: I’m not sure, for the DNA or something.

Phillipa describes DNA as having little numbers under it that decipher DNA or “something”. In her argumentation, Phillipa confuses the microscopic level and the symbolic level of the genetic code (which are usually letters, not numbers) that is used by biologists to represent the genetic code. For her, DNA does not encode something itself but contains information encoded by a series of numbers. Therefore, she refers to a container schema in which the DNA is an object that literally contains a code. Scientists conceptualise DNA as containing information, and thus, also refer to a container schema.

From an experientialist’s point of view, Phillipa takes the metaphor’s source literally and maps it onto the target domain. This mapping leads to a misunderstanding of the metaphor: while the teacher intended to communicate the metaphor DNA Is a Code, Phillipa

conceptualises DNA Has a Code. The difference in the understanding of the metaphors is ontological—in the first metaphor, genes are information, whereas in the latter metaphor, they contain information. Students also understood genes to be a code and reified the gene as a container containing the code in a study conducted by Tsui and Treagust (2007).

Why does this happen? The literal meaning of a code is a system of words, numbers, or symbols used to decipher secret messages. Unfortunately, Phillipa was not asked about her conceptions of a code, but her argumentation makes it obvious that she imagines it to be a series of numbers. Phillipa does not understand the teacher's idea that the gene itself consists of a sequence of bases coding information because her concept of a code is limited to the idea of numbers and not enlarged to encompass substances such as bases.

This phenomenon indicates a simple but important source of misunderstandings of metaphors: if the metaphor's source domain is understood differently than intended, the metaphor itself, and thus, the target domain will be understood differently. Terms from everyday life are often employed analogically as technical terms, and many words in science are used in an alternative way in everyday language (Treagust & Chittleborough, 2001). While often, a student makes sense of scientific terms by using the everyday interpretations of the words, the interpretation is not the one intended by the teacher or textbook writer. This phenomenon is due to the (missing) embodiment of the source: Concepts such as balances, circles or containers, as discussed above, are very basic and commonly experienced by students and scientists. Unlike these concepts, which can be experienced physically, the concept of a code lacks direct physical experience; it is a cognitive construct for describing a series of numbers, figures, and so on—it is imaginative and not embodied.

Force Is in Muscles—When a source omits the needed experience

The following example is special insofar that the interviewer provides not only a metaphor or analogy but also an “analogical experience” for the student. This means that the teacher not only talks about the source domain but also provides an experience for the students.

In a well-known study carried out by Brown and Clement (1989), a student named Mark considered the question of whether a table exerts an upward force on a book lying on the table. This question requires teaching the concept of passive forces, namely, that gravity is pulling down on the book. Because the book is not moving, the net force must be zero. This implicates an upward force exerted by the table.

Initially, Mark rejects the idea that the table exerts a force and states that the table “is just a barrier between the floor and the book”. This statement is not astonishing because many students believe that inanimate objects may serve as barriers that stop or redirect motion but not as agents of a force (Halloun & Hestenes, 1985). To provide an analogous experience for the student, the interviewer proposed the notions of (1) a hand pressing down on a spring and (2) a book lying on a spring. Mark believed that the spring would push up against his hand. However, he views the book on the spring and the hand on the spring as not being analogous:

Mark: The force being exerted on the spring by the book is only the mass of the book and the gravity. But the force of the hand is the muscle in your hand. [...] I wouldn't say that the spring is pushing up on the book. The spring itself doesn't initiate any movement.

Mark argues that by pushing down on the spring, he has to exert a force. For Mark, this force is caused by his muscles. He bases his argumentation of force on the experience of feeling the rising tension and thus the force of the spring when pushing it down. The forces

exerted by mass and gravity seem to be different for Mark: he believes that they exert a force on the book, but he rejects the analogous situation of the hand pushing down on the spring. For him, the concept of force is connected to the existence of muscles: Force Is in Muscle. A second experience Mark connects to his concept of force is the idea of movement. The spring exerts no force because it exerts no movement. This relates to an additional idea Mark holds: Force Is Movement. These conceptions result from Mark's experience: force is something you have—it is exerted by using muscles to do work such as moving objects.

To bridge the conceptual gap between the student's ideas of the hand on the spring and the book on the spring, the interviewer introduced the example of a hand pressing down on a book on a spring. Mark said that the spring would push up against the book in this case. Now that Mark believed that the spring exerts an upward force on the book, the interviewer attempted to establish the concept of books lying on a flexible board instead of a spring:

Mark: I would not say that the board is pushing up against the books. The board is just a barrier between the books and the area underneath the board. This board might have some of the properties of the spring, depending on whether the board is flexible.

From a scientific perspective, force is not a quality of an object but a result of the interactions of two objects. Adapted to the example, a physicist would say that the table is exerting an upward force on the book, balancing the downward force of gravity. For Mark, it seems to be very difficult to reconstruct his conception of force: while he accepts that there can be forces without muscle power (i.e., those exerted by gravity, a spring or a flexible table), he still connects his concepts of force to movement because in his argumentation, only flexible tables can exert a force. Even if Mark comes to the correct conclusion about the forces exerted on the table, he bases his argumentation on the experience of the movements of

a flexible board. To understand the scientific perspective, Mark needs to develop a concept of a force that does not exert a movement but inhibits a movement, as is, for example, experienced when holding up books and preventing them from falling down.

This example shows that even if sources used to understand a concept are based on direct experience, and thus embodied, an adequate understanding is not guaranteed. Many authors stress the need for scientifically adequate analogies, meaning that many aspects from the source domain can be mapped onto the target domain. The example of Mark shows that additionally, the learning demand of the student needs to be understood and accounted for. If the learning demand is not taken in account while teaching with an embodied source domain, this source domain (i.e., movement) might be mapped successfully onto the target (i.e., force), but the intended target (passive forces) is missed because the embodied source domain did not aim at the target.

How metaphors and analogies can engender a conceptual understanding

In the sections above, we analysed, using experientialism, why some conceptual metaphors communicated via different metaphors and analogies do not help students to gain scientific understanding. In the next section, we will analyse examples in which metaphors and analogies were successful and led to scientific understanding.

Searching for a source for understanding dynamic equilibrium

In the following example, also taken from Harrison and De Jong's (2005) study, chemical equilibrium is introduced with the example of dissolving sugar in a teacup. In this example, the teacher focuses on discussing an experience he wants the students to use as a source for understanding the concept of chemical equilibrium in chemical reactions. Thus, this example constitutes the conceptual metaphor Dynamic Equilibrium Is Sugar in a Teacup:

Teacher: You put in five sugar lumps in the hot tea. What happens to the sugar if the tea becomes cold?

Student: It becomes lumpy at the bottom.

Teacher: The tea cools and sugar falls out. What we've got is a situation where for every one molecule that actually comes out of solution and forms a solid, another molecule can dissolve. [...] Imagine you can see the sugar on the bottom. I can sit and look at that and after two minutes nothing appears to be happening. But as a chemist you are well aware that for every molecule that solidifies, another one dissolves.

The source domain *sugar in a teacup* is used by the teacher to illustrate the dynamic aspects of equilibrium (target domain). When introducing the example, the teacher refers to the experience of tea saturated with sugar. The student uses his imagination to state that this will cause sugar to fall out when the tea cools. From a chemical perspective, the sugar dissolves because of the decreasing solubility of sugar with decreasing temperature. By explaining a scientific perspective with this example, the teacher provides a parallel between sedimentation and the dissolving of sugar-molecules. At the end of this example, the teacher points out the problem of the given metaphor—the dynamic properties of the equilibrium cannot be observed. The only part of the example that can be experienced is the occurrence of sugar sediment in the teacup. After being introduced to the metaphor, the students were asked to explain their observations while dissolving salt in water. One student gave the following explanation:

Student 2: Some of the salt molecules have dissolved into the water, but some stayed at the bottom because the water is saturated. It reached its maximum, so that is why the salt molecules are still sitting at the bottom.

The example shows that the student does not explain the dynamic nature of equilibrium. He neither uses the concept of dynamic equilibrium to explain his observations nor refers to the presented conceptual metaphor. Experientialism shows that both student and teacher are arguing on the basis of a process schema (Johnson, 1987). However, while for the teacher, the process (sedimentation and solving) is continuous and thus an ongoing process, the student argues on the basis of a process that has come to an end. This argument indicates that the dynamic aspects of the example Sugar In a Teacup might not be understood or at least not mapped onto the new situation.

After introducing the teacher's metaphor Sugar in a Teacup, another student generates his own example derived from experience:

Student 3: Is that happening when you have got food in a pot and you' have got a lid on, and when some evaporates at the same time some is condensing and dropping down at the same time?

The student constructs his conceptions of the dynamic aspects of equilibrium with an observable phenomenon—the evaporation and condensation in a covered pot on a stove. The student generating this example is referring to a process-schema, in which the process is imagined to be continuous. This reveals that Student 3 uses the same experiential basis to understand the concept of a dynamic equilibrium as the teacher.

The latter example demonstrates the importance of student-generated analogies, which was pointed out by Zook, (1991), who argued that teacher-supplied analogies are easy for students to access but difficult to use for their own construction of knowledge; alternatively, student-generated analogies are easy for students to map but difficult to generate. From an experientialist perspective, this can be explained by the embodiment of the use of an analogy's source domains. While the teacher made reference not only to everyday life but also to professional scientific experience, he could have used more complex sources for understanding the concept. Embodied metaphors and analogies are based on an imaginative mapping of an embodied source to an abstract target. However, in the teacher's example, the students have to use imaginative skills to understand the source because the dynamic traits of the sedimentation and dissolving sugar cannot be observed. To bolster his understanding of dynamic equilibrium, a student refers to another source: an observable phenomenon acting as an embodied source domain.

Both examples are related to experiences of everyday life. The difference between the student's and the teacher's metaphorical understanding of dynamic equilibrium is that in the *Sugar In a Teacup* example the students have to use imagination to understand the source (solving/dissolving sugar) and use this imagining for a second imagining to understand the target (dynamic equilibrium of chemical reactions). In the student's example, imagination only has to be used to map the embodied source (evaporating/condensing water) onto the target (dynamic equilibrium of chemical reactions).

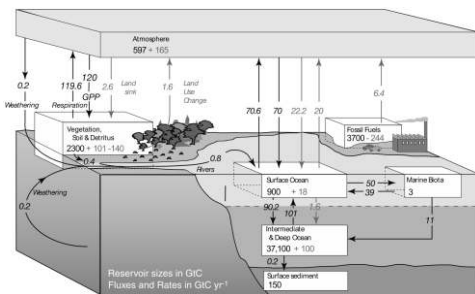
Understanding climate change with containers

Niebert analysed students' and scientists' conceptions of the global carbon cycle in climate change (Niebert & Gropengießer, 2010). Guided by an analysis of the embodied

conceptions, he described the thinking patterns guiding the conceptions of the carbon cycle (Figure 1).

Anthropogenic Imbalance

“Carbon cycles between the atmosphere, oceans and land biosphere. [...] These fluxes have become significantly different from zero. In [the] figure, the ‘natural’ fluxes [are indicated] in black and ‘anthropogenic’ fluxes in red [here indicated as grey]...”



(IPCC 2007, 501 f.)

Natural vs. Man-made CO₂

“Humans emit CO₂ through respiration. This CO₂ is captured by plants. It is a fact that the CO₂ emitted by burning has another structure than the CO₂ emitted by respiration. [...] The CO₂ from burning cannot be captured again by photosynthesis” (Dave, 18 yrs.).

Figure 1: Conceptions of the carbon cycle in global warming

Although on a content level, these conceptions are very different, scientists and students refer to the same schemata when thinking of the global carbon cycle—the container schema, which is adapted as a “container-flow schema”. This container-flow schema is used to conceptualise the atmosphere, ocean, and vegetation as containers enclosing carbon, which flows from one container to another (i.e., from fossil carbon to the atmosphere) via different routes (i.e., burning, respiration).

Scientists and students differ in their use of the container-flow schema. Scientists ascribe climate change to unbalanced flow rates of carbon into the atmosphere and thus an increasing amount of content (CO₂) in the atmosphere. Students instead attribute climate change to the existence of a different content (man-made vs. natural CO₂) in the atmosphere. On the basis

of this judgement, man-made CO₂ is attributed with devastating and detrimental properties, while an atmosphere without CO₂ or with only natural CO₂ is thought to be in an undisturbed, healthy state.

Niebert used this analysis for the development of learning environments. Students who adhered to the conception of natural vs. man-made CO₂ read a narrative adapted from “The Periodic System” by Primo Levi (1975). In this narrative, Levi describes the carbon cycle as the cycling of a virtual carbon particle. While reading the story, the students were requested to model the carbon cycle presented in the story in the container-flow model, which consists of boxes that represent the carbon pools and balls that represent the carbon particles. The students were asked to reflect the schema against the backdrop of the story and the model:

Dave: CO₂ emitted by burning has another structure than the CO₂ emitted by respiration. CO₂ from burning cannot be captured by photosynthesis.

After reading the story, Dave rejected the distinction between natural and man-made CO₂. To prove his conceptual development, he was asked to model his conceptions with boxes and balls:

Dave: My idea with the natural and the man-made CO₂ was humbug, because in the story, the carbon, which was burned, is captured again by photosynthesis. So the idea of a natural and a man-made CO₂ with different properties must be wrong. CO₂ is CO₂. [...] The cause of emitting CO₂ by burning is man-made [putting one ball from a box he named “fossil carbon” to “atmosphere”]. The emission of CO₂ by respiration is natural.

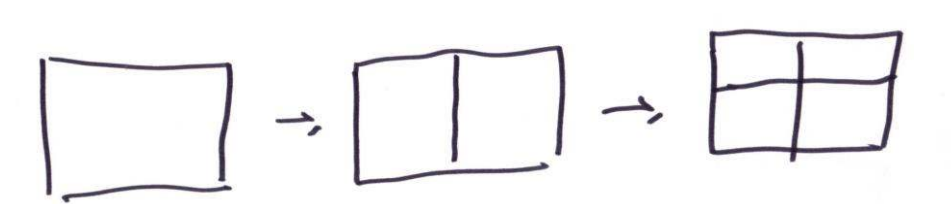
The reason for this conceptual development is the idea that “CO₂ is CO₂,” which is mediated by the story, in which both CO₂ emitted from fossil carbon and CO₂ emitted by

respiration is fixed again by photosynthesis. However, the distinction between natural vs. man-made played an important role in Dave's argumentation. After modelling the carbon cycle in the container-flow schema, he no longer assigned the natural vs. man-made distinction to the matter (CO₂ Is Man-Made) but rather to the cause of the carbon flow (Burning Is Man-Made).

Moving balls from one labelled glass box to another is a materialised representation of the embodied conceptions employed in understanding the carbon cycle. By working with this representation, students re-experience the inherent structure of the embodied conceptions and reflect on how they employ it for imaginative conceptions for understanding the carbon cycle (Niebert & Gropengießer 2009).

Understanding cell division by breaking a bar of chocolate

In a study by Riemeier and Gropengießer (2007), an onion with roots growing into a water-filled jar was shown to students who were 15 years old. Asked to explain what happened to the onion roots, one student drew her conception of cell division:



Required parameters are missing or incorrect.

Figure 2: A students' conception of cell division

The figure shows that the student adhered to the literal meaning of the term "division". She thought of division, and thus, duplication of cells exclusively. Thus, she accepted the idea that more cells suffice to accomplish the growth of onion roots. The students were seduced by a chain of false reasoning: (1) more pieces are obtained by division, (2) more pieces of root

cells result in more root, and (3) more root means growth. In contrast to the students' conception, the scientific concept of cell division involves the division of cells as splitting accompanied by growth of cells. Otherwise, no growth would occur.

On the basis of experientialism, Riemeier and Gropengießer (2007) explored the conceptual understanding of "division". Two different embodied meanings of "division" can be distinguished according to the outcomes of the process of splitting: division can be conceptualised as (a) more single parts or (b) parts that are smaller than the whole object. Thinking about growth solely in terms of division of cells follows a logic that holds that growth requires "becoming more," whereas "becoming smaller" sounds contradictory. The analysis of the embodied source of the concept of growth by cell division shows that the students' misunderstanding of cell division in the context of growth is traceable and to be expected on the basis of the scientific term "cell division."

At this point, Riemeier and Gropengießer (2007) offered a learning activity to the students: a bar of chocolate was shown, and the students were asked to break it and compare this process to cell division. In doing so, the students recognised that despite the increased number of chocolate pieces, the pieces were smaller than the whole bar of chocolate.

Student 1: But in case of a cell, it wouldn't yield anything; it would be the same size.

Student 2: The cell divides itself in the middle and grows thereupon.

Student 1 assumed that the cell would not divide in the sense of getting smaller but rather result in two cells of similar size, while student 2 pushed the idea somewhat further. Dividing a bar of chocolate helped to bring the schema of division to students' critical attention, and reflection about the various meanings of division could be advanced. Thereupon, they were able to recognise that cells have to divide and increase to a normal size. A representation of

the conceptual schema of division induced students' reflection and enlarged the students' embodied conceptions of division. By basing the conceptions of division on a broader basis with different embodied conceptions (dividing is becoming more, and dividing is becoming smaller), breaking a bar of chocolate fostered students' conceptual progression towards scientific understanding.

Discussion

In the preceding sections, we re-analysed conceptual metaphors (metaphors and analogies) used with instructional intentions. Our theory-guided analysis focused on the source domains that metaphors and analogies refer to in communicating a scientific concept. On the basis of this analysis, we were able to describe various aspects of why some metaphors and analogies are successful in engendering a conceptual understanding and others not. The analysis shows that experientialism can act as a fruitful framework for explaining students' understanding of science. In the following section, we will reflect on the role that experientialism can play in analysing students' conceptual development on scientific topics and discuss why some metaphors or analogies are fruitful and others not.

From a focus on everyday examples to embodiment

Many researchers stress the importance of students' familiarity with the analogy's or metaphor's source domain to understanding the concept to be taught (Adbo & Taber, 2009; Duit, 1991; Gabel & Samuel, 1986; Treagust, Harrison, & Venville, 1998). All of the analogies and metaphors analysed above use sources that refer to situations from everyday life. Nevertheless, some of them did not lead to a scientifically adequate conception. What went wrong? The analysis shows that referring to everyday life seems to be an important but insufficient constraint: the metaphors and analogies discussed in this paper (Dynamic

Equilibrium Is a School Dance and Dynamic Equilibrium Is like Sugar in a Teacup) are examples in which the source domain of the analogy refers to an everyday-life-setting. A school party and teacup with sugar are both situations that should be familiar to every student. However, it apparently takes more to construct a fruitful metaphor. Although these source domains refer to everyday life, neither setting was founded in students' real experience, and thus, was not embodied. The example of the school dance, with pairs coming together, meeting in a separate room and breaking up is imaginable—somehow. However, it is a very constructed setting that will rarely be experienced. The source domain *sugar in a teacup* on the other hand holds similar problems: the experience of witnessing sugar at the bottom of a teacup might be accessible for all students who put sugar in their tea. However, the dynamic aspects of the process, the continuous solving and dissolving of sugar are not visible and are, thus, inaccessible for direct experience. Therefore, this source domain is also not embodied.

This lack of experience poses a problem: According to experientialism, the task of a metaphor or analogy is to build a bridge between an experience-based source and an abstract target via imagination. However, in the cases discussed above, the source domains (solving/dissolving sugar, class party) were not embodied. Thus, in these cases, students need imaginative skills not only to build a bridge between the source and the target but also to understand the source domain.

This requirement applies similarly to very popular instructional metaphors and analogies such as the Eye Is a Camera, the Atom Is a Galaxy, the Cell Is a City, the Cell Is a Factory or the Electric Circuit Is a Water Cycle: When students have to use imaginative thinking to understand an imaginative thinking tool such as an analogy or metaphor, the analogy or metaphor may be understood differently than intended. It also poses a problem for the teacher: if a teacher chooses an analogy or a metaphor with instructional purposes, he or she chooses a source domain for the students' construction of the concept to be taught. However,

if the chosen source domain is not embodied, too complex and requires imagination to understand the source, the students alternatively draw on their own embodied conceptions to build up a new source domain to understand this alleged source of the instructional metaphor or analogy. Therefore, by providing an overly complex source domain, the teacher passes over his or her intention to control the students' selection of the source for understanding a scientific concept.

Everyday-life experience evokes ambiguous meanings

Metaphors such as *The Gene Is a Code*, for explaining genetic concepts, or *Growing by Division*, for explaining the growing of plants resulting from cell division, indicate another aspect of the experientialist perspective on learning: it is common knowledge in science education that terms used to describe scientific concepts in terms of everyday phenomena often pose a problem for students (i.e., Carey, 1992; Ioannides & Vosniadou, 2002). To solve this problem, it is often said that we should be careful and use, for example, different, unequivocal terms to describe scientific concepts. However, this perspective reflects the myth of objectivism, that words have fixed meanings that are incorporated in the words themselves. According to this perspective, we need words whose meanings are clear and precise and words that correspond with reality. However, the findings of constructivism, experientialism and neurobiology show that 1) there is no natural connection between reality and the words we use to describe it, and 2) language and thinking are strongly correlated: language makes use of concepts. Concepts are what words express. The terms we use to talk about a specific aspect of a concept describe our understanding of the concept. Thus, we cannot simply change words without changing meaning. With this in mind, it is important to recognise the different meanings that a term can have and reflect these different meanings. The example of understanding cell division by breaking a bar of chocolate shows that we can experience the

limitations that specific words and their underlying conceptions have in understanding a phenomenon. When people communicate with the same words, they do not automatically communicate the same conceptions. If they connect different experiences to different words, they incorporate different meanings of the word. In these cases, “understanding is only possible through the negotiation of meaning” (Lakoff & Johnson, 1980, p. 233).

Fruitful instruction requires research on students’ conceptions and their experiences

The example of Mark and his conceptual metaphor Force Is Movement shows that finding fruitful metaphors is a complex issue: while the well accepted constructivist approach points out the necessity of connecting learning environments to students’ prior conceptions, experientialism, operationalised in the analysed example of Force Is Movement, shows that fruitful learning is connected not only to prior conceptions but also to prior experience. In the example above, the student argued on the basis of his experience of exerting power by moving an object. However, the target to be understood consists of the concept of forces without movement (passive forces conceptualised as counterforces). Thus, the student would need to experience exerting force without movement, but the teacher does not address this requirement. Our analysis reveals that sometimes, an experience provided (by a metaphor or directly) misses its target because it does not refer to the intended aspects of the target. This simple omission has extensive consequences. If teachers want a conceptual metaphor or an experience provided with instructional purposes to be fruitful, they have to satisfy the students’ learning demand. Therefore, teachers have to analyse not only the student’s pre-instructional conception but also the experiential basis for the concept to be taught. The model of educational reconstruction (Duit, Gropengießer, & Kattmann, 2005) in combination with an analysis based on experientialism has served as a fruitful research design in studies with this purpose (e.g., Niebert & Gropengießer 2011; Riemeier & Gropengießer, 2008).

Experientialism in theoretical frameworks in science education

In the following section, we will place experientialism as a theory of understanding within other theoretical frameworks developed empirically in science education. As our study reanalysed conceptual metaphors (metaphors and analogies) with instructional intentions, we draw connections from experientialism to various approaches developed in the field of conceptual change research that likewise explores students' understanding of a scientific concept in relation to instruction.

Chi (2008) described understanding science on the basis of three primary ontological categories: matter, process and mental states. The ontological status of the initial and scientific conceptions determines the difficulty of learning: if the two conceptions are ontologically compatible (e.g., both are matter), learning is relatively easy. If the two conceptions are ontologically distinct, learning is more difficult (Chi, Slotta, & de Leeuw, 1994). What Chi identified as ontological misclassifications of concepts by students reflects an inadequate mapping of the science concept of a source on a target. More specifically, the ontological misclassifications reveal that students compare a familiar and an abstract domain in terms of surface similarity rather than in terms of a deeper relational structure. The above analysed examples of understanding the carbon cycle (natural/man-made matter rather than processes) or the structure of genes (genes having or being a code) show that experientialism reveals the difference in ontological classification between scientists and students described by Chi. Experientialism is different than the theory of Chi's ontological categories insofar that it provides basic approaches to explaining why some ontological categories are chosen (because of experience), and how these mismappings can be used to develop learning environments: The example of the carbon cycle shows that some students describe CO₂ as either man-made or natural (Niebert & Gropengießer, 2010), and thus, ascribe a certain

quality (natural vs. man-made) to the matter (CO₂). Working with a model of the schemata that students use to understand the carbon cycle helped them to shift their argumentation from matter to process: after explicating and reflecting the employed schemata, the students no longer identify CO₂ itself as man-made, but rather, identify the process of CO₂-emission, burning, as man-made.

From another theoretical perspective of conceptual change, Vosniadou, Vamavakoussi, and Skopeliti (2008) describe understanding of topic-specific content theories as being based on framework theories. The development of the framework theory encapsulates humans' intuitive knowledge of the physical world and makes it possible for them to function in it. While this early competence forms the necessary foundation for further learning, it may also hinder the acquisition of scientific knowledge. This hindrance occurs because scientific explanations of scientific phenomena often violate fundamental principles of everyday thinking. We assume that there are parallels between Lakoff's definition of source and target domains and Vosniadou's definitions of framework and content specific theories. As with described schemata, which act as source domains, framework theories are built early in infancy and consist of certain fundamental ontological and epistemological presuppositions. Content specific theories describe the internal structure of an abstract conceptual domain, such as the target domain (see table 2).

Table 2: Embodied frameworks used to understand scientific concepts

Framework	Scientific content
Counterforce schema/Blockage schema	Passive forces
Balance schema/Circle schema	Chemical equilibrium
Container schema	Structure of genes and DNA
Container schema	Carbon cycle

DiSessa's knowledge-in-pieces approach (diSessa, 1993) argues that knowledge is based on small knowledge structures called phenomenological primitives (p-prims). P-prims are small knowledge structures that conceptualise experience at a medium level. DiSessa argues through the use of evidence that these p-prims often play functional, albeit different, roles in the conceptual system and reasoning of both scientists and students. Comparing the theoretical approach of knowledge-in-pieces and the perspective of experientialism, we believe that there are similarities between what diSessa calls p-prims and what Lakoff and Johnson call conceptualised experiences such as schemata and basic level categories: the container schema, for example, is a conceptualised experience used by scientists and students to understand the concept of genes and the greenhouse effect, although it is used differently for each of these concepts. The same applies, for example, to the division schema that is used to understand the concept of cell division and vegetative growing.

In the above section, we connected experientialism as a theory of understanding to different approaches of science education research on conceptual change. Therefore, we conflated explanations dealing with students' conceptual understanding of a scientific phenomenon described in different theoretical approaches. Our attempt was to find a level of conflation that is appropriate to and fruitful for describing students' understanding of science in different domains. The analysis above indicates that the level of experience and embodied conceptions seems to be an appropriate grain size for a) relating different theoretical approaches to each other and b) explaining students' and scientists' understanding of a phenomenon.

How experientialism can help in the development of learning environments

In the sections above, we discussed the role of experientialism in the analysis of students' conceptions and scientific concepts and its position in different approaches of science education research. In this section, we outline the conclusions that experientialism offers for the design of learning environments. It should first be pointed out that—as constructivism—experientialism is an epistemology and not a theory of learning: experientialism provides explanations for how phenomena and concepts are understood (directly or imaginatively via metaphors or analogies). Furthermore, experientialism shows that successful metaphors and analogies have embodied sources. However, experientialism provides no direction on how these metaphors can be implemented in science classrooms, how affective aspects communicated with a metaphor might influence learning, or how a teacher should present a metaphor or analogy to his or her students. There are some models described in the literature of how to implement analogies or metaphors in science classrooms (e.g., Glynn, 2007; Harrison & Treagust, 2006), but these are based on methodological and not theoretical positions.

With these limitations in mind, some conclusions can be drawn regarding the design of learning environments: the model of the global carbon cycle, as presented in Figure 1, represents a scientific conception of the movement of carbon on earth. Every depiction of a mental model, i.e., the cell cycle, the principle of Le Châtelier, and postulates of quantum mechanics, falls into this category of representations. Many well-known figures, models, symbolic systems, analogies and scientific terms represent the scientific way of thinking. In their discussion of the implications of the conceptual metaphor perspective for mathematics education, Nuñez, Edwards, and Matos (1999) noted that the insistence on the rigorous, abstract characterisation of concepts omits the reality of their grounding in experiential intuitions. As shown here, this grounding in experiential intuitions applies equally to science

education: students and scientists ground their understanding of science not on abstract concepts but on embodied conceptions.

It is common knowledge in science education that learning environments based solely on abstract conceptions often pose a problem for students (Niebert, Riemeier, & Gropengießer, 2011). 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 obtained by scientific experience to the scientific phenomena that they are meant to represent.

Experientialism as a theory of conceptual metaphors views understanding as being based on experience and distinguishes between direct conceptions and imaginative conceptions. This categorisation can be used as a guide for developing experience-based learning environments:

- Enable experience in target domain. Science often uses methods such as experiments in which variables are controlled or instruments such as a microscope are used to experience previously imperceptible entities. While the core of our conceptual system is grounded in everyday experience, many scientific concepts are grounded in scientific inquiry. This grounding makes it difficult for students to understand scientific principles. In Brown and Clement's example of the discussion of the forces exerted on a table, the teacher asked the student to do the activity, that is, to form experiences, and reflect upon them. From the perspective of experientialism, this is probably the most effective teaching strategy: providing an experience and developing the scientific topic to be taught by reflecting this experience. For example, denoting the demanded experience by referring to it in a classroom conversation would have also sufficed as a second-hand experience. There are different ways of enabling experience, such as pictures taken through a microscope, a chromatogram, short movies of chemical reactions, and a view of a DNA sequencing gel.

These experiences, whether of first- or second-hand origin, prepare the basis for the development of conceptions through experiences.

- Refer to an embodied source domain. Conceptual metaphors are the basis for understanding science. As we always use those metaphors to understand abstract conceptions, we cannot understand science without them. The example of Dynamic Equilibrium Is a Dance shows the importance of choosing source domains that are experience-based and not simply possible to imagine. Experientialism views our conceptual system as being embodied. Thus, the examples and source domains to which metaphors or analogies refer need an embodied basis.
- Reflect an embodied source domain. Moving balls from one labelled box to another is a materialised model of a cognitive schema employed in understanding the carbon cycle. By working with this model, students re-experience the inherent structure of the schema and reflect on how they employ it in their effort to understand the phenomenon. Re-experiencing and reflecting on the hidden hand helps students to understand complex and abstract phenomena. To this end, students need to work with representations that throw light on the schema they employed in their endeavour to understand. Awareness of the schemata can be deliberately deployed to understand the scientific conception of the phenomena. A comparison of the different types of representations is needed as well. For example, students develop an adequate conception of the global carbon cycle by re-experiencing the concept of containers and transferring these conceptions to representations such as those presented in Figure 1. Beyond that, students are encouraged to critically think about the limits and possibilities of the representations used so far.
- Reflect the highlighting and hiding. Systematically extracting the schematic basis of a certain concept projected via metaphor or analogy suggests that many of the experiential notions identified will not be directly related to the domain of phenomena that the concept

addresses. The analysed example of the greenhouse effect reveals that the mapping-process requires reflection on the highlighting and hiding of a conceptual metaphor. If students recognise only surface similarities between the source and the target, they need to be aided in describing similarities and dissimilarities between the analogue and target concepts in constructing adequate conceptions. This approach – which is more a question of how to negotiate the meaning of a metaphor or analogy than of its structure – addresses the problem many authors describe when teaching with metaphors and analogies, recognising that an analogy can be a “friend or a foe” (for an overview see Harrison & Treagust, 2006). Introducing the conceptual metaphor helps to sharpen students’ conceptual understanding by providing the opportunity of thinking about their own embodied conceptions.

Conclusions

Many authors have discussed the role of metaphors and analogies in teaching science. The metaphor of the two-edged-sword nearly became a synonym for teaching strategies on the basis of imaginative thinking because the appropriate knowledge they generate is often accompanied by alternative conceptions. However, the results of our analysis show that understanding science is not just a matter of using metaphors or analogies in teaching science. It is a matter of how to use imaginative thinking and thus metaphors or analogies: Metaphors and analogies need to be embodied and they need to be reflected. The theory and the examples discussed in this article provide evidence of the following:

- abstract thought is largely based on metaphors and analogies,
- metaphors and analogies engendering a conceptual understanding are embodied, meaning grounded, in real experience, and
- imaginative thought is unavoidable and ubiquitous in understanding science.

We introduced the concept of conceptual metaphors to analyse metaphors, analogies and experience of the same grain size. An analysis of conceptual metaphors employed by students, scientists, and teachers in understanding a phenomenon helps to identify the imaginative structure of scientific theories and students' experiences. On the basis of the theory of experientialism, we were able to show that when communicating science, teachers must relate to students' embodied conceptions, and thus, their direct experience. All examples in our meta-analysis referred to source-domains from everyday life. However, despite this referral to everyday life, some of these imaginative thinking tools are ineffective at engendering an adequate conceptual understanding. On the basis of our analysis, we have shown that in these cases, students do not understand the source domain in the intended way. This supposition leads to a central finding: imaginative thinking tools, such as examples from everyday life, metaphors and analogies, have to be embodied to be effective in understanding science. We found that instructional metaphors and analogies that do not lead to the intended understanding of a scientific concept primarily do not refer to a source domain that students understand directly. If conceptual metaphors constructed by a teacher are too complex and are even possible to imagine but not embodied by the students, then they often miss their target.

The results of our analysis in this article indicate that integrating experientialism as a theory of understanding into science education can be fruitful for understanding and initiating conceptual development. The explanations of students' understanding generated by experientialism can be related to different theoretical approaches in science education and can explain why students develop and use certain conceptions. Furthermore, an analysis of the experiential background of everyday and scientific conceptions can provide a fruitful basis for the development of learning environments.

With our analysis, we would like to put forward experientialism as a helpful theory for explaining why students hold certain conceptions and what role experience plays in developing new conceptions. By locating experientialism in the theoretical frameworks of science education, we would like to invite the science education community to make use of and critically reflect on this theory in terms of existing and new data.

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