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Understanding Plant Nutrition—The Genesis of Students' Conceptions and the Implications for Teaching Photosynthesis

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Abstract: Plant nutrition and photosynthesis is one of the most difficult issues teachers are confronted with in science classes. This can be due to alternative conceptions students' hold, which are often profoundly contrary to their scientific counterparts. Consequently, fruitful learning environments should build on learners' alternative conceptions to initiate conceptual change towards a more scientific understanding. In this qualitative case study, high-school students' pre-instructional conceptions about plant nutrition were identified empirically. Afterwards these students were exposed to the van-Helmont experiment in order to create a cognitive conflict. The learning processes and signs of conceptual change were identified using Qualitative Content Analysis. The results show that the van-Helmont experiment does not trigger conceptual change but reinforces students' pre-instructional conceptions. Ultimately, a cognitive-linguistic analysis using Conceptual Metaphor Theory was conducted. Interestingly, underlying embodied conceptions and image schemas about human nutrition became evident. These thinking patterns were used metaphorically and, therefore, can be seen as the basis to understand plant nutrition. As a result, we propose a reverse approach of teaching photosynthesis and nutrition. Our *Dissimilation-Before-Assimilation* approach takes learners' alternative conceptions and underlying image schemas into account in order to promote a fruitful learning of the concepts of plant nutrition.

Keywords: students' conceptions; plant nutrition; photosynthesis; conceptual change; Conceptual Metaphor Theory

1. Introduction: Students' Conceptions about Plant Nutrition

To consider students' conceptions is one of the most important skills science teachers must have to create fruitful learning environments [1,2]. Within the last 30 years, there has been a lot of research done that aims to identify students' conceptions in a diverse range of biological topics like genetics [3] and ecology [4] and evolution [5]. Also in the field of plant nutrition and photosynthesis, students' conceptions are well described. A great amount of studies point out that assimilation processes are poorly understood within all ages. In a study conducted with 13-year-old students, 26% of them were convinced that plants receive all nutrients from their environment [6]. Furthermore, older students, too, face severe problems when it comes to explaining plant nutrition. In that context, Anderson, Sheldon and Dubay showed that 98% of the interviewed non-major college students answered that plants take their nutrition from the soil [7]. Even elementary and high school teachers struggle in elaborating on the origin of wood [8–10].

But why is it so difficult to understand plant nutrition and photosynthesis? Driver and her colleagues argue that students construe abstract phenomena like plant nutrition on the basis of everyday experiences [1]. Due to a large body of studies learners' fundamental conceptions about plant nutrition are well known [11–14]. However, up to this point, little research has been done that sets focus on the genesis of students' conceptions. In a constructivist sense, learning processes are based on existing cognitive structures. But where do these structures come from and in which way can this be used to teach photosynthesis more effectively? Based on these questions, this study not only aims to identify and change students' conceptions about plant nutrition but also is set up to analyze students' use of language. By that, it is possible to reconstruct students' learning pathways in order to draw conclusions about the genesis of these conceptions. This can be used to evolve effective learning environments.

2. Theoretical Background

Our understanding of learning is based on a moderate constructivism [15,16] and a revised conceptual change approach [17,18]. Thus, learners need to learn actively and self-directed using existing conceptions. Derived from everyday experiences, these conceptions can be beneficial or obstructive for learning [19,20]. Rather than using *conceptual change*, Kattmann argues for using the term *conceptual reconstruction* that theoretically frames learning processes in which learners develop their mental structures by forming new conceptions on the grounds of their own imagination and experience [21]. The term indicates that students need to *reconstruct* their pre-instructional conceptions.

For a deeper understanding of students' conceptions, we use the Conceptual Metaphor Theory [22,23]. This theory is based on the notion that by looking at language it becomes possible to draw conclusions about possible learning pathways. Consequently, this approach is a tool to analyze interview transcripts from a language point of view and helps to draw conclusions about the genesis of students' conceptions. The cognitive-linguistic theory is founded on the premise that every human being interacts with its environment in a physical and social way. These individual experiences are thought to form mental thinking patterns within a human's neuronal circuitry, for example so-called image schemas [24]. These mental structures are conceived directly and, thus, are called embodied conceptions [25]. For our research, it is important to state that embodied conceptions are used metaphorically to conceive abstract ideas such as plant nutrition [26]. This means that metaphors are not seen as a stylistic device but as the result of a neuronal process where embodied conceptions in the source domain are mapped onto specific target domains [27]. Consequently, embodied mental structures (image schemas) are used to grasp abstract conceptions. By applying image schemas metaphorically, it becomes possible to conceive and articulate abstract, imperceptible ideas. Thus, it becomes feasible to analyze learning pathways more effectively by taking these fundamental embodied conceptions and image schemas into consideration.

As an example, to understand plant nutrition students often conceptualize plant nutrition as a form of absorption and, thus, apply the *Container Schema* [23] and *Source-Path-Goal Schema* [28]. These embodied image schemas express the idea that organisms are containers with an outside-barrier-inside orientation. The transport of so-called nutrients and water from the soil into the plant container explains plant nutrition insufficiently. Besides mineral nutrition, scientific conceptions focus on the production of nutrients such as carbohydrates. As a consequence, further image schemas are used for conceptualization: *Transformation Schema* [29], matter can be conversed and turned into new structures with new characteristics and functions; *Component-Integral-Object Schema* [30], organisms consist of different substances conceived as building blocks, here especially organic substances such as carbohydrates, fats, and proteins play an important role; *Becoming-Bigger Schema* [31], the conception of growth is embodied and seen as an increase in size.

Teachers and researchers are aware of their students' alternative conceptions and the problems that are affiliated with them and, in a constructivist view, confront their students using learning environments to trigger conceptual reconstructions. However, basic image schemas are not considered. One of the techniques most often used is to create a conflict to show the limits of students' conceptions [32]. One of the most commonly used experiments addressing the learners' conception *plants grow by absorbing water and nutrients* is the van-Helmont experiment. The Belgian scientist planted a willow tree (2.5 kg) in a plant pot containing 90 kg of soil. During the next five years, van-Helmont looked after the tree by watering and providing sunlight. After that period, he measured the tree's and the soil's weight. Thus, he found out that the soil's mass slightly decreased to 89.9 kg whereas the tree gained about 82.5 kg. The intention is to create a conflict by showing that the willow's increase in mass cannot be explained by using the conception *plants grow by absorbing water and nutrients* due to the law of conservation of mass. But does this really work? Does conceptual change happen here?

Due to these theoretical considerations, our main research questions are:

(1) What conceptions do students have to conceive plant nutrition and photosynthesis? (identification of conceptions)
(2) What embodied conceptions and image schemas are fundamental for these conceptions to evolve? (genesis of conceptions)
(3) What influence do alternative conceptions towards the van-Helmont experiment and the learning process in general have? (potentials of conceptions)

3. Research Design and Methods

This research project is part of a larger study framed by the Model of Educational Reconstruction [33]. Its main intention is to identify and analyze students' as well as scientists' conceptions in order to derive sustainable learning environments. In this part of the study, we focused on the identification of students' conceptions and image schemas in the field of human diet and plant nutrition. To do this, we conducted a teaching experiment with 15-year-old German high school students (n = 12). The students interacted in triads while being exposed to the teaching experiment [34,35]. This lasted about 30 min and included a guided interview followed by the van Helmont experiment. The students have been chosen randomly and on a voluntary basis without regard to their gender. All personalized data were made anonymous. A researcher conducted the teaching experiment following a structured guideline. The teaching experiment was videotaped for Qualitative Content Analysis [36] and was divided into two parts:

(i) Interview about students' conceptions towards plant nutrition. This part was meant to elicit and identify students' concepts about plant nutrition (1). First, the interviewees were asked to complete a sketch regarding plant and human nutrition. In addition, questions about the absorption and production of substances as well as the function of nutrients were asked. Furthermore, the students were questioned to compare human and plant nutrition. By that, we hoped to identify embodied concepts that give hints to the genesis of the students' conceptions of plant nutrition (2);
(ii) Group discussion about the outcome of the van-Helmont experiment. In this part of the teaching experiment, the triads were exposed to the van-Helmont experiment. They were asked to describe and explain the results of the experiment. During the second part, the researcher merely guided the discussion. This part was meant to give information about the influence of different students' conceptions on the learning efficacy in case of a cognitive conflict (3). Furthermore, the discussions provided the basis to analyze students' learning pathways.

We used Qualitative Content Analysis to identify the conceptions and underlying image schemas students used in each part of the teaching experiment [36,37]. For reliability, coding and interpretation of students' statements were analyzed by two researchers working independently. The findings of both were then aligned if necessary. As a result, we were able to derive a category system representing the students' conceptions about plant nutrition. Besides the identification of conceptions, statements were also interpreted in the context of Lakoff and Johnson's Conceptual Metaphor Theory. The identified conceptions were analyzed and according to their linguistic and semantic structure assigned to specific image schemas. By that it was possible to create concept maps showing the conceptions and assigned image schemas students held before and during the van-Helmont experiment. Thus, it was possible to reconstruct learning pathways by linking identified conceptions according to the conceptual changes the students made [38].

4. Results

4.1. Learners Understand Plant Nutrition Predominantly as Absorption of Matter

According to our research question (1), we focused on the identification of pre-instructional conceptions. In consistence with a broad body of research (e.g., [11,12]), our results confirm the idea that students often hold non-scientific conceptions about plant nutrition. For an overview about the most relevant concepts we identified see Table 1. Interestingly, most of these identified concepts join the idea that plant nutrition is understood as absorption of matter from the environment. Tim (15 years), for example, states that *"plants take nutrients and water from the soil to grow, they consume them"* (conception *plants grow by absorbing nutrients and water*). Most of the interviewed students (n = 11) held similar conceptions and claimed that plants feed exclusively on nutrients from the soil. In most cases (n = 8) the terms *nutrients* and *minerals* were used synonymously. The finding shows that students reduce nutrition to the absorption of water and minerals from the environment. Only a few students (n = 3) figured the importance of glucose production to be essential for plant nutrition (conception *plants produce nutrients*). One student was able to link carbohydrate synthesis with plant growth (conception *plant growth is based on nutrient production*).

Table 1. Most relevant pre-instructional conceptions held by the interviewed students in the first part of the teaching experiment (n = 12).

Identified Conception	Number of Students	Underlying Image Schema	Anchor Example
plants grow due to enlargement	12	Becoming-Bigger Schema	*"Plants grow because their roots become bigger."*
plants grow due to cell division	6	Becoming-Bigger Schema	*"Cell division makes a tree to build up more tissue and as a result it starts growing."*
plants grow by absorbing water and nutrients	11	Container Schema Source-Path-Goal Schema	*"I guess a plant mostly needs water and those nutrients from the soil as food. Then it is able to grow."*
plants absorb carbon dioxide	5	Source-Path-Goal Schema	*"A tree is able to breath in carbon dioxide from the air."*
plants converse carbon dioxide into oxygen	2	Container Schema Transformation Schema	*"Plants take in carbon dioxide and release oxygen. This is essential for humans."*
plants produce nutrients	3	Transformation Schema Component-Integral-Object Schema	*"Plants feed on glucose. They produce this themselves by photosynthesis."*
plant growth is based on nutrient production	1	Transformation Schema Component-Integral-Object Schema	*"Plants produce food on their own. They use glucose to grow."*

4.2. When Talking about Plant Nutrition, Learners Often Refer to Their Own Diet

As our data shows, students referred to plant nutrition in terms of the human diet. Conceptions like "*plants eat and drink like humans but in a different way*" (Tim, 15) or "*plants are able to grow by consuming food*" (Antonia, 15) were found throughout all interviews. Obviously, experiences about the way humans acquire food play an important role when it comes to plant nutrition. It seems that students transfer this experiential knowledge to the topic of autotrophic nutrition. Driver points out that students use analogies in order to conceive abstract biological phenomena like plant nutrition [1]. This, however, does not explain where these conceptions come from. According to Lakoff and Johnson, it seems that in this case alternative conceptions have their origin in embodied experience about their own human body. First, the human body is perceived and by that conceived with the help of the *Container Schema* [39,40]. Second, this image schema is used to understand human nutrition simply as food consumption. The underlying image schema to conceive the process itself is the Source-Path-Goal schema. It describes the motion of a trajectory (food) which is relocated from a starting point (source: outside the container "*human body*") to an intended target (goal: inside the container "*human body*"). Third, these embodied schemas about human nutrition are metaphorically transferred onto the unobservable biological phenomenon plant nutrition. Thus, alternative conceptions are likely to derive from image schemas linked with the human diet.

4.3. Alternative Conceptions Can Be Fostered by the Van-Helmont Experiment

The identified conceptions were subsumed into different frames [37]. In correlation with their underlying image schemas it was possible to create a conceptual map showing the students learning steps during the teaching experiment (Figure 1). As the figure shows, the identified conceptions were assigned to three different frames: conceptions belonging to the frame *Growth due to Enlargement* were found among all students ($n = 12$). This approach, however, does not explain why the tree's mass has increased. They are based on the *Becoming-Bigger Schema*. Conceptions providing a true explanation belonged to the frames *Nutrition due to Absorption* and *Nutrition due to Nutrient Production*. The explanation of the tree's mass increase, however, was predominantly given with alternative conceptions. Most students concluded the absorption of nutrients ($n = 11$) (also called minerals; $n = 8$), the water provided during the experiment ($n = 11$) and the presence of the "substance light" ($n = 4$) caused the tree's growth. By applying conceptions of the frame *Nutrition due to Absorption*, these students were able to explain the van-Helmont experiment without any difficulty. Only few students tried to look for alternative solutions because they assumed that the absorption of water and minerals would be insufficient. From a scientific point of view, absorption of minerals and water is a small part of plant. The greater part is due to the production of organic substances.

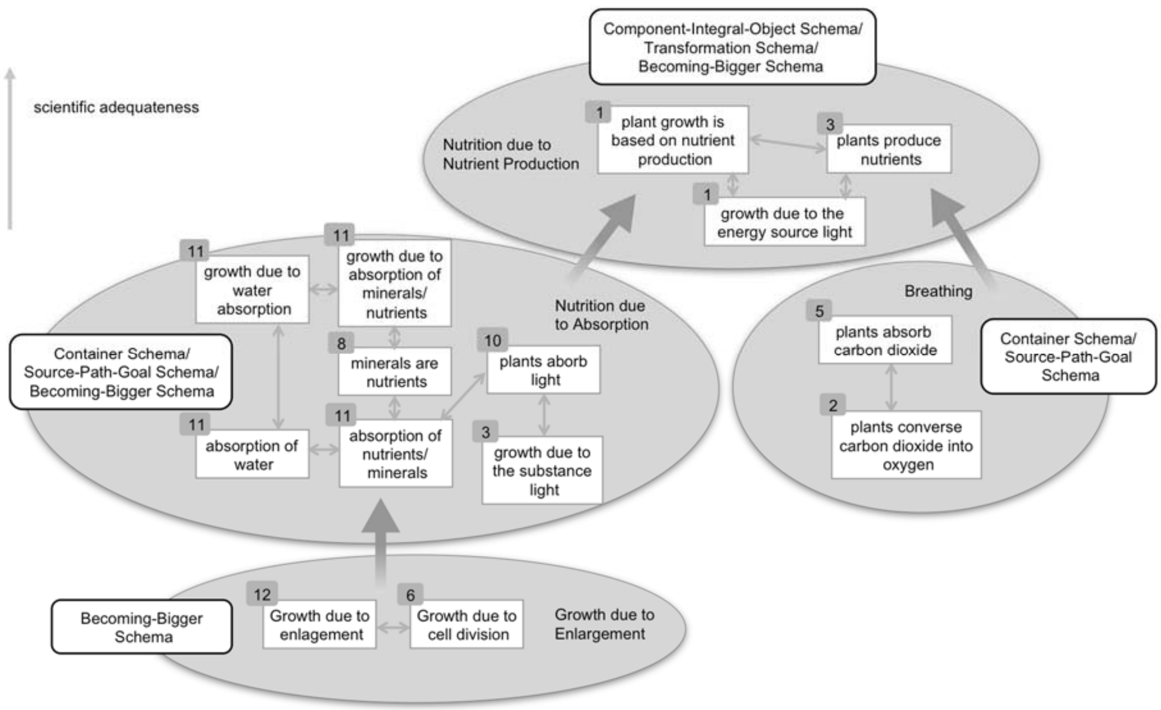

Figure 1. Identified conceptions, frames and image schemas for teaching photosynthesis. Learning pathways are performed according to arrows ($n = 12$). Numbers in boxes are the absolute numbers of the expressed conception; circles include conceptions based on the same frames and image schemas.

Only a few students (n = 5) explained plant growth using conceptions of the frame *Nutrition due to Nutrient Production*. In this case the students held the conception that plants additionally absorb carbon dioxide. However, this was sometimes not due to nutrition needs but for conversion to oxygen (n = 2)—a phenomenon called "inverse respiration" [12]. Here carbon dioxide absorption is related to breathing instead of photosynthesis. Only three of the students argued the plant's carbon dioxide absorption as the precondition for glucose production. One single student noticed that plants are composed of organic substances and continued that the production of these substances is the precondition for plant growth. This conception is based on the *Component-Integral-Object Schema* and the *Transformation Schema*.

As a result, our data shows that the van-Helmont experiment does not elicit a cognitive conflict and, therefore, does not trigger conceptual changes towards a better scientific understanding. Conceptions that are part of the frame *Nutrition due to Nutrient Production* are not fostered. Rather, the van Helmont experiment reinforces students' alternative conceptions in the frame *Nutrition due to Absorption* by providing a plausible explanation for the plant's mass increase.

5. Discussion and Conclusions

5.1. Genesis of Alternative Conceptions

Due to these findings, we can state that students often hold non-scientific conceptions about plant nutrition (I). These conceptions derive from our embodied experience about the human diet as a food-taking process (II). Thus, they are based on the *Container Schema* and the *Source-Path-Goal Schema*. This leads to the observed phenomenon that plant nutrition is also conceptualized as a food-taking process. As a consequence, the van-Helmont experiment inevitably does not trigger learning processes (III) [41]. Subsequently, students' concepts are not changed but reinforced because they are proven appropriate. But how can we deal with the problem of teaching plant nutrition? We assume to teach photosynthesis from a different perspective.

The embodied conceptions students have about nutrition cannot be erased or changed. However, they have to be used as learning potentials [21,42]. The challenge is both: to change the learner's perspective that plants are thought as food-taking—in a way heterotrophic organisms—to see them as food-producing, autotrophic organisms and to take embodied conceptions into account.

5.2. Using Alternative Conceptions and Image Schemas for Conceptual Change

International curricula like in the US, Great Britain, or Germany suggest structuring the topic of plant nutrition in the following way: *Assimilation-before-Dissimilation*. In this context, assimilation is understood as the process of providing essential nutrients. Heterotrophic organisms realize this by digestion processes. Autotrophic organisms produce their own nutrients. Furthermore, the term dissimilation is defined as the usage of high-energy nutrients for energetic and constructive reasons. This leads, for example, to the topics of growth, cell division, and cellular respiration.

The curricular approach first introduces the process of photosynthesis to the students to convey the biological concept of producing organic matter (assimilation). Second, it points out the importance of the produced substances like glucose and starch for, for example, cellular respiration (dissimilation). In conclusion, photosynthesis as a necessary assimilation process is preliminary for cellular respiration, a proceeding dissimilation process. We claim that the described *Assimilation-before-Dissimilation* structure is not fruitful to elicit conceptual reconstruction. Neither does this lesson plan take learners' mental frameworks and embodied knowledge into account, nor does it effectively link human and plant nutrition by showing important similarities and differences [43]. When it comes to plant nutrition, a change in thinking must take place: instead of conceiving nutrition as a process of food taking, the concept of food production has to be constructed.

Seen from a learner's perspective, plant nutrition has to be thought from embodied conceptions about the human diet. Thus, the identified conceptions, frames, and underlying image schemas are to be seen as learning potentials. Therefore, we suggest reversing the *Assimilation-before-Dissimilation* structure to a *Dissimilation-before-Assimilation* approach.

(I) Humans and plants alike need the same types of substances to stay alive. In a first step, it has to be elaborated on the usage of nutrients for energetic (cellular respiration) and constructive metabolism (growth, etc.). Nutrients are seen explicitly as high-energy substances such as carbohydrates, fats, and proteins. Questions like "*What do humans and plants need in order to grow?*" have to be part of a constructive teaching unit (see Figure 2). Thereby, embodied cognition about human nutrition is mapped onto plant nutrition. As a consequence, students are able to discover that plants and humans are similar by using the same low-energetic substances like water, minerals, and high-energy nutrients to stay alive (similarity: usage of nutrients). Here the comparison of plants and humans points out that both are conceptualized as objects that consist of different types of substances (*Component-Integral-Object Schema*). An increase in numbers of these substances automatically leads to growth (*Becoming-Bigger Schema*). Subsequently, they are experienced as living organisms of the same structure (*dissimilation aspect*). For means of reduction, vitamins and fibers needed by heterotrophic organisms were left aside.

(II) After addressing dissimilation processes by showing the *similarities* between humans' and plants' usage of nutrition, the inevitable question about the acquisition of these fundamental substances and, thereby, the *differences* between human and plant nutrition can be derived—"*Where does the organism get water, minerals and nutrients from?*" Talking about human nutrition (source domain), learners' know that they have to consume necessary substances (*Container Schema*, *Source-Path-Goal Schema*). Because the only source that consists of high-energy nutrients comes with other (living) organisms, humans are called heterotrophic—obtaining their food by consuming other organisms. As far as plant nutrition is concerned (target domain), it is essential to point out that plants need to absorb minerals, water, and carbon dioxide (*Container Schema*, *Source-Path-Goal Schema*) to produce high-energy nutrients (frame *Nutrition due to Nutrient Production*). These nutrients are the building units used for plant growth (*Transformation Schema*, *Component-Integral-Object Schema*). For many students it remains unclear that humans as well as plants actually consist of the same types of substances leading to the genesis of alternative conceptions such as *absorption of nutrients from the soil*. The learning potential can be seen in pointing out the similarities both types of organisms have regarding their kind of nutrition: Plants need the same nutrients, but produce them themselves. They both need to absorb minerals and water (frame *Nutrition due to Absorption*). In this way, the topic of plant nutrition can be addressed by using embodied conceptions based on human nutrition.

Steps	Teaching Objectives		Teaching Structure
I step	What substances do **humans** need to stay alive?	What substances do **plants** need to stay alive?	Change in thinking: Pointing out **similarities** of human and plant nutrition
	▸ carbohydrates, fats, proteins, water and minerals		
II step	Where do **humans** get these substances from?	Where do **plants** get these substances from?	Change in thinking: Pointing out **differences** of human and plant nutrition
	▸ eating and drinking (heterotrophic)	▸ water and minerals from soil ▸ nutrients from photosynthesis (autotrophic)	

Figure 2. Proposed teaching approach about human and plant nutrition to point out basic similarities and differences.

In the second part of the teaching unit, it is now possible to confront students with their own conceptions using the van-Helmont experiment. The preconditions to create a conceptual conflict are provided [32]. In this particular context, water and minerals do not suffice anymore to explain the plant's growth. Consequently, there has to be a different way to acquire high-energy nutrients. Here the *differences* between human and plant nutrition have to be pointed out. Whereas humans are heterotrophic by consuming other organisms, the idea of plants as food producers can be introduced. After the teaching unit, plants should be seen as food-taking organisms as far as water and mineral consumption is concerned and, more of importance, food-producing organisms in regard to high-energy nutrients (see Figure 2).

By pointing out similarities and differences of human and plant nutrition, a different approach in teaching has been suggested in this paper. Our findings indicate that teaching *dissimilation* processes *before assimilation* processes makes it easier for learners to reconstruct sustainable knowledge based on embodied knowledge. This new approach may function as a door opener when it comes to teaching plant nutrition. First results, where students (N = 16) were confronted with this alternative approach, seem very promising and indicate that conceptual reconstruction towards a more accurate scientific understanding takes place. However, changing learners' conceptions is not only about cognitive variables. One has to take social and emotional parameters into account. Therefore, conceptual change does not merely happen on the basis of a singular intervention [44]. Nevertheless, photosynthesis is a recurrent topic in science education. The learning pathways shown offer the opportunity to capture students with their individual learning stages. This makes it possible to create learning-friendly environments based on relevant frames and image schemas to trigger gradual and continuous learning processes. Consequently, further studies about the efficacy and sustainability of the *Dissimilation-before-Assimilation* approach have to be done surveying long-term effects and focusing on the degree of understanding.

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