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LEARNING

Promoting Conceptual Coherence Within Context-Based Biology Education

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ABSTRACT: In secondary science education, the learning and teaching of coherent conceptual understanding are often problematic. Context-based education has been proposed as a partial solution to this problem. This study aims to gain insight into the development of conceptual coherence and how context-embedded learning-teaching activities (LT) can promote this. We describe a case study in which a context-based lesson sequence about protein-rich food production was designed and conducted in a 10th-grade biology class. The conceptual framework consisted of transformations of forms of energy and matter in photosynthesis, cellular respiration, and biosynthesis. All relevant concepts and their interconnections (propositions) were captured in a reference concept map. A research scenario was used to evaluate whether the lesson sequence was conducted as intended. Learning outcomes were determined by analyzing written products on the occurrence of propositions from the reference concept map. Additional interviews provided insight into the development of conceptual coherence in relation to three context-embedded LT activities: using graphic visualizations, writing, and concept mapping. The results indicated that students improved in mentioning propositions from the reference concept map. Propositions relating metabolic processes and including forms of energy were still difficult. Finally, successful elements of the three LT activities are considered. © 2015 Wiley Periodicals, Inc. *Sci Ed* **99:**958–985, 2015

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INTRODUCTION

Research on learning and teaching natural science has shown that students' conceptual knowledge at all educational levels is often incoherent (e.g., DiSessa, Gillespie, & Esterly, 2004; Wandersee, Mintzes, & Novak, 1994). This lack of coherence is reflected by students' inability and inconsistency to retrieve and connect concepts: for example, students often have difficulty explaining and predicting natural phenomena and events. Moreover, students have difficulties transferring concepts to other situations than those in which they were learned (Bransford, Brown, & Cocking, 2000b). Because traditional teaching and learning approaches are often inappropriate in terms of helping students to assimilate coherent frameworks of concepts, an international trend toward context-based education has developed in science education (e.g., Gilbert, 2006).

Context-based approaches generally aim to improve students' engagement by situating science learning in real-world contexts (King & Ritchie, 2012). This framing helps students to appreciate the role science plays in their own lives and in society. Because various concepts come together within a context and reappear in other contexts, they are assumed to provide a basis for the development of coherent mental maps of the relationships between them (Gilbert, 2006). In this paper, we refer to the term "conceptual coherence" as the ability of a person's cognitive network to establish meaningful connections between concepts.

Until now, there has been limited empirical evidence proving that context-based education has a significant impact on the development of students' conceptual coherence (Bennett, Lubben, & Hogarth, 2007). Tsai (2000) found that a science–technology–society instructional approach, similar to a context-based approach, improved the extent, richness, and connectivity of students' cognitive structures compared with traditional teaching. Barker and Millar (2000) found in a longitudinal study on the Salters Advanced Chemistry course that a gradual introduction and revisiting of chemical ideas in different contexts appeared to have a significantly positive impact on the learning outcomes of a high proportion of students. Although these findings indicate that context-based courses can facilitate the development of students' conceptual coherence, the underlying mechanisms that describe how this development proceeds still need to be unraveled (Gilbert, Bulte, & Pilot, 2011; Pilot & Bulte, 2006). Therefore, identifying the principles underlying learning-teaching (LT) activities that foster the development of students' conceptual coherence is regarded as one of the major challenges in research on context-based science education.

In response to this challenge, we have adopted a design research approach (McKenney & Reeves, 2012; Van den Akker, Gravemeijer, McKenney, & Nieveen, 2006). In this paper, we describe a case study that focuses on the design and evaluation of a context-based lesson sequence. We pay specific attention to a two-step evaluation procedure, which provides profound insight into the teaching and learning processes. First, we evaluate the lesson sequence based on its practicability and determine the extent to which the lesson sequence is conducted as intended. The methodological approach is built on a previous study within our research project in which we described how a research scenario was used to compare the intentions of the design with the way in which it was enacted in the classroom (Ummels, Kamp, de Kroon, & Boersma, 2015). Second, we evaluate the lesson sequence based on its effectiveness. This evaluation is built on another study within our research project in which we showed that determining changes in how students mentioned concepts and their interconnections (propositions) from a reference concept map during a lesson sequence gives information about students' development of conceptual coherence (Ummels et al., 2013). We thus determined to what extent students' conceptual coherence has developed.

The learning goals of the lesson sequence are aimed at a conceptual framework in the domain of biology that is complex and difficult to learn and teach: transformations of forms of energy and carbon-substances in photosynthesis, cellular respiration, and biosynthesis (Amir & Tamir, 1990; Brown & Schwartz, 2009; Cañal, 1999; Lin & Hu, 2003; Mohan, Chen, & Anderson, 2009). This conceptual framework is embedded in contexts that are related to the social and scientific debate on the impact of protein-rich food production on the environment (McMichael, Powles, Butler, & Uauy, 2007). A context is defined as a representation of "an authentic community of practice within society" wherein students, supported by the teacher, work collaboratively on relevant tasks in a problem-centered way for a sustained period (Gilbert et al., 2011). During these tasks they are expected to deal with biological concepts and to establish relationships between these concepts. Our aim is to explore how students' conceptual coherence develops to contribute to optimizing context-based science lesson sequences in general. Such information will be valuable for educational researchers who examine how context-based lesson sequences work in practice, educational designers of similar context-based lesson sequences in similar settings, and teachers who conduct these lesson sequences. Consequently, we address the following two research questions:

1. How does conceptual coherence develop for students during a context-based lesson sequence?
2. How do context-embedded LT activities influence the development of conceptual coherence?

THEORETICAL FRAMEWORK

Conceptual Learning

This research is built on the theory that concepts are fundamental units of knowledge and that learners do not store these concepts as isolated bits of information but form connections between concepts (Ausubel, 1968). Conceptual learning occurs when a new concept is assimilated actively and meaningfully in someone's cognitive structure. This is also one of the basic assumptions of constructivist approaches on learning (Ogborn, 1997). This theory implies that a new concept is connected to one or more relevant "existing" concepts. This process proceeds when more elaborate connections are established between two or more concepts (Mintzes, Wandersee, & Novak, 2005). So, the more connections (or cognitive pathways) established between concepts, the greater the chance of retrieving these concepts. Studies on expert learning showed that an easy retrieval of concepts is supported by a systematic or hierarchical organization of concepts in cognition because memory easily "travels down" these well-worn pathways (Fisher, 2001). Moreover, a more coherent organization of conceptual knowledge enables experts to represent and solve new problems more successfully than novice learners (Bransford et al., 2000a). One characteristic of this coherent conceptual organization is the presence of inclusive or core concepts that structure other, often more descriptive, concepts.

One way to represent the (intended) conceptual relationships within a learner's cognitive structure is to make use of concept maps (Novak & Cañas, 2008). A concept map is a graph consisting of concepts connected by labeled lines. Two of these connected concepts within a concept map are known as a proposition. Therefore a proposition can be regarded as the smallest unit of coherent conceptual knowledge (Mintzes et al., 2005).

Context-Based Biology Education

There are many variations in the definition of context-based approaches in science education (King & Ritchie, 2012). Here, we focus on a specific form of context-based education in the domain of biology that is currently a focus of Dutch educational reform: the concept-context approach (Boersma et al., 2007). This approach is rooted in cultural historical activity theory (Vygotsky, 1987). In this approach, contexts are defined as representations of existing scientific, professional, or real-life practices. To engage students in contexts, suitable social practices need to be transformed for classroom use in such a way that students experience them as relevant. This transformation happens when students recognize the perspective of participants of such social practices or imagine themselves as these participants. From this perspective, they perform goal-oriented activities in which they enter into a *cognitive apprenticeship* with the teacher. The teacher demonstrates how a context and its activities might be interpreted, being aware of individual students' *zones of proximal development*. Finally, relevant concepts are summarized and their meaning in the given context considered. The different, often subtle, meanings of a concept in two or more contexts can be compared. This comparison facilitates the process of recontextualization, which means that a concept is transferred from one context to another (Van Oers, 1998).

Learning Teaching Activities

This research focuses on conceptual learning that takes place during LT activities that are embedded in contexts. We define LT activities as delimited educational units that consist of an introduction phase, an action phase, and reflection phase in which students and teacher perform activities. Literature provides evidence that several LT activities (or elements that can be integrated in LT activities) are associated with conceptual learning. One of these LT activities is writing. It was shown that writing activities about real-life topics improve the abilities of students to integrate concepts and apply concepts to real-world problem solving (Keselman, Kaufman, Kramer, & Patel, 2007). During the writing process, students are stimulated to brainstorm, which activates associations among concepts that are stored in long-term memory (Galbraith, 1999). Moreover, writing prompts students to organize their conceptual knowledge and to express relationships between concepts when formulating sentences.

There are strong indications that constructing concept maps, another LT activity, is associated with increased knowledge retention and transfer (Nesbit & Adesope, 2006). This can be explained because the brain organizes concepts in a parallel way (Novak & Cañas, 2008). Concept mapping appears to be particularly useful in assisting students to understand the interconnectedness of complex biological relationships (Kinchin, 2011). Other visualization tools, such as flow charts, also seem to help improve student comprehension and learning (Davidowitz & Rollnick, 2001; McCabe, 2011). They can reveal interrelationships and connections within knowledge and can therefore be seen as a tool to make students' conceptual thinking visible (Ritchhart, Turner, & Hadar, 2009). Finally, teacher–student conversations play an important role in developing students' conceptual understanding. The kinds of questions the teacher asks and the way in which the teacher articulates these questions can stimulate students to construct new relations between concepts (Chin, 2007).

Design Principles

We used four design principles, specific to the concept-context approach, to steer the design of a lesson sequence and in particular the structuring of LT-activities within contexts. Following Van den Akker et al. (2006), we defined these design principles as theoretically and empirically grounded constructs, linking strategies with intended pedagogic effects. In the following formulations, where possible, we refer to findings of a previous case study within our research project (Ummels et al., 2015).

Building upon concepts students are expected to be familiar with. In line with constructivist approaches to learning and teaching, attention to previously acquired (conceptual) knowledge is a prerequisite for learning new concepts (Novak, Mintzes, & Wandersee, 2005). This implies that when a context is introduced in the classroom the initial focus should be on concepts with which students are expected to be familiar from personal life or prior education. These concepts can function as "stepping stones" to introduce new concepts. The previous case study showed that the questions asked by the teacher are important in scaffolding students to widen their thinking from the concepts they are familiar with to new concepts.

Focusing on core concepts. Studies on expert learning have shown that experts organize their knowledge around core concepts that guide their thinking (Novak & Cañas, 2008). Introducing core concepts in a drip-feed manner in different contexts and constantly reinforcing them in different ways seem to be fruitful learning and teaching strategies (Barker & Millar, 2000). Our previous case study also provided indications that a problem-posing approach (Klaassen, 1995), in which a context-related problem is solved in a guided step-by-step fashion, could be a useful strategy for creating a motive to focus on core concepts within a context.

Stimulating students to interconnect concepts. When students are stimulated to interconnect concepts actively and frequently it is expected that their cognitive connections between these concepts will be reinforced (Fisher, 2001). In the previous case study, it became clear that LT activities embedded in contexts, in which students had to link concepts meaningfully, challenged them to make their conceptual thinking visible and to discuss the correctness of propositions with each other and with the teacher.

Reflecting on conceptual relationships within a context. Learning to recontextualize concepts from one context to another is assumed to enhance conceptual coherence (Van Oers, 1998). Recontextualization requires that students are supported to reflect on the interrelationships of concepts within a context (Wierdsma, 2012). The previous case study showed that if there was no need for students to reflect on propositions within a context this resulted in a teacher-guided noninteractive recapitulation of concepts and propositions.

Although there is no prescribed order in which these design principles should be applied it seems natural that the first design principle is elaborated at least at the beginning of a context and the fourth design principle at least at the end of a context.

METHODS

Reference Concept Map

The concepts and propositions students were expected to learn during the lesson sequence were presented in a concept map. Because each proposition that students mentioned could be pointed out in this concept map, we called it the *reference concept map*. This reference concept map was used to guide the design and as a tool to assess improvements in mentioning propositions during the course of the lesson sequence.

The concepts to be learned were selected from two biology textbooks for upper secondary education and the national Dutch exam standards (CvE, 2009) and were based on the question of which photosynthesis-related concepts are important to teach to 10th-grade biology students in senior general secondary education. Next, we conducted an analysis of the relevant literature about learning and teaching photosynthesis and other metabolic processes. We identified the following three main problems:

- Students do not understand cellular "processes." They consider photosynthesis and cellular respiration as exactly opposite processes or purely as "gas exchanging" processes (Cañal, 1999; Kose, Usak, & Bahar, 2009).
- Students are not used to seek explanations at the cellular or subcellular level of biological organization when they are asked to explain observable natural phenomena (Flores, Tovar, & Gallegos, 2003; Songer & Mintzes, 1994).
- Students are not able to link the living world to the nonliving world. They often do not grasp the idea that in living things energy can be captured, transferred, or released and that chemical elements (like carbon) can be transformed in a cyclic way from one molecule to another (Amir & Tamir, 1990; Lin & Hu, 2003; Mohan et al., 2009).

This last problem is not surprising considering that textbooks do not convey the idea that the metabolic processes (photosynthesis, cellular respiration, and biosynthesis) in living things are instances of matter and energy conservation and transformation (Roseman, Linn, & Koppal, 2008). After discussions with researchers in the field of ecology and upper secondary biology teachers, the following two guidelines for the construction of the reference concept map were devised:

- The three metabolic processes of photosynthesis, cellular respiration, and biosynthesis need to be related to each other at the cellular level.
- Each process should present how matter (with a focus on carbon-containing substances) and forms of energy (light energy, chemical energy, heat energy, and energy for cellular work) are converted.

On the basis of those two guidelines, we defined the relationships between concepts, which resulted in four groups of propositions focused on the *core* concepts of photosynthesis, cellular respiration, biosynthesis, and energy. The propositions related to energy refer to the release of heat energy or energy for cellular activity from chemical forms of energy. Figure 1 shows the reference concept map containing all these propositions.

Overview of Lesson Sequence

To guide the selection of authentic social practices which can be transformed into contexts, we chose a socioscientific topic: the environmental impact of producing meat and other protein-rich food products (Tytler, 2005). After making an inventory of social practices that related to this topic, we focused on those that (1) had the potential to provide a framework for the setting of "focal events: important or typical events that draw the attention of learners while remaining imbedded in its cultural setting" (Gilbert et al., 2011); (2) could be transformed into contexts that covered as many concepts and propositions from the reference concept map as possible; and (3) could be interlinked by a storyline. Eventually, we chose three practices that could be interconnected by a guiding question.

The first context is representative of a family-life practice: a family discussing whether to become vegetarian or not from a biological perspective. In this discussion, vegetarianism is linked to the agricultural journey of meat and meat substitutes. Students role-play a discussion about meat consumption. It is assumed that students recognize that such discussions could reflect their own situations. This context ends with the question: *Will we still be allowed to consume meat in the future (from a biological perspective)?* In this context, the following concepts from the reference concept map are introduced: carbon dioxide, proteins, and energy for cellular activity (Figure 1). So far, no propositions from the reference concept map are introduced.

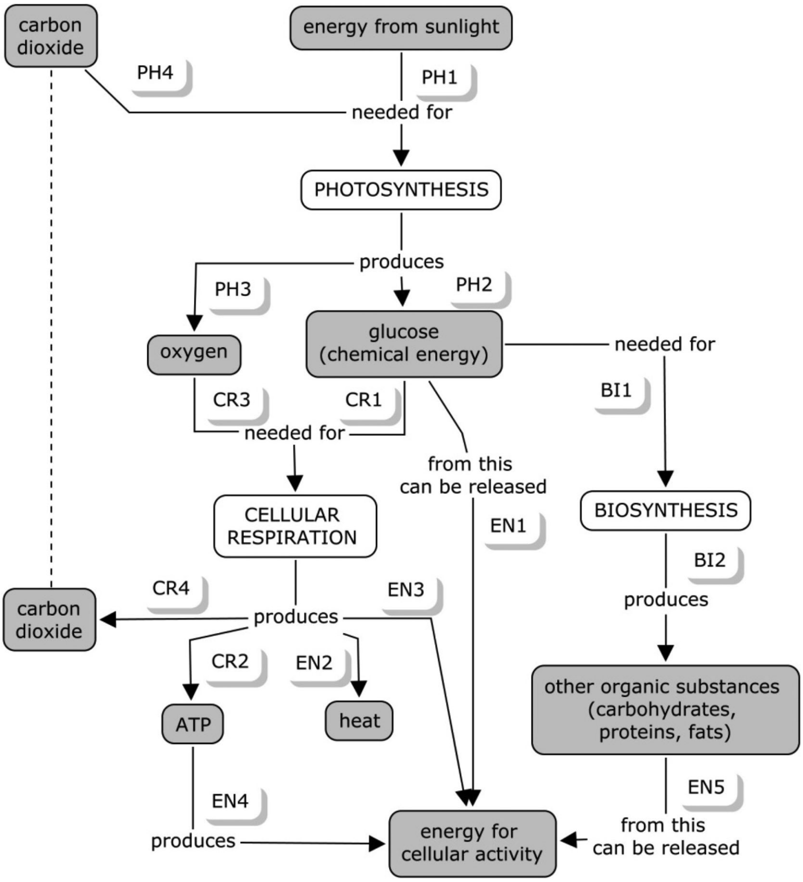

Figure 1. Reference concept map. The relationships between the three metabolic processes (white boxes) with an emphasis on transformations of forms of energy and matter (gray boxes) are indicated with proposition codes. Four groups of propositions are distinguished that are related to the core concepts of photosynthesis (codes: PH1–4), cellular respiration (codes: CR1–4), biosynthesis (codes: BI1–2), and energy (codes: EN1–5).

The second context is representative of the professional practice of an environmental advisor. The task of this advisor is to describe the impact of the agricultural production of meat and meat substitutes. Because students may not be familiar with this profession, a chart is developed to visualize the context. This graphic visualization is used to introduce the relation between the greenhouse effect and food production, with a focus on carbon dioxide emissions during the production of various plant- and animal-based protein-rich food products. Figure 2 shows the graphic visualization of the context in which the role of the environmental advisor (in front) in the protein-rich food production chain has been displayed. Protein-rich food is specified as meat for beef burgers and soya for vegetable burgers. Other participants involved are a consumer, a cattle farmer, a crop (soya) farmer, and an agricultural researcher.

Students use the graphic visualization of the context to indicate where in the production chain there is a release and an intake of carbon dioxide. Figure 3 shows the arrows students are expected to draw in the graphic visualization of the context. Furthermore, the graphic visualization of the context is used to link carbon dioxide to two processes in cells: cellular respiration and photosynthesis. Specific attention is given to the propositions PH4 and CR4

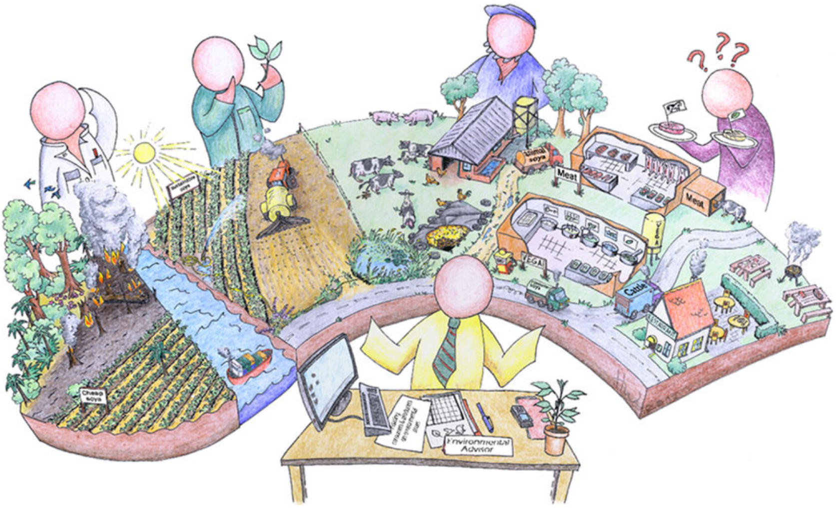

Figure 2. Graphic visualization of context. In front the environmental advisor who has to deal with the impact on the environment during the production chain of protein-rich food products. Other participants involved (anticlockwise): a consumer, a cattle farmer, a crop farmer, and an agricultural researcher.

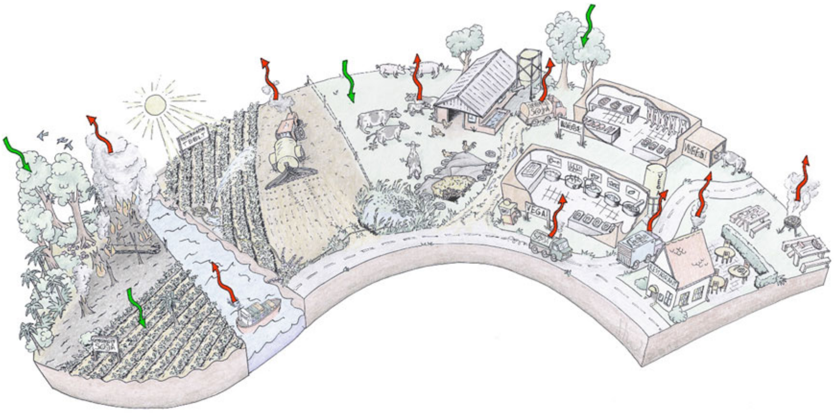

Figure 3. How the graphic visualization of the context is used to indicate where in the food-production chain there is an intake and a release of carbon dioxide.

(Figure 1). To explain this, the teacher uses the graphic visualization of chloroplasts in plant cells and mitochondria in animal and plant cells (Figure 4). In this explanation, he emphasizes the propositions PH4, PH1, PH2, CR1, CR4, EN2, and EN3 (Figure 1). The use of these graphic visualizations is the first LT activity we focus on in this article. At the end of the second context, students have to write advice destined for a public information association named “Consumer and Environment” from the perspective of the environmental advisor. This is the second LT activity we focus on in this article. The guiding question is specified as *will we still be allowed to consume meat in the future with regard to carbon dioxide emissions?* It is expected that students mention in this draft version at least the propositions that include carbon dioxide: CR4 and PH4 (Figure 1).

The third context is representative of the scientific practice of researchers in agriculture. These researchers study the production of soya plants in relation to the production of animal

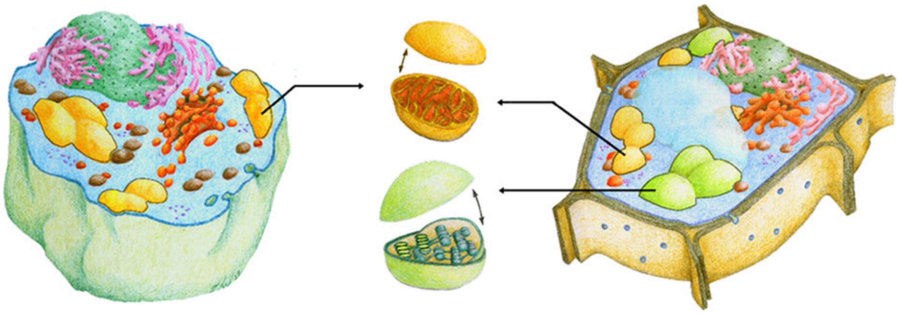

Figure 4. Graphic visualizations of an animal cell (left) and a plant cell (right), mitochondrion (top, center) and chloroplast (bottom center) used by the teacher to focus on cellular respiration and photosynthesis.

and plant proteins in the food we eat. Students weigh in pairs all soya beans from one soya plant and calculate how much larger surface of agricultural land is needed for the production of 1 kilogram of proteins in meat compared to 1 kilogram of proteins in soya plants. To explain this difference, the teacher provides students with knowledge of the metabolic process of biosynthesis (and relates this to photosynthesis and cellular respiration). The propositions BI1 and BI2 (Figure 1) are introduced. Furthermore, students construct concept maps about how the three metabolic processes are involved in protein production in both plant and animal cells. They are expected to establish the propositions PH1 to PH4, CR1 to CR4, BI1 and BI2, and EN1, EN2, and EN4 (Figure 1). This is the third LT activity we focus on in this article.

Finally, the lesson sequence returns to the perspective of the environmental advisor. Students perform a second writing task in which they use their earlier written text and information from the manual to write a final version of the advice to the public information association "Consumer and Environment." For a correct and complete explanation, it is expected that students use the propositions PH4, PH2, CR1, CR2, CR4, EN2, and EN3 (Figure 1). The guiding question is now extended to *will we still be allowed to consume meat in the future with regard to both carbon dioxide emissions and the use of agricultural land?* This is the second part of the second LT activity we focus on.

Performance of the Lesson Sequence

The lesson sequence was conducted in a 10th-grade biology class of 29 students, aged 15–16, in senior general secondary education. This type of education prepares students for studies at a University of Applied Science. To assess the abilities of these students, we compared their average biology grades for 1 year with those of students from a parallel class. The former class, on a scale of 1–10, scored an average grade of 6.17 ($SD = 0.66$), whereas the latter class scored an average grade of 6.35 ($SD = 0.64$). This is not significantly different at a 95% confidence interval: $t(58) = -1.12$; $p = .269$. The school was located in a semirural area in the east of The Netherlands. The teacher, who specializes in teaching students in senior general secondary education, had about 15 years of teaching experience and is a highly competent biology teacher. In advance of each lesson, the first author and the teacher discussed the intended LT approach. To support the teacher during the lessons, there were digital presentations that provided him with information: for example, the questions he could ask in a classroom conversation. Instructing and preparing the teacher as accurately as possible minimizes the influence of undesirable actions on students' learning processes. Because the school participated in a pilot project for the implementation of biology education based on the concept-context approach, students were familiar with this type of education. The lesson sequence was conducted in 10 consecutive lessons within a period of 3 weeks. To limit the variation in students' time spent on the lesson sequence, students were not allowed to take their manual home during this 3-weeks period. Only for the final test, they were allowed to study the manual at home.

Research Scenario and Evaluation

A research scenario predicts and theoretically justifies in detail the expected LT process and why it is expected to happen in that particular way (Lijnse & Klaassen, 2004). In this study, we constructed a research scenario that included a stepwise description of context-embedded LT activities that were expected to contribute to students' conceptual coherence. These expectations were based on a pedagogical analysis of the content to be taught (see the section Reference Concept Map) and a previous case study on concept-context-based education (Ummels et al., 2015). In this case study, we examined why LT activities were effective from the students' perspective. Table 1 demonstrates this research scenario. For the purpose of this article, only three LT activities are presented here. They are called *using graphic visualizations, writing,* and *concept mapping*. Data from video recordings in the classroom were collected and transcribed verbatim to evaluate these LT activities on practicability. This evaluation focused on the degree of correspondence of the intended steps and what actually happened in classroom practice.

One of the following scores was assigned to each step: positive (+) when the step was fully recognized in the transcripts; negative (–) when the step was not recognized in the transcripts; or intermediate (±) when the step was partially recognized in the transcripts. A second rater (second author) followed the same procedure. The level of agreement between the raters appeared to be high (Cohen's kappa = 0.87). Observational remarks on intermediate and negative scores were noted. The scores were used to interpret how characteristics of the design might have contributed to students' learning processes. The assumption is that when essential steps are missing or not performed as intended this might interrupt the development of conceptual coherence.

The first four steps (1.1–1.4) of the first LT activity (*using graphic visualizations*) were scored positively. Therefore, it was expected that students could relate carbon dioxide to cellular respiration (mentioning proposition CR4; see Figure 1) and photosynthesis (mentioning proposition PH4). The teacher made some incorrect formulations, however, about the concept of energy during the reflection phase when chemical equations were discussed (Step 1.5). For example, the teacher said: "Here is glucose and during cellular respiration this matter is partly transformed into energy." This might have resulted in a problematic understanding of transformations of matter and forms of energy.

Concerning the second LT activity (*writing*), the teacher introduced and instructed the writing assignment as intended (Steps 2.1–2.3). Students asked the teacher many questions during the brainstorm phase of the writing assignment (Step 2.4) and when they were supposed to write individually (Step 2.5). Obviously, they experienced problems in applying conceptual knowledge when giving explanations. Moreover, interaction that prompted students to reflect on conceptual relationships did not really take place (Steps 2.6 and 2.7). To help students to write the final advice, the teacher started with an introduction (Step 2.8) that missed the essential point, which had to be explained in the advice: the impact of consuming meat on both carbon dioxide emissions and the use of agricultural land. Students wrote their texts individually and used the manual as intended (Step 2.9). Furthermore, final reflection (Step 2.10) did not take place.

TABLE 1
Research Scenario for Three Context-Embedded LT Activities of the Lesson Sequence

Specification of LT Activities	Score	Observational Remarks on Intermediate and Negative Scores
LT Activity 1: Using graphic visualizations (part of Context 2)		
1.1 Teacher uses graphic visualization of context (Figure 2) to make clear that environmental advisor studies carbon dioxide emission in food production chain.	+/+	
1.2 Teacher gives instruction to draw arrows in graphic visualization of context indicating carbon dioxide exchange.	+/+	
1.3 Students discuss in pairs and draw arrows in graphic visualization of context (Figure 3).	+/+	
1.4 Students check correctness of arrows in graphic visualization of context.	+/+	
1.5 In reflection phase, the teacher uses graphic visualizations of contexts (Figures 2 and 3) in combination with graphic visualizations of plant and animal cells (Figure 4) to explain the link between cellular respiration and photosynthesis mentioning the propositions PH1, PH2, PH4, CR1, CR4, EN2, and EN3.	+/±	The teacher did not formulate the concept of energy correctly.
LT Activity 2: Writing (part of Contexts 2 and 3)		
Part 1: Draft version		
2.1 Teacher legitimizes why an environmental advisor writes advice.	+/+	
2.2 Teacher indicates that the texts should make clear how carbon dioxide emission in the production of protein-rich products of a vegetable origin is lower than for those of animal origin.	+/+	
2.3 Teacher instructs on steps in writing process.	+/+	
2.4 Students brainstorm in pairs: They discuss the line of reasoning and go through their manual.	±/±	Many procedural questions from students indicated that they did not seem to understand the assignment.
2.5 Students individually write a draft version.	±/±	Teacher's support still needed.
2.6 In reflection phase, the teacher asks students to point out essential points in argumentation. There is an emphasis on the use of propositions CR4 and PH4.	±/±	Reflection was limited to just a presentation of a slide.

(*Continued*)

TABLE 1
Continued

	Specification of LT Activities	Score	Observational Remarks on Intermediate and Negative Scores
	Part 2: Final version		
2.7	Students read each other's written products and give feedback on established propositions.	–/–	Reacting to each other's products did not occur. Time was lacking.
2.8	Teacher indicates that the text of the final version of the advice should make clear how it is possible that both carbon dioxide emissions and use of agricultural land for the production of protein-rich products of a vegetable origin can be lower than those of animal origin.	±/±	Teacher recapitulates activities in prior lessons but does not mention the main focus of the final version.
2.9	Students individually write a final version and use manual.	+/+	
2.10	In reflection phase, the teacher points out essential points in argumentation. In this argumentation there is an emphasis on the propositions PH4, PH2, CR1, CR4, EN2, EN3, BI1 and BI2.	–/–	This step was not recognized. There was no time
LT Activity 3: Concept mapping (part of Context 3)			
3.1	Teacher explains goal: shows in two concept maps how plant cells and animal cells produce proteins.	+/+	
3.2	Teacher instructs on steps in mapping process and gives each student in group a responsible role.	+/+	
3.3	Students construct maps and interact about connections between concepts to be made.	+/+	
3.4	Teacher gives each group feedback and asks students to explain connections they have made.	+/+	
3.5	Students compare own concept maps with those of other groups.	+/+	
3.6	In reflection phase, the teacher challenges students to use concept maps to explain why proteins are produced more efficiently in plant cells than in animal cells, referring to transformations of forms of energy. The following propositions are mentioned: PH1-PH4, CR1-CR4, EN1, EN2, EN4, BI1 and BI2.	±/±	There was limited time, the teacher recapitulates with limited interaction.

Each step of an LT activity was scored with regard to how well it was performed compared with the intended performance. The proposition codes refer to Figure 1. The scores of two researchers (divided by /) are presented as follows: a positive score (+) when a step was observed as intended; a negative score (−) when a step was not observed as intended, and an intermediate score (±) when a step was partially observed as intended. Observational remarks on intermediate and negative scores are presented in the last column.

The first five steps of the third LT activity (*concept mapping*) were performed as intended. Students looked focused, worked cooperatively in groups when trying to establish propositions, and followed the procedural steps to construct a concept map (Steps 3.1–3.3) and to check with other groups (Step 3.5). Moreover, the teacher interacted with each group and gave feedback (3.4). Only the last step (3.6), in which it was intended that the teacher would ask students to use the concept map when giving explanations, was not recognized. Here the teacher taught by telling and did not interact with students. Possibly, the teacher did not recognize the propositions that were not fully understood by students.

Data Collection and Analysis

Various data sources were collected by multiple means and at different points to shed light on how this lesson sequence improved the development of students' conceptual coherence. These data sources consisted of video recordings of all lessons, written responses on a pretest, a posttest, and a final test, semistructured interviews with four students and the teacher, and short written evaluations of all students after each lesson (postlesson evaluations). Moreover, we collected two "naturalistic" data sources (products of the lesson sequence itself): concept maps as products of group work and the draft and final texts of the writing assignment. Each data source provides a different insight into students' learning processes. Therefore, the triangulation of these data was used to describe how students' conceptual understanding developed during the lesson sequence.

Pretest, Posttest, and Final Test. Identical pre- and posttests were performed, consisting of explanatory tasks and defining tasks. In the explanatory tasks, students had to predict what would happen with a number of shrimp and green algae that were trapped for 1 year in a sealed ecosphere, containing water and with unrestricted sunlight. They also had to predict what would happen with a mouse and a green plant that were individually trapped in a sealed container with unrestricted water and sunlight. This task was derived from an empirical study on the understanding of cellular respiration and photosynthesis of college-level biology students (Songer & Mintzes, 1994). Our intention with these tasks was to confront students with inconsistencies in their thinking and persuade them to formulate plausible solutions to biological problems. Correct responses should refer to photosynthesis as *a process to capture energy* and to cellular respiration as *a process to release energy*. Moreover, students had to explain the relationship between animals and plants in terms of oxygen and carbon dioxide release and intake. This task was inspired by a study of Tamir and Amir (1990) who showed that 11th- to 12th-grade students often think that cellular respiration only takes place in animals and that photosynthesis is the opposite process of cellular respiration. Most students do not know that the processes are complementary.

In the defining tasks, students were asked to formulate a definition of the following concepts from the reference concept map: cellular respiration, biosynthesis, photosynthesis, organic substances, and adenosine triphosphate (ATP). Moreover, they had to relate some given concepts from the reference concept map: photosynthesis, sunlight, carbon dioxide, heat, cellular respiration, ATP, glucose, water, and oxygen. We assumed that the propositions mentioned in these defining tasks could be obtained from merely reproductive learning. The propositions mentioned in the explanatory tasks, in which no core concepts were given, are more likely to be the result of meaningful learning (Mintzes et al., 2005). The posttest was performed immediately after Lesson 10. Students responses on the pretest prediction tasks were returned to them, and they were asked to check these responses and to indicate adjustments. For the defining tasks, students were also asked to adjust their definitions given in the pretest and to add definitions they could not formulate in the pretest.

In the final test, the responses to 10 questions were analyzed: eight context-oriented open questions in which students had to give explanations, comparable with the explanatory tasks in the pre- and posttest, and two multiple-choice questions. These were selected because a correct choice required students to relate four propositions to one another. In one question students were asked to relate the core concepts of photosynthesis and cellular respiration, and in the other question they were asked to relate photosynthesis and biosynthesis. If students are able to relate a combination of two metabolic processes, this indicates a high degree of conceptual understanding.

For all three tests, we coded the propositions from the reference concept map that were expected in correct responses. For each proposition, we quantified how many students were able to mention it at least once in each test exactly as described in the reference concept map. In line with previous work, we assumed that mentioning propositions is an indicator of the degree to which conceptual coherence has developed (Ummels et al., 2013). A second rater followed the same procedure for five randomly selected students. In this procedure, students' concept maps and written products collected during the execution of the lesson sequence were also included (see the section Products of Concept Mapping and Writing Assignments). The level of agreement between the raters was high (Cohen's kappa $= 0.97$). Apparently, the codebook that described which remarks had to be scored as a correct proposition was unambiguous. The results obtained from responses on the defining and explanatory tasks were compared between pretest, posttest, and with the open context-oriented questions in the final test. Statistical analysis was conducted between the identical pre- and posttests. Because of the relatively low numbers of students, we conducted a nonparametric sign test to determine whether there was a significant increase between the two tests in the numbers of students who mentioned propositions correctly. The results of the two multiple-choice questions were compared to provide additional information on students' abilities to establish combinations of propositions. These results should be treated with considerable caution because the validity of multiple-choice questions is often doubted (Mintzes et al., 2005).

Semistructured Interviews. Semistructured interviews (Southerland, Smith, & Cummins, 2005) were conducted with four students individually after every two lessons and after the pre- and the posttest. Each student was interviewed six times. An interview lasted about 30 minutes and had a similar structure. These students (two males, aged 16 and 17, and two females, aged 15 and 16) were selected by the teacher on the basis that they represented different learning styles and were cooperative. We compared these four students' grades for biology during 1 year with the grades of the other students in the class. The mean grades of the four students were on average –0.67 standard deviations lower than the mean grades of the whole class ($n = 30$ students). Standardized differences of these four students ranged from –1.91 (student 26) to +0.51 (student 11). This shows that these four students were not outliers. The research scenario was used to formulate appropriate probes and follow-up questions to gain a complete understanding of the interviewees' views. Video recordings of these interviews were transcribed verbatim and analyzed by close reading and highlighting passages that indicated how students' learning processes had occurred with respect to understanding and interconnecting core concepts from the reference concept map. We focused on remarks that included single propositions (e.g., photosynthesis produces glucose) and combinations of propositions connecting two or more core concepts (e.g., photosynthesis produces glucose which is needed for cellular respiration and biosynthesis).

This was followed by axial coding, which allowed the information to be clustered and summarized. Students' ideas about the usefulness of each of the three LT activities were also inventoried. Three semistructured interviews were conducted with the teacher. The transcripts of these interviews were analyzed by looking for passages that indicated how the teacher perceived that the LT activities influenced students' development of conceptual coherence, either positively or negatively.

Products of Concept Mapping and Writing Assignments. Two data sources were collected from the "naturalistic setting": the texts of the writing assignment and concept maps as products of group work. The two texts of the writing assignment were analyzed by coding the propositions from the reference concept map and counting the numbers of students who mentioned each of these propositions. In the draft version, students had to link consumption of meat and other protein-rich food products to carbon dioxide emissions. In the final version, students had to explain how consuming meat is also related to use of agricultural land. The concept maps were analyzed by coding each proposition from the reference concept map, indicated by an arrow and a label connecting two concepts. For each proposition, we counted how many times it was recognized in nine concept maps. Identifying which and to what extent students were or were not able to establish propositions provides information about students' development of conceptual coherence.

RESULTS

Changes in Mentioning Propositions Before and After Lesson Sequence

Figure 5 shows the numbers of students who mentioned each proposition in defining and explaining tasks in the pretest, posttest, and final test. We discuss the results with respect to the propositions related to each of the four core concepts: photosynthesis, cellular respiration, biosynthesis, and energy.

In the pretest, more students were able to mention propositions in relation to the core concept of photosynthesis than the other core concepts. This is not surprising because the chemical equation of photosynthesis was taught in an earlier module. In the defining tasks, many students wrote down this chemical equation when asked to define photosynthesis. Fewer students mentioned propositions related to photosynthesis in the explanatory tasks. This might indicate that establishing propositions in new situations is more difficult than reproducing propositions. There were only two students (no. 5 and no. 16) who mentioned proposition PH2: "algae produce glucose (as a food source for shrimps) by photosynthesis." Although there were more students who stated: "algae produce food for shrimps" without mentioning glucose, this was not scored as a correct proposition. Ten students mentioned the propositions PH3 and PH4 in one sentence: "Algae use sunlight in photosynthesis to turn carbon dioxide into oxygen." This indicates that these students consider photosynthesis mainly as a gas exchanging process. This problem is also reported in the literature (Amir & Tamir, 1990; Cañal, 1999).

Interviews with four students (no. 11, 13, 21, and 26) conducted after the pretest made clear that their prior knowledge contained the idea that photosynthesis is a "mysterious" process taking place in plants and that plants need sunlight, use carbon dioxide, and produce oxygen. One of the students (no. 21) said, "Plants perform all kinds of tricks like photosynthesis." These students often reasoned from the perspective of the organism, focusing on what a plant needs and produces. The process of cellular respiration seemed to be largely unknown to these students. Each of the four students mentioned that animals

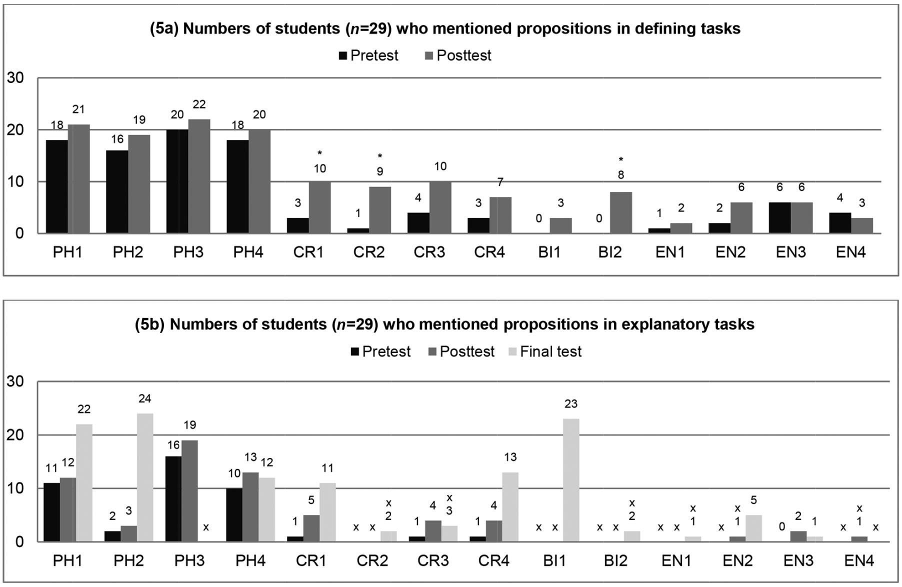

Figure 5. Numbers of students who mentioned propositions related to the concepts of photosynthesis (PH1–4), cellular respiration (CR1–4), biosynthesis (BI1–2), and energy (EN1–4) in defining tasks at pre- and posttest (a) and at the explanatory tasks at pretest, posttest, and final test (b). The asterisks (*) in Figure 5a indicate significant differences between pre- and posttest scores. The final test was not included in statistical analysis. The crosses (x) in Figure 5b indicate propositions that were not evoked and therefore not expected. EN5 was in none of the tasks evoked and is excluded from these figures. The codes refer to the propositions shown in the reference concept map as presented in Figure 1.

need oxygen but could not explain this by referring to cellular respiration. Student no. 13 said, “I think oxygen is needed for blood circulation.” Only student no. 26 said, “I think that plants also use a bit of oxygen but I’m not sure.” All four students had problems shifting their locus of explanation from the organism level of organization to the cellular or subcellular level. From the defining tasks, it became clear that none of the students could describe biosynthesis. Furthermore, the students were not able to describe how forms of energy could be converted into one another—for instance, that light energy could be captured as a form of chemical energy (glucose) and that this chemical energy could be transformed into energy for cellular work. Student no. 13 said, “Energy from sunlight is turned into oxygen.” None of the four students were able to describe any transformations of forms of matter or energy during one of the metabolic processes. This phenomenon was also recognized by Lin and Hu (2003).

Total test scores were computed for the number of correctly mentioned propositions in both the pre- and the posttest. The sign test showed a significant increase in the total number of propositions that were mentioned correctly in both defining tasks (16 positive and three negative differences and 10 ties, $p = .004$) and explanatory tasks (10 positive differences and no negative differences and 19 ties, $p = .002$) between pre- and post-test. For each proposition separately, the only significant increase between pre- and posttest was found for the propositions CR1 (seven positive differences and 22 ties, $p = .016$), CR2 (nine positive and one negative differences and 19 ties, $p = .021$) and BI2 (eight positive differences and 21 ties, $p = .008$) in the defining tasks. No significant differences between pre- and posttest were found for the other propositions (for all: $p > .05$).

Although students adjusted their responses, they often only mentioned concepts they had not mentioned before (mainly concepts related to cellular respiration) and they did not establish any new propositions. There were only three or four students who mentioned three propositions concerning cellular respiration—CR1 (four), CR3 (three), and CR4 (four)—in the explanatory tasks, but they did not mention these propositions in the pretest. For example, one of the students (no. 10) said in the pretest, "The plant (in the sealed container) is going to die because it needs carbon dioxide to live. This carbon dioxide is transformed into oxygen and when it runs out of carbon dioxide it dies." The student corrected this response in the posttest into the following: "The plant needs carbon dioxide for photosynthesis, which also requires water and sunlight. This process produces oxygen and glucose which the plant needs for cellular respiration. From this process carbon dioxide, water and sunlight are released." Although this student related the process of photosynthesis to cellular respiration, he seemed unfamiliar with the concept of chemical energy and the transformations of forms of energy during these processes. This problematic understanding did not seem to be limited to that student, as shown by the fact that only a small number of students (two out of 28) mentioned the relation between glucose and the production of energy for cellular work (EN3) correctly in the explanatory tasks.

Interviews with the four students conducted immediately after the posttest revealed that they were able to mention correct propositions in relation to photosynthesis and cellular respiration in a conversation when appropriate cues were offered. However, the interviewed students had problems with the concepts of biosynthesis and energy, in accordance with the results of all students as presented in Figure 5. This difficulty is illustrated by a quote from student 21. In the pretest, this student mentioned the propositions PH1, PH2, PH3, and PH4 in the defining tasks by writing down the chemical equation of photosynthesis. In addition to the four PH propositions, he also mentioned the propositions CR1, CR2, CR3, CR4, and BI2 in the defining tasks on the posttest. This might indicate that this student knew the chemical equations of photosynthesis and cellular respiration and that proteins are produced by biosynthesis. Yet in the explanatory tasks in the posttest, he only mentioned PH3 (photosynthesis produces oxygen).

Interviewer (I): So, the question with the shrimps and algae in the sealed container. You adjusted your previous answer by adding: algae perform photosynthesis producing oxygen for the shrimps. (The student mentioned proposition PH3.)

Student (S): Yes, I thought algae are green plants which performs photosynthesis producing oxygen needed for the shrimps to live. The first time [referring to the pretest] I hadn't thought about that.

I: Can you tell me what is needed for photosynthesis?

S: Water is needed, which is there anyway, and light energy, maybe from a light bulb, and carbon dioxide which must be added to the container or released from cellular respiration. (The student mentioned proposition CR4 and the first part of propositions PH1 and PH4.)

I: So what is produced by photosynthesis that allows the shrimps to live?

S: Oxygen and glucose. (This refers to propositions PH2 and PH3.)

I: And can you be more specific about this light energy, where is it going when it enters the container?

S: That is still difficult for me, because it has something to do with ATP. I think it is important for the biosynthesis which produces proteins (he mentioned BI2). But I'm quite sure the light energy is used somehow.

From this fragment, it becomes clear that this student learned to shift his locus of explanation to the (sub)cellular level of organization because he was now actively reasoning, as shown by his mentioning cellular processes. This reasoning process, however, was not observed during the interview conducted after the pretest. Although he did seem to partially understand the relation between photosynthesis and cellular respiration, he did not understand the relation between photosynthesis and biosynthesis. This disconnect might be attributed to a misunderstanding of the conversion of energy from one form to the other. Moreover, he did not grasp the idea that molecules can contain energy. The low numbers of students who mentioned energy-related propositions (EN1-4) as shown in Figure 5 indicates that he was not alone.

The results of the explanatory questions in the final test showed high numbers of students who mentioned the following propositions correctly compared with the explanatory tasks in the posttest: PH1 (from 12 to 22), PH2 (from 2 to 24), CR1 (from 5 to 11), and CR4 (from 4 to 13). Although it is possible that the formulation of questions in the final test prompted students rather better to mention these propositions, many students appeared to make considerable progress compared with the results of the posttest. Furthermore, 23 students mentioned proposition BI1 whereas only three students mentioned this proposition in the defining tasks in the posttest. The responses showed that students learned to give biological explanations by switching to metabolic processes at the cellular level of biological organization. For instance, in a context-oriented question about the growth of algae more than 20 students mentioned the concept of photosynthesis as a glucose-producing process that is dependent on the presence of light and referred to PH1 and PH2. The number of students who mentioned proposition EN2 (five) and EN3 (one) was still low, however. Although 11 students mentioned that glucose is needed for cellular respiration only one student mentioned that this process generates the energy for cellular activity (EN3). The results of the multiple-choice questions in the final test were as follows: Two students gave a correct response to the first question, which required the propositions PH4, PH2, BI1, and BI4, and 20 students gave a correct response to the second question in which the propositions PH4, PH2, CR1, and CR4 were required. Although 23 students mentioned the individual proposition "Glucose is needed for biosynthesis" (BI1; Figure 5b), apparently it was difficult for students to relate all four propositions to each other in the multiple-choice question. This trend corresponds with the results from the interviews and indicates that most students lack the ability to mention propositions that connect two (or more) metabolic processes.

Influence of Three Context-Embedded LT Activities

In this section, we first describe how students' conceptual coherence, in terms of their ability to mention certain propositions, seemed to have developed during each LT activity. Next, we try to identify how each LT activity contributed to the growth of students' conceptual coherence. In addition, we present how students perceived the usefulness of each LT activity.

LT Activity 1: Using Graphic Visualizations. Graphic visualizations of the context (Figures 2 and 3) were used to relate differences in the production chains of meat and organic protein-rich food products to carbon dioxide emission and uptake. During the reflection phase, graphic visualizations of mitochondria and chloroplasts (Figure 4) were used to indicate the location within the cell where these processes take place. It was expected that students would learn that carbon dioxide is needed for photosynthesis (proposition PH4), that photosynthesis produces glucose (proposition PH2) which can be used for cellular respiration (proposition CR3) in plant and animal cells, that cellular respiration produces carbon dioxide (proposition CR4) which in turn can be used for photosynthesis (proposition PH4), and that cellular respiration converts chemical energy in glucose into heat (proposition EN2) and energy for cellular activity (proposition EN3).

During the interviews, all four students (numbers 11, 13, 21, and 26) could relate the release of carbon dioxide to cellular respiration (proposition CR4) and the uptake of carbon dioxide to photosynthesis (proposition PH4). They also understood that cellular respiration takes place in both plant and animal cells, and they switched between the organizational level of the organism (plant) and the (sub)cellular level. Moreover, three students (numbers 11, 21, and 26) mentioned that during photosynthesis glucose was produced (proposition PH2) and three students (numbers 11, 13, and 26) mentioned that cellular respiration also produces energy for movement (proposition EN3). Surprisingly, they connected both processes only by mentioning carbon dioxide and did not notice glucose. One student (no. 11) said: "A plant needs carbon dioxide which is directed to the chloroplasts. There photosynthesis takes place and the part of carbon dioxide that is not used in this process is the carbon dioxide that is emitted by the plant." This student also remarked: "Carbon dioxide is converted into oxygen." None of the other students seemed to understand that the carbon (C) atom of carbon dioxide is fixed in glucose.

Possibly, when using the graphic visualization of the context (Figure 2) the initial focus on carbon dioxide emission and uptake reinforced students' ideas that the processes are mainly opposite gas exchanging processes and that cellular respiration only takes place in animals and humans. These misunderstandings seem to be associated with unfamiliarity with the concept of chemical energy and the involvement of cellular respiration in transformations of forms of energy. When asked where the energy (for movement) produced by cellular respiration came from, none of the students responded correctly. Obviously, the teacher's incorrect formulations of how energy was transformed during these processes (Table 1) were not helpful. Moreover, conservation of matter appeared to be a totally unfamiliar principle to the students. They thought that matter (C atoms) could just disappear during metabolic processes. One of the students (no. 11) said: "Carbon dioxide is turned into oxygen." When the interviewer asked: "Can you explain what happens with the C of carbon dioxide?" the student responded: "I don't have a clue."

An analysis of the video recordings of this lesson revealed that when the teacher used the graphic visualization of the cells to explain the chemical equations of the metabolic processes, he wrote on the whiteboard carbon dioxide as a chemical notation (CO_2) and spelled glucose as a word without mentioning its chemical notation ($C_6H_{12}O_6$). This might have prevented students from tracing C atoms. The teacher also did not explain the concept of chemical energy in relation to glucose. He said: "Glucose is turned partially into energy like movement and heat." This oversimplification could explain students' misunderstandings about the transformations of forms of energy and matter, which persisted after the lesson sequence, as shown in the section Changes in Mentioning Propositions Before and After Lesson Sequence. Moreover, because the teacher described the forms of energy "movement and heat" as the result of cellular respiration, students intuitively tended to relate this process to (homoeothermic) animals at the organizational level of the organism. Consequently, it is not surprising that they did not link cellular respiration to plant cells. Because during the reflection phase there was no focus on the use of energy within an animal or plant cell, e.g., the movement of cellular particles during growth, students' ideas that cellular respiration only takes place in animals (and animal cells) were reinforced.

From the interviews, it became clear that students perceived that the graphic visualizations were supportive of their learning processes. When we asked them to explain how an environmental advisor deals with carbon dioxide emissions during the production chains of meat and soya, all students mentioned that they thought immediately of the graphic visualization of the production chains (Figure 2). One student (no. 21) said, "By studying the

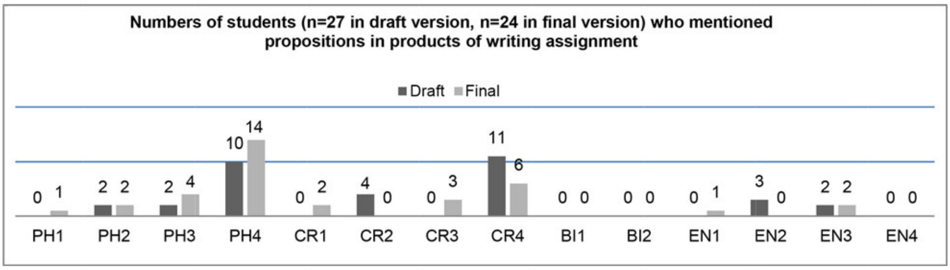

Figure 6. Numbers of students who mentioned propositions in written texts. The codes refer to the propositions shown in the reference concept map as presented in Figure 1.

graphic visualization I got an overview and by drawing the arrows it was clear to me where carbon dioxide was used and produced.” The teacher also recognized this usefulness during an interview. He explained, “By showing the graphic visualization of the context I could explain in a concrete manner which activities an environmental advisor performs. Students collaborated constructively when drawing the arrows to indicate carbon dioxide uptake and release.” He continued: “From carbon dioxide I could easily switch my explanation to the chemical equations of photosynthesis and cellular respiration.” All students confirmed that the graphic visualizations of chloroplasts and mitochondria were very useful for locating where in a cell photosynthesis and cellular respiration take place and seeing the differences between plant and animal cells.

LT Activity 2: Writing. Students had to write a draft version (Part 1) and a final version (Part 2) of advice from the perspective of the environmental advisor. We expected that in the draft version students would mention at least propositions CR4 and PH4 (Figure 1). In the final version, we expected students to also mention propositions PH1, PH2, CR1, CR2, EN2, and EN4. From the evaluation of the steps in the research scenario (Table 1), it was evident that students asked the teacher many questions during the brainstorm phase of Part 1 of this LT activity. They seemed to experience difficulties when starting to write. Moreover, the reflection phases of both parts and Part 2 of this LT activity were not conducted as intended. In Part 1, reflection was limited to a short presentation by the teacher without interaction, whereas in Part 2 the reflection phase was not observed at all.

Figure 6 shows the numbers of students who mentioned propositions from the reference concept map. It appears that not many propositions were mentioned except for proposition PH4 (carbon dioxide is needed for photosynthesis) and CR4 (cellular respiration produces carbon dioxide). Surprisingly, propositions CR2, CR4, and EN3 were mentioned even less frequently in the final version of the written products. Furthermore, it was remarkable that some students wrote a text in which they explained the differences in carbon dioxide emissions between the production chains of animal and plant protein-rich food products without referring to cellular processes.

From the interviews conducted after Part 1 of this LT activity, it was clear that students were able to explain the aim of writing environmental advice. For example, one student (no. 21) said, “To show how the production of proteins in both plants and animals leads to carbon dioxide emissions.” The interviews conducted after Part 2 of this LT activity showed that the four students were able to mention most of the individual propositions but found it hard to apply these propositions in the advice. Student 21 said, “I don’t know how these cellular processes are involved in the growth of animals.” Moreover, interrelating cellular respiration and biosynthesis was difficult. Students seemed to regard the conversion of

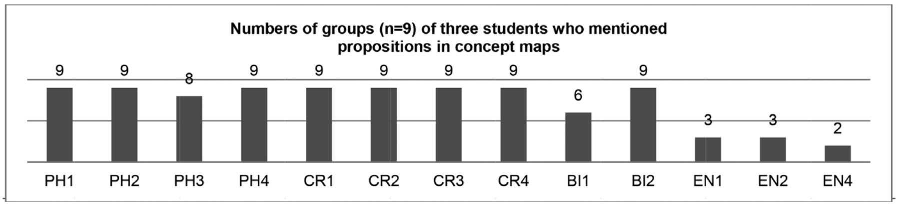

Figure 7. Numbers of groups consisting of two, three, or four students who mentioned propositions related to the concepts of photosynthesis (PH1–4), cellular respiration (CR1–4), biosynthesis (B1 and B2), and energy (EN1, EN2, and EN4) in products of a concept-mapping activity. The codes refer to the propositions shown in the reference concept map as presented in Figure 1.

glucose into either carbon dioxide or proteins as unidirectional processes. One student (no. 21) said, "As soon you have the proteins, they can't be used for cellular respiration and turned into carbon dioxide anymore." Another student (11) said, "If a chicken eats proteins, it grows because proteins are building blocks." It appears that ignorance of digestion processes, chemical structures of molecules, and other chemical breakdown processes (besides cellular respiration) hinders students in establishing a clear line of reasoning.

Although students understood the aim of the advice, they all said they needed more support at the beginning of the writing process. This mainly concerned the first part of this LT activity in which students had to write a draft. One student (11) said, "After the teacher explained which cellular processes had to be used in the advice it became clear to me. I found it hard to find the appropriate information from the manual myself." Apparently, more guidance was needed to switch from the context to the (underlying) concepts. When asked how they valued both writing activities, the four students agreed that they considered them useful. Student no. 26 explained, "The writing activities forced me to think about everything, so I learned from it. The written text was a kind of summary of the lesson sequence." The postlesson evaluations revealed, however, that the students had divergent opinions about the usefulness of the writing assignments. Ten students mentioned that the assignments were too difficult for them. This was also confirmed by the teacher who said,

> The step from constructing chemical equations during my explanation to integrating these equations in a text is too big for many of these students. They had to explain differences in energy loss and carbon dioxide release during protein production by connecting these complex chemical processes. During the brainstorm phase I noticed this was very difficult for them and, although they really tried, most of them did not know how to start writing their texts. I think the time spent on this topic in advance of the writing activity was too short.

LT Activity 3: Concept Mapping. In this LT activity, nine groups of students constructed two concept maps over the course of two lessons. The focus questions of these concept maps were as follows: *How do plant cells produce proteins?* and *How do animal cells produce proteins?* We expected that students would show the following propositions in their concept maps: PH1 to PH4, CR1 to CR4, BI1 and BI2, and EN1, EN2 and EN4 (Figure 1). This LT activity was broken into several steps spanning the mapping process. In the reflection phase, it was intended that the students would be prompted to explain the differences between the processes in plant cells and animal cells. Only this last step was not recognized as intended (Table 1).

Figure 7 presents the groups of students who showed propositions in their concept maps. It was mainly the energy propositions (EN1, EN2, and EN4) which were incorrect or lacking. Obviously, students' conceptual understanding of the core concept of energy was still problematic. The teacher recognized this trouble, saying in an interview, "I noticed that many students had problems with the term chemical energy and even more with ATP." It also appeared that the concept maps helped the teacher to point out exactly which propositions were problematic for students.

In interviews conducted after this LT activity, students were asked to explain how the three metabolic processes are involved in protein production in plant and animal cells. All four students explained the relation between photosynthesis and cellular respiration. They seemed to feel confident when talking about these processes, but they all had problems when linking photosynthesis to biosynthesis. The role of glucose as a "building block" to produce proteins was not clear to them. Student no. 26 said: "I think the proteins in animal cells are there because animals consume protein-rich food." He also remarked that biosynthesis was still a rather vague concept. Student no. 21 thought that only ATP and minerals are needed for biosynthesis to produce proteins. When asked to explain why photosynthesis is the basis for protein production only student no. 11 was able to connect this to the production of glucose needed for biosynthesis.

Students rated the concept-mapping activity as very useful, and this rating was confirmed by almost all students in the postlesson evaluations. Students specifically highlighted interacting in groups and comparing and discussing their own concept maps with those constructed by other groups as positive aspects of this LT activity. Moreover, during the mapping activity the teacher prompted students to explain the relations between concepts and gave feedback.

DISCUSSION

The two central research questions addressed in this study were as follows: *How does students' conceptual coherence develop for students during a context-based lesson sequence?* and *How do context-embedded LT activities influence the development of conceptual coherence?* Following a design-based research approach, we described how a context-based lesson sequence in biology was designed, conducted, and evaluated on its practicability and effectiveness. Next, we discuss reported changes in mentioning propositions (as presented in the section Changes in Mentioning Propositions Before and After Lesson Sequence) and give explanations for unexpected findings. Then, we reflect on the three examined context-embedded LT activities (as presented in the section Influence of Three Context-Embedded LT Activities). Finally, we reflect upon the usefulness and limitations of the research scenario and the reference concept map with a view to future research on context-based science education.

Development of Conceptual Coherence

The significant gains in test scores for mentioning propositions from the reference concept map indicated that students' conceptual coherence developed during the lesson sequence. More specifically, students were better able to mention propositions related to just one of the core concepts than propositions between core concepts. Mentioning propositions that included the core concept of energy appeared extremely difficult, even at the end of the lesson sequence. Other consistent findings in our data included students' attempts to mention more concepts and propositions in their explanations. This indicates that they improved their abilities to switch their reasoning to the cellular level of biological organization.

Nevertheless, the results indicated limited gains in mentioning propositions. This is slightly surprising because much effort was made during the design process to support students in overcoming the reported learning problems on this topic. It is possible that the conceptual framework as presented in the reference concept map might have been too difficult for many of these students at this level of education, especially given in the short time span of ten lessons. In a study on similar explanatory tasks, Songer and Mintzes (1994) showed that even between novice and experienced university biology students, there were hardly any significant increases between their ideas on photosynthesis and cellular respiration. Difficulties in both teaching and learning this topic were also recognized by Mohan et al. (2009) who reported that even by the end of high school no more than half of the students were attempting to use, more or less consistently, chemical processes to explain macroscopic and large-scale events. Only 10% of the students distinguished matter from energy during metabolic processes. The other 90% of the students were not able to describe chemical changes based on scientific principles such as the conservation of matter and energy. These results are in line with our findings.

We found that alternative (incorrect) understandings concerning the energy concept did not disappear. Students still had problems interrelating two (or more) metabolic processes, and they did not understand the conservation and transformations of matter and forms of energy in metabolic processes. Lin and Hu (2003), who showed that 13-year-old students failed to interrelate biological concepts concerning energy flow and matter cycling, pointed out that a lack of chemical and physical interpretations when teaching biology is one of the causes of this failure. Moreover, it seemed that at the beginning of the lesson sequence there was a lack of basic understanding of the concepts of energy and matter. Therefore, we recommend that lessons in chemistry, physics, and biology pay more attention to providing a common base for these concepts. For instance, in 9th-grade science lessons the focus could be on conversions of forms of energy and matter in meaningful contexts. In addition, we recommend that the conceptual network (or parts of it) be frequently revised during the course of the curriculum. There are opportunities to relate the conceptual network to a variety of context-areas such as health, sport, and environment.

As an explanation for the limited gains in mentioning particular propositions (and thus in the development of conceptual coherence), we think that the order of the contexts in the lesson sequence restricted the order in which the concepts and propositions from the reference concept map were introduced. This is illustrated with the following two examples.

First, in the beginning of the lesson sequence too much attention was given to the concepts of carbon dioxide and oxygen. This emphasis supported students' intuitive ideas. They persisted in thinking that photosynthesis and cellular respiration are solely opposite gas-exchanging processes (Cañal, 1999), without regarding them as energy-transforming processes. In the beginning of the lesson sequence, there was a lack of attention to the chemical notation of glucose ($C_6H_{12}O_6$) and the idea that the C-bindings contain energy in a chemical form. Because of this oversight, students found it hard to trace matter (C atoms) and energy once the three metabolic processes were introduced.

We therefore propose that the beginning of the lesson sequence should focus more intensively on glucose as a connecting concept between the metabolic processes. Glucose can be regarded as a *threshold concept* because it "opens up a new and previously inaccessible way of thinking about something" (Roseman, Stern, & Koppal, 2010). We expect that if students understand the chemical structure of glucose, this understanding will support them in learning the concepts of chemical energy and transformations of forms of energy and matter in relation to the three metabolic processes. One possibility is to extend the first context with an LT activity in which students build a chemical model of glucose (paying attention to the energetic bindings between the C atoms) to find out why humans need organic substances for energy. Such LT activity could be conducted after the role-play in which is stated that people need meat or meat substitutes for energy.

Second, the introduction of the concepts of biosynthesis and chemical energy lasted until the end of the second context. Therefore, relatively less time was available to master these concepts (compared with photosynthesis and cellular respiration). This suggests that the number of concepts that are introduced in a lesson sequence should be balanced with the number of lessons. According to the theoretical basis of the concept-context approach, however, it is preferable that there is a logical reason to introduce a new concept (Boersma et al., 2007). This dilemma is bound up inextricably with the design and study of a single context-based lesson sequence as presented in this paper. A sequence of contexts in a spiral curriculum would solve this problem. Then each concept could be drip-fed into the lesson and revisited in-depth and in more than one context.

Influence of Context-Embedded LT Activities on Development of Conceptual Coherence

Our evaluation of the first LT activity *(using graphic visualizations)* showed convincingly that graphic visualizations help students to structure their thoughts and to link contexts to concepts. They were used for a hands-on activity (Figures 2 and 3) and for a classroom discussion (Figures 2–4). However, the graphic visualizations did not reveal conceptual misunderstandings with respect to transformations of forms of energy and matter. Possibly, a third graphic visualization in which glucose and other substances at the molecular level are depicted would be helpful.

From the evaluation of the second LT activity (*writing*), it became clear that establishing propositions when reasoning during an individual writing process proves to be difficult for many students. Although students understood the context and the goals of the advice that had to be written, most of them were not able to use biological concepts and propositions in their writings. Moreover, we observed much variation between students in their abilities to write a text. This variation could be associated with metacognitive abilities required to structure writing. Therefore, differentiation and scaffolding is needed, for instance, by providing sample sentences to individual students on demand.

During the third LT activity (*concept mapping*), students showed the intended propositions, with the exception of propositions related to the core concept of energy. It is not surprising that students showed many propositions because they constructed the concept map during a group discussion and all concepts had already been given. This result is in line with previous research showing that concept mapping is a supportive LT activity that promotes active thinking and construction of new propositions (Nesbit & Adesope, 2006). Moreover, having students express conceptual thinking allowed the teacher to ask questions and to provide feedback. However, the teacher did not respond adequately to propositions that were difficult for students. In future implementations, it might be useful to offer the teacher a set of feedback questions to help students check their concept maps and focus their attention on the way they established propositions, including energy-related concepts.

From the evaluated research scenario, it became clear that none of the reflection phases of these three LT activities were conducted as intended. More guidance on structuring reflection is apparently needed. A well-thought questioning strategy could be helpful here. Such a strategy should elicit what students think, encourage them to elaborate on their previous answers and ideas, and help them to construct conceptual knowledge. The teacher should be prepared in terms of which questions to ask and the sort of responses to be expected from students. We suggest that parts of the reference concept map underlying the contexts can function as a “roadmap” to structure such a question strategy and help teachers to adapt questions to students’ answers. The “question-based discourse” analytic framework developed by Chin (2006) would be useful to stimulate productive thinking during reflective moments. Therefore, as a specification for the fourth design principle (reflection on concept), we advise the use of a questioning strategy when reflecting on conceptual relationships in a context.

Reflection on Use of the Reference Concept Map and the Research Scenario

Studying the influence of a context-based learning environment on conceptual learning is a challenge, which is also recognized in other context-based projects (e.g., Pilot & Bulte, 2006). We showed that a design-based research approach can shed light on the mechanisms involved in teaching strategies and learning processes. This section reflects on the usefulness and limitations of two innovative elements in our design-based research approach: the reference concept map (Figure 1) and the research scenario (Table 1).

Reference Concept Map. The reference concept map was used in two ways: to guide the design process and to assess students' learning outcomes. Because the reference concept map was the result of a systematic analysis of school books, literature, and discussions with experts, it functioned as a theoretically and empirically underpinned framework from which learning objectives could be derived. During the design process, decisions could be legitimized by pointing out which concepts and propositions from the reference concept map were involved. Therefore, implicit decisions about the selection of social practices, the transformation of these social practices into contexts suitable for integration into the lesson sequence, and the structuring of promising LT activities could be explicated.

With respect to the evaluation of students' learning outcomes, this study showed that using the reference concept map as an assessment tool gave a clear focus for analysis. Multiple types of data sources, including those which were derived from a naturalistic setting, were analyzed on the occurrence of (intended) propositions systematically and with high validity, as indicated by the high Cohen's kappa values (see the section Research Scenario and Evaluation). Analyzing these multiple data sources in a unified way allowed triangulation. Although analyzing changes in concept maps of individual students could be a useful—and often logical—methodological approach to measuring conceptual coherence (Pearsall, Skipper, & Mintzes, 1997; Novak, 2005), this would not have been suitable for the purposes of the study presented here. Testing the effects of concept-mapping activities would have clouded the learning effects of the intervention, all the more because the reported intervention covered a relatively short period of only 10 lessons.

There were two limitations in the way; we used the reference concept map to assess students' conceptual understanding, however. First, different types of data sources cannot be compared one to one with high validity if they are not identical. For instance, the extreme rise of PH2 in the final test compared with the explanatory tasks in the posttest (from 3 to 24, Figure 5b) could suggest that the cues that prompted students to mention this proposition were different. In the posttest, this proposition was probably elicited more easily. Second, scoring only correct propositions from the reference concept map seems to give only a rough indication of students' conceptual coherence. A subtle improvement in students' understanding, such as the observation that students gradually shifted their locus of explanation from the organism to the (sub)cellular level of biological organization, could not be detected. We observed that students often used common language instead of biological terms ("Animals need food to burn and to get energy"). On the other hand, when students mentioned the biological terms as presented in the reference concept map they often did not formulate the exact proposition ("Sunlight is needed to produce glucose").

These indications of a certain development of conceptual coherence were not detected with our reference concept map–based assessment method. This might also explain the relatively low number of students who showed improvement in the posttest and, to a lesser extent, in the final test.

For future research, an even more discriminating assessment tool could be developed in which each proposition is subdivided into progressive levels of understanding. Students' responses could be categorized into these levels. For instance, when a student remarks, "A plant needs sunlight to produce food" this statement is correct but does not prove an understanding of the involvement of metabolic processes at the cellular level of biological organization. Therefore, this remark could be seen as an intermediate level of understanding of the propositions PH1 (energy from sunlight is needed for photosynthesis) and PH2 (photosynthesis produces glucose). This would require test items to be developed carefully to evoke responses in which different levels of propositional understanding could be recognized.

Moreover, different test items that trigger students to mention the same proposition should be validated. Furthermore, analyzing the degree to which students mention combinations of propositions in one response would indicate their conceptual coherence at a higher level. We should, however, be aware that a single assessment tool always gives a limited interpretation of student's understanding (Mintzes et al., 2005). We have shown in this paper that a reference concept map is a robust instrument to analyze multiple data sources obtained through multiple means of data collection, resulting in a coherent description of the learning and teaching processes.

Research Scenario. The aim of the research scenario was twofold. First, because it was constructed in parallel with the design of the lesson sequence the designers were forced to carefully consider each step of the lesson sequence. Second, it was used to evaluate the design on its practicability (Ummels et al., 2015). This evaluation (section Research Scenario and Evaluation and Table 1) provided insight into the quality of each of the LT activities within the lesson sequence. Steps that were conducted as intended by the teacher but did not result in the intended learning outcomes gave useful input for adapting the written design. If steps were not conducted as intended by teacher or students, the learning outcomes had to be considered carefully.

This analysis made it clear that the specific actions of the teacher are extremely important to students' conceptual learning. For instance, the language and phrasing used by the teacher when explaining complex concepts like the energy concept need to be balanced: On the one hand, simplifications of a complex topic can all too easily confirm students' misconceptions; on the other hand, students become lost when the teacher gives too much content-specific information. In conclusion, for future design-based research on learning concepts within context-based education, we recommend both the use of a reference concept map and a research scenario to keep a focus on the research aims and to gain an in-depth understanding of teaching strategies and learning processes.

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