Routledge
Taylor & Francis Group

International Journal of Science Education

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

Developing the ability to recontextualise cellular respiration: an explorative study in recontextualising biological concepts

Menno Wierdsma, Kerst Th. Boersma, Marie-Christine Knippels & Bert van Oers

INTERNATIONAL JOURNAL OF SCIENCE EDUCATION, 2016
VOL. 38, NO. 15, 2388–2413
http://dx.doi.org/10.1080/09500693.2016.1246779

Developing the ability to recontextualise cellular respiration: an explorative study in recontextualising biological concepts

Menno Wierdsma[a], Kerst Th. Boersma[b], Marie-Christine Knippels[b] and Bert van Oers[c]

[a]School of Education, Hanze University of Applied Science, Groningen, The Netherlands; [b]Utrecht University, Freudenthal Institute for Science and Mathematics Education (FIsme), Utrecht, The Netherlands; [c]Faculty of Psychology and Education, VU University Amsterdam, Amsterdam, The Netherlands

ABSTRACT
In many science education practices, students are expected to develop an understanding of scientific knowledge without being allowed a view of the practices and cultures that have developed and use this knowledge. Therefore, students should be allowed to develop scientific concepts in relation to the contexts in which those concepts are used. Since many concepts are used in a variety of contexts, students need to be able to recontextualise and transfer their understanding of a concept from one context to another. This study aims to develop a learning and teaching strategy for recontextualising cellular respiration. This article focuses on students' ability to recontextualise cellular respiration. The strategy allowed students to develop their understanding of cellular respiration by exploring its use and meaning in different contexts. A pre- and post-test design was used to test students' understanding of cellular respiration. The results indicate that while students did develop an acceptable understanding of cellular respiration, they still had difficulty with recontextualising the concept to other contexts. Possible explanations for this ack of understanding are students' familiarity with the biological object of focus in a context, the manner in which this object is used in a context and students' understanding of specific elements of cellular respiration during the lessons. Although students did develop an adequate understanding of the concept, they do need more opportunities to practice recontextualising the concept in different contexts. Further research should focus on improving the strategy presented here and developing strategies for other core concepts in science.

ARTICLE HISTORY
Received 27 July 2015
Accepted 5 October 2016

KEYWORDS
Biology education; conceptual development; context-based learning; recontextualising

1. Introduction

In the last decades, scientific understanding in our western society has accelerated, so that knowledge and skills acquired in formal education in the past may not be valid and useful later in our lifetimes. To follow these changes, it is necessary to continuously acquire new knowledge and skills in life-long learning. The problem for formal education is

CONTACT Menno Wierdsma m.d.m.wierdsma@pl.hanze.nl School of Education, Hanze University of Applied Science, PO Box 70030, Groningen 97047AA, The Netherlands
Supplemental data for this article can be accessed at http://dx.doi.org/10.1080/09500693.2016.1246779

multifaceted. It seems that much of what is traditionally included in science education no longer has social or scientific relevance. Therefore, we should focus education on knowledge and skills that make sense in today's society. Additionally, the position of that knowledge and those skills in our society should also make sense from a students' perspective, to retain or stimulate their interest in them. A logical consequence of this line of reasoning is the implementation of context-based science education. Consideration of many science curricula and textbooks indicates that the primary obstacle to recognising science relevance is probably not the relevance of that science. The true culprit is that we present scientific content without discussing the (social) practices and cultures in which it is used. In other words, content is detached from context. Restoration of this connection between science knowledge, skills and contexts seems an obvious step. Simultaneously, new scientific knowledge is being developed that requires implementation in science curricula in order to keep pace with the societal impact of scientific development. This means that restoration of the connection with contexts cannot be the only approach. New topics are waiting for implementation, and that of course evokes the need to skip others. Curricular overload is a continuous concern.

In considering these requirements for the nature and content of context-based science education, the question arises if the selection of goals for science curricula can benefit from another perspective. If we reflect on the rapid changes in scientific content as an issue we have to cope with, science education could benefit if we could discern some concepts and skills that remain relevant for several decades. As far as skills are concerned, lines of reasoning similar to the one in the previous paragraph led to the articulation of generic skills and the so-called twenty-first century skills (Binkley et al., 2011; Kay & Greenhil, 2011). For scientific knowledge this line of reasoning is less articulated, although it was quite popular in the 1970s, and resulted in the articulation of core concepts. Since it seems inconceivable that concepts like energy and cell will lose their relevance in the forthcoming decades, it seems worth the effort to focus on the development of these core concepts. A core concept can be considered a basic aspect of disciplinary knowledge, and is as such likely to be applied or elaborated in a large variety of contexts. Thus, in selecting goals for science curricula, selecting core concepts and skills is a major issue, along with the need to articulate how these can be used in a variety of contexts.

The opportunity to explore this issue in school practice emerged when the Dutch Minister of Education mandated a committee to develop new examination programmes for upper secondary biology education. This committee recognised the need to focus on the development of core concepts, and selected a list of core concepts. Additionally, the committee indicated context-based biology education as a promising vehicle for students to develop biological concepts in direct relation to their use in today's society. Because of the large variety of contexts that use these core concepts, the committee indicated that students should learn to apply these core concepts in a variety of contexts (Boersma et al., 2007). This requires that students are able to transfer such core concepts to different contexts. Unfortunately, educational research on transfer has frequently shown very disappointing results (e.g. Lobato, 2006). Furthermore, it became evident that biological concepts may have different meanings in different contexts (van Weelie, 2001), which seemed to aggravate the problem of transfer. There are, however, some new trends in transfer research, based on cultural-historical activity theory, which consider transfer not as a spontaneously occurring phenomenon, but as a part of the learning process in which students learn to adapt previously acquired knowledge and skills to new contexts. In this theory, knowledge is understood as a tool that is used in the performance of cultural-historically defined activities through the accomplishment of goal-directed actions (Kozulin, 2001, 2003). Between activities, their participants, the objects involved and goals can be modified depending on the requirements of the activities. Also, the knowledge that is used can differ across activities. At the very least, different activity settings (contexts) often require different interpretations of the knowledge or concepts that they share. Different interpretations imply that the meaning of a concept can be different in different activities. Having these theoretical considerations in mind, transfer should be redefined as the process in which one context-specific meaning of a concept is transformed or adapted to another context-specific meaning of the same concept in another context. This process is called recontextualising (van Oers, 1998a, 1998b).

Until now recontextualising has mostly been explored at the theoretical level; empirical studies and learning and teaching (LT) strategies indicating how students may learn to recontextualise in current school practice are not yet available. Considering the urgency to have one or more of such strategies available in context-based biology education, as it was recently defined and implemented in examination programmes in upper secondary education, a study was conducted focusing on the development of a learning and teaching strategy for recontextualising (Wierdsma, 2012). This study focused on the concept of cellular respiration for several reasons.

The first reason for choosing that concept is that cellular respiration can be considered a core concept in biology (e.g. Songer & Mintzes, 1994), which until recently received only a small amount of attention in research (see also Ummels, Kamp, de Kroon, & Boersma, 2014). The second reason is that available research studies show several learning difficulties linked to this concept, such as confusion with the everyday terms respiration and breathing (Songer & Mintzes, 1994) and everyday ideas about energy (e.g. Lin & Hu, 2003; Ummels, 2014), the biochemical nature of the concept which implies that it requires understanding at the cellular, sub-cellular and molecular level (e.g. Songer & Mintzes, 1994), and consequently the problem of connecting these levels of biological organisation (Van Mil, Boerwinkel, & Waarlo, 2011). The final reason to select cellular respiration was that it refers to different processes: aerobic respiration and many variants of anaerobic respiration, such as lactic acid and alcoholic fermentation. This distinction results in concrete differences between the processes that are indicated with the term cellular respiration. These inhibit students from merely transferring their understanding from one context to another. Students have to decide which processes are indicated by the term from interpreting other contextual clues, such as the organism(s) involved and the presence of free oxygen. Furthermore, students need to study different types of cellular respiration in a variety of contexts in order to develop a complete understanding of these different types. As such, studying a concept in just one context does not appear to be a fruitful exercise if generalisation and transfer of the concept are the goal. Aside from differences in the processes that are indicated by the term, professional practices also focus on different aspects of the concept. For example, vintners and bakers focus on the products of cellular respiration that help them produce their wine (alcohol) and bread (carbon dioxide), respectively. In contrast, many biological research practices focus on the biological function of cellular respiration across all living organisms, requiring a more generalised description than many professional practices do (Wierdsma, 2012).

Summarising, the aim of this study is to develop an effective and practicable strategy for recontextualising cellular respiration. It requires determining the practicability of a strategy in the classroom and the desirable learning outcomes. This article focuses on the learning outcomes. The design of the strategy and its practicability were published recently (Wierdsma, Knippels, Van Oers, & Boersma, 2015).

The study described here is an explorative study because it is unclear how recontextualising may be operationalised in practice. Also, it cannot be excluded that different strategies have to be followed for learning and teaching the concept, when considering the characteristics of the concept and the diversity in the contexts in which it is used. Furthermore, the explorative nature of the study could give rise to new research questions. Therefore, this study not only aims to determine students' ability to recontextualise cellular respiration, but also to find explanations for it. Consequently, this article answers the following research questions:

1. To what extent do students develop the ability to recontextualise cellular respiration in context-based biology education?
2. How can students' ability to recontextualise cellular respiration in other contexts be explained?

In the next section, the theoretical framework is presented. Then, in Section 3, the designs for the lesson module and methodology are reported, while the corresponding results are presented in Section 4. In the final section, the research questions are answered and possible implications for recontextualising biological concepts are discussed.

2. Theoretical framework

The issue of transfer has been studied extensively (Beach, 1999; Bransford & Schwartz, 1999; Dyson, 1999; Engeström, 1991; Engle, 2006; Greeno, 2006; Lobato, 2006; Marton, 2006; Schönborn & Bögeholz, 2009; van Oers, 1998b). Traditionally, transfer is viewed as the spontaneous application of previously learned knowledge or skill in a new situation (Lobato, 2006). However, in traditional behavioural and cognitive views on transfer, it is often unclear how and to what extent a situation in which a concept or behaviour was learned differed from the situation to which the knowledge or skill was to be transferred. While traditional behavioural perspectives on transfer focused primarily on similarity of superficial stimuli between two tasks between which knowledge was to be transferred, most cognitive perspectives seemed to focus more on conceptual similarities between tasks. Although both these perspectives do acknowledge culture and social interaction as influencing knowledge construction and transfer, they seem to ignore these or treat them as independent variables when focusing on an individual's cognitive construction (Royer, Mestre, & Dufresne, 2005). By the end of the last century, a number of authors proposed a rethinking of the process of transfer itself and adopted different perspectives on the subject (Beach, 1999; Bransford & Schwartz, 1999; van Oers, 1998a, 1998b). Compared to previous theories on transfer, these new perspectives shifted the view from the individual learner to the learner as a participant in a cultural community; it was supposed that knowledge cannot directly be applied to a new context because the meaning of knowledge is context dependent.

This means that previously learned knowledge has to be adapted to fit new situations. This cultural-historical view shifts the perspective on the phenomenon as an event to a more action-oriented perspective. Recontextualising is an activity or pattern of affordable actions in itself that can be studied and understood. Instead of obscuring a view on this activity by focusing on its results in a given transition from one situation to the other, a view on transfer as recontextualising allows us to focus on the activity or actions people perform to adapt their prior understanding to fit a new situation. Such a perspective can be valuable for education, since understanding the process can help us to develop educational strategies to stimulate recontextualising – and as such transfer – in the future. Beach (1999) uses the term 'consequential transition' to refer to the transfer of knowledge from one social practice to the next, while van Oers (1998a, 1998b) uses the term 'recontextualising' to refer to the transfer process and changes in activity. Both views appear similar and seem to refer to the same process. However, where consequential transition focuses on a significant and personal change in a person's role and personality, recontextualising focuses on the process of change rather than its personal consequences. Thus, recontextualising is always involved in consequential transition, but not the other way around.

According to activity theory (Kozulin, 2001, 2003; van Oers, 1998a, 1998b) people engage in cultural-historically defined activities in which they manipulate objects towards a specific goal, driven by their own needs. While participating in these activities, they use and share all kinds of tools that can be mental as well as material. People form communities around the practice of shared, central activities. Such social practices (Wenger, 1999) can involve several activities that differ between practitioners.

Considering knowledge as a tool, the focus is often on concepts, since a concept can be defined as the *perception* of a regularity or pattern in objects or events, based on a generic principle or model (Novak, 1990; Novak & Cañas, 2004, 2007; van Oers, 2001). The formation of concepts is driven by and drives the systematic explanation and communication of these perceived patterns and regularities, and can structure diverse objects or events in a related whole. It is the activity that people are engaged in that shapes their perception of objects and events. In social practices, concepts are used to communicate and structure the knowledge within and between practices.

Most concepts are traditionally described in definitions, which focus on the relations between phenomena that a concept refers to. A definition of a concept is essentially created for purposes of communication. It is a product of activity and connected to the social practice(s) that needed the definition. This implies that education should not be merely about teaching definitions. Instead it should allow students to study and use a concept in different contexts, enabling them to develop a flexible perspective on the concept that they can re-evaluate and change if the need arises. In other words, a concept might be better described as the act of defining, rather than its product. Acquiring the ability of defining implies progressive recontextualising (van Oers, 2001), that a generalised – biological – meaning of the concept becomes a tool that students can use to solve problems in several contexts, and that a student becomes more and more proficient in interpreting different contexts and solving problems from the perspective provided by the concept. For educational practices, we define recontextualising as the conscious process by which students interpret and redefine their understanding of a concept when they move from exploring a concept in one context to another. Although this can occur spontaneously, it will usually require conscious effort by a student, especially when confronted with contexts that appear to be different from those that were used to develop a concept initially.

For exploring a concept in a social practice, it seems motivating for students to explore social practices that they already know to some extent and/or can easily identify with. Due to their complex nature, such social practices need to be adjusted to educational practices (Prins, Bulte, & van Driel, 2008; Westbroek, Klaassen, Bulte, & Pilot, 2005). Studies on teaching and learning the concept of biodiversity in a context-based lesson module (van Weelie, 2001, 2014; van Weelie & Wals, 2002) provide an example of how students develop this concept by reviewing and reformulating its definition for different contexts, that is, by recontextualising biodiversity.

It is necessary to make a clear distinction between cultural-historically defined activities, embedded in social practices, and learning (and teaching) activities in context-based science education. In the latter, activities embedded in social practices are adapted so they can be used to attain educational objectives or aims. Therefore, this study makes a distinction between social practices and activities, which belong to the world outside school, and contexts, adaptations of activities and social practices for educational purposes. A context is the focus on a specific part or *key activity* in a social practice: an activity that aims to solve a specific problem or question that arises from the central activity in a practice. A biological context then focuses on changing or understanding a biological object of focus that is central in a practice. This is often a specific organism, species or taxon, but can also be a particular type of cell, an ecosystem or an organ. For instance, in our example of exercise physiology, the biological object of focus is the athletes, a bioengineer may focus on a bacterium and ecologists focus more on a population or ecosystem. Of course school can be understood as a social practice as well, where the activity (or activities) of science learning and teaching are performed. This coarse-grained activity consists of many fine-grained learning and teaching activities. In cultural-historical terminology, these fine-grained components of activities would be indicated as actions.

From this theoretical framework about recontextualising, and from two explorative case studies (Yin, 2003) showing different experimental approaches to recontextualising photosynthesis, cellular respiration and behaviour, a number of design principles were derived to ground the design of the lesson module. This lesson module focused students on a context of exercise physiology and the differences between short-track and long-distance runners. During a series of LT activities, students developed their initial understanding of cellular respiration as a type of ‘biological combustion’ towards a complex concept that refers to a variety of enzyme-mediated, metabolic processes that involve the breakdown of large, organic molecules to smaller ones, while making the energy from breaking those chemical bonds available to fuel other metabolic processes. Students developed this complex understanding of cellular respiration by studying how the concept is interpreted and used in a variety of biological practices and organisms in order to eventually use their understanding to explain the physiological differences between both types of athletes (Wierdsma, 2012; Wierdsma et al., 2015).

3. Design and methodology

3.1. Design of the study

An educational design research approach was adopted (e.g. van den Akker, Gravemeijer, McKenney, & Nieveen, 2006; Lijnse, 1995) to answer the two research questions. This approach allows for the elaboration of recontextualising in classroom practice and consists of cycles of designing, testing and adapting a sequence of learning and teaching activities. The study started with an explorative phase which consisted of a literature study and two explorative case studies (Yin, 2003). Next, two empirical cycles were conducted, each consisting of two empirical case studies.

The study focused on general upper secondary education, since the experience of most biology teachers shows that learning complex and abstract concepts like cellular respiration causes more learning difficulties in general upper secondary education than in pre-university education.[1]

The outcomes of the explorative phase were used in the first empirical cycle to design a preliminary learning and teaching strategy; a sequence of learning and teaching activities. This preliminary strategy was developed in cooperation with two teachers and conducted in their school practice. To assess the practicability and outcomes of the preliminary strategy, it was elaborated in a storyline, scenario and corresponding learning and teaching materials. The storyline described students' stepwise development of the concept of cellular respiration, and their intended physical and mental actions. The scenario is a research instrument; it indicates a detailed description of the sequence of the teachers' and students' actions (Lijnse, 1995). After data collection by observation, and elaboration of the observations in transcripts, the scenario allows to assess whether the intended actions were practiced, and where adaptation of the learning and teaching materials, storyline and scenario would be desirable. Furthermore, methods for data analysis and a draft of the recontextualising test were developed in the first empirical cycle.

This sequence of design, enactment in school practice, data collection and analysis was repeated in the second empirical cycle. This article focuses on the results of this second cycle, since a largely practicable final design and articulated research instruments were applied in this cycle. Table 1 presents the structure of the lesson module in terms of contexts and storyline, in relation to data collected for evaluating students' development of the concept of cellular respiration.

3.1.1. Storyline and scenario

To design a learning and teaching strategy, three social practices were chosen: exercise physiology, biotechnology and biological research (see also Table 1). For a detailed argumentation for this selection we refer to Wierdsma (2012). The basic idea for sequencing the contexts derived from these social practices was that, according to the problem posing approach (Klaassen, 1995), students explore a problem in a specific context, but this context cannot provide a satisfying answer and evokes a motive to explore a second context, and so on, until the students have a sufficient answer. The choice for these contexts and the sequence of LT activities was discussed in detail between three researchers in biology education and a pedagogy researcher specialised in activity theory, until inter-subjective agreement was reached (Patton, 2003; Smaling, 1992).

Table 1. Structure and data-sets of the teaching module.

	Pre-test	Lesson module				Reflection	Recontextualising test	Post-test
Storyline	Not applicable	Episodes 1–5	Episodes 6–8	Episodes 9–14	Episodes 15–18	Episode 19	Episode 20	N/A
Context	Not specified	Exercise physiology	Biological research	Biotechnology	Exercise physiology	Other	Others	Not specified
Focus object	Not specified	CR in muscle cells	CR in model organisms	CR in yeast	CR in muscle cells	CR in various objects	CR in various objects	CR in general
	C. 1 + 2	C. 1 + 2	C. 1 + 2	C. 1 + 2	C. 1 + 2	C. 2	C. 1 + 2	C. 2
	T0			T1 Episode 14	T2 Episode 15		T3 Episode 20	T4
	Individual concept maps			Collaborative concept maps	Collaborative concept maps		Written answers to context-based items	Individual concept maps
	$n = 38$[a]			$n = 45$[a]	$n = 40$[a]		$n = 44$[a]	$n = 23$[a,b]

Notes: The upper part shows the sequence of contexts, corresponding figures of episodes and focus objects. Data-sets (T0–T4) are indicated in the lower part. C = case study, CR = cellular respiration. There are no contexts specified for the pre- and post-tests, since these invited the students to describe their understanding of cellular respiration without limiting this to a particular context. There are also no episodes given for these tests, since they were not considered to be a part of the learning and teaching strategy.

[a]Only administered in the second case study.

[b]Sample sizes change due to the varying absence of some students during the lessons, but since these were part of collaborative groups of students, they were not excluded from the study.

The sequence of learning and teaching activities was divided into several episodes, which together formed a storyline for the development of the concept of cellular respiration. In the first context of exercise physiology, students try to find an answer to the question of how to explain the differences between short-track and marathon runners (episodes 1 and 2). To answer this question students study muscle physiology (episodes 3 and 4). In the reflection, it is concluded that this does not provide a sufficient answer to the question, and the practice of biological research is introduced as a context where a better answer can be found (episodes 5 and 6). Then, the idea is put forward to explore how cellular respiration works in a model organism (episode 7). Several model organisms are discussed and yeast is selected as the most appropriate one (episode 9). Students orient themselves with the practice of biotechnology, with the intention to identify two possible methods of cellular respiration: aerobic and anaerobic. Students then design and conduct an experiment with yeast to measure differences between aerobic and anaerobic respiration (episodes 10–12). However, the experiment shows unexpected results, which offers the opportunity to introduce results of another experiment that cannot be conducted in class due to time limitations (episode 13). This second experiment visualises the differences in speed between aerobic and anaerobic respiration (episode 14). Finally, students return to the exercise physiology context with this new understanding and discuss how alcoholic fermentation is incompatible with human physiology and lactic acid fermentation is introduced as a variant of anaerobic respiration (episodes 15–17). Finally, the question that was raised in the first context is solved (episode 18).

3.1.2. Sample

In the second research cycle, the learning and teaching strategy was implemented in two subsequent cases in two different schools in the Netherlands. The sample sizes for data collection change during the series of lessons (see Table 1) due to the absence of some students during some of the lessons. However, these students were not excluded from our qualitative analysis of the concept maps since those students were part of groups that collaboratively constructed concept maps. Although this fact can be noted as a weakness in the design of this study, it is a consequence of the decision to test the learning and teaching strategy in a real school practice, instead of an experimental setting. An important reason for this choice was the question of practicability of the strategy in school practice (Wierdsma et al., 2015). For the purposes of this study, the absence of a small number of students during part of the lessons in the lesson module was not expected to be too much of a problem. Both case studies involved classes in senior general secondary education, and were chosen because of the teachers' availability and willingness to take part in the study. Both teachers and schools were also involved in the first research cycle. The schools were located in two different parts of the country and although both are described as urban, they also had numerous students from smaller communities nearby. Relevant information for both case studies is presented in Table 2.

3.2. Data collection

3.2.1. The concept maps

In the pre- and post-tests, students were invited in a personal assignment to construct a concept map (e.g. Novak, 1990; Novak & Cañas, 2007). The students were given a set

Table 2. Basic characteristics of the two case studies.

	Case study 1	Case study 2
School	Denominational, urban	Denominational, urban
School size	Approximately 1200 students	Approximately 700 students
Education level	Senior general secondary education (HAVO)	Senior general secondary education (HAVO)
Year	10 (HAVO 4)	10 (HAVO 4)
Students	Mixed gender, ages 15–16 $n = 21$ students (one class)	Mixed gender, ages 15–16 $n = 24$ students (one class)
Teacher	Male, 11 years of experience	Female, 7 years of experience
# lessons	9 (50 min/lesson)	9 (45 min/lesson)

of 9 or 10 concept labels and asked to construct a concept map using these labels. Both the pre- and post-tests first started with an explanation of the process of concept mapping, stressing the importance of the descriptions that connect the labels. Because students' unfamiliarity with concept mapping could hinder their construction of concept maps, the test also invited students to describe each label separately. The concept labels that were given were the same in the pre-test and the post-test ('glucose', 'oxygen', 'cell', 'cellular respiration', 'anaerobic respiration', 'aerobic respiration', 'energy', 'metabolism' and 'mitochondrion'). Accidentally, 'cellular respiration' was replaced by 'carbon dioxide' in the second case study. However, since 'aerobic cellular respiration' and 'anaerobic cellular respiration' ensured the inclusion of 'cellular respiration', it could be expected that students who did not use these labels in their concept maps would also not be able to use a separate label for cellular respiration. Therefore, the data from these two tests in the second case study are still useful for our purposes. Because most students had not previously encountered a process labelled as 'cellular respiration', but were familiar with the term 'combustion', the labels 'glucose', 'oxygen' and 'energy' were added to provide students with a means of describing 'combustion'. Unfortunately, the post-test was eliminated during the first case study due to time limitations and incompatibility with the school's timetable.

In episodes 14 and 15, the students constructed concept maps in a group assignment (see also Table 1) that was selected because priority was given to pedagogical motives. In episode 14, the students were invited to explain the unexpected results from the experiment and to explicate cellular respiration in a concept map. A group assignment would give them the possibility to exchange ideas. A similar assignment was given in episode 15, when students returned to the problem in exercise physiology about needed energy supplies, and explicated the differences by applying what was learned from the biotechnology context (episodes 9–14).

3.2.2. The recontextualising test

The recontextualising test was administered in both case studies shortly after the last lesson in the module, before the post-test (see Table 1). As indicated in Table 1, the post-test was only administrated in the second case study. For the design of the recontextualising test, the literature provided only a small amount of valuable information (see Section 2). Therefore, a test was developed including paper-and-pencil items in a diversity of contexts. Similar tests are part of the national exams, making it reasonable to incorporate such a test. The different items were designed so that they each required different conceptual elements as part of a correct answer or solution.

All items were designed and redesigned based on students' written answers collected in the first research cycle. Items 10 and 11 are an exception; these items were added in case study 2 to mirror items 6 and 7. The context was tested by three students in an interview after the recontextualising test. For further validation all items were rated on difficulty in a web-based questionnaire by five experienced biology teachers and researchers in (biology) education. Although the experts' rating of the items differed greatly for some items, the ratings indicate that no items were too difficult or too easy for students at this level of secondary education.

Each context was introduced with a text describing a specific social practice, focusing on an activity related to a specific problem in that practice. Each context included one or two questions that required students to solve or explain (a part of) the problem of focus in that context. Table 3 presents the contexts, expected activities and the conceptual elements needed for a complete answer for the different items. A translated version of the recontextualising test items is included as an appendix to this article (see online Appendix I). This appendix was first published as part of the doctoral thesis of the first author of this article (Wierdsma, 2012). In the first case study, the test included 5 contexts and 9 items; in the second case study it consisted of 11 questions distributed along 6 items and contexts. The fifth column from the left in Table 3 contains the key cognitive elements needed for a complete answer. To decide whether a written answer could be interpreted as a result of successful recontextualising, not all the elements were needed. The rightmost column describes the minimal answer needed for an answer to be judged as proof of successful recontextualising. Key cognitive elements and the minimal answer needed for each problem were derived from extensive analysis of the contexts in the test and discussed between the researchers involved in this study, three of whom are biology educators and researchers in biology education, until they reached inter-subjective agreement on the key elements and minimal answers needed for a correct answer to each problem (Patton, 2003; Smaling, 1992). We have made a distinction between an ideal or complete answer and minimal proof of successful recontextualising because most students tended to answer the open questions with as short an answer as possible. Most of them never gave a complete or ideal answer to the question, although many of their answers did imply that the student made a correct deduction, but simply neglected to write down the complete path of reasoning for arriving at that answer.

3.3. Data analysis

An answer to the first question is found through analysis of data-sets collected during the enactment of the module in school practice, and analysis of the results of a recontextualising test that was administrated afterwards. The second research question was answered with a detailed analysis of the recontextualising test.

To answer the question to what extent students can recontextualise cellular respiration, it was necessary to develop an instrument that would provide a more detailed view of how students actually used the concept. During the design of the scenario in the first research cycle, it became apparent that with different contexts, different aspects of the concept are important. For instance, the successful production of wine or bread does not require a detailed understanding of cellular respiration; understanding that yeast produces alcohol and/or carbon dioxide when no oxygen is available is sufficient. In contrast,

Table 3. Characteristics of the items in the recontextualising test.

Context no.	Item no.	[Social practice] Context	Expected activity performed by the students answering the test item	Conceptual element(s) needed for a complete answer	Minimal elements needed for successful recontextualising
1	1	[Bio engineer] Produce yeast	Choose and explain a suitable method for production (replication) of yeast (aerobic or anaerobic).	A: *energy release* C: *oxygen requirement* D: *products* + *core (=A + B + D)*	Correct choice (aerobic ≈ C) + A *aerobic CR leads to more energy, which enables reproduction*
2	2	[Exercise physiologist] Support and design the training of athletes: understand the differences between power- and endurance-focused athletes	Explain and describe the differences in muscular structure and function between short-track and marathon runners.	A: *energy release* B: *substrate (glucose)* C: *oxygen requirement* D: *waste products* E: *mitochondria*	N/A
	3		Explain and describe the differences in energy use and supply between white and red muscle fibres.	F: *speed*	N/A
3	4	[Amateur Vintner] Produce wine	Explain the need for an anaerobic environment in wine production.	C: *oxygen requirement* D: *waste products*	D *anaerobic CR leads to alcohol production*
	5		Name the gas that is released during the production of wine.	D: *waste products*	D *Gas is carbon dioxide*
4	6	[Bio engineer] Design and breed a type of mouth-dwelling bacteria that do not cause tooth decay	Explain the bacteria's inability to perform a complete breakdown of glucose to carbon dioxide and water.	E: *mitochondria*	E *Lack of mitochondria explains lack of aerobic CR (which is breakdown of glucose to carbon dioxide and water)*
	7		Explain what would happen to (these) bacteria if they had no ability to break down glucose.	A: *energy release*	A *No CR means no energy and thus, death.*
5	8	[Bio engineer] Design part of a wastewater treatment facility	Explain the advantage of an aerobic environment in wastewater cleaning.	A: *energy* C: *oxygen requirement* D: *products* + *core (=A + B + D)*	Correct choice (aerobic ≈ C) + core *aerobic CR leads to most complete breakdown* Or
	9		Choose and explain a suitable method for cleaning wastewater using bacteria (aerobic or anaerobic).		Correct choice (aerobic ≈ C) + A *aerobic CR leads to more energy and thus more reproduction of bacteria → more breakdown.*
6	10	[Medical professionals] Care for chronically fatigued patients	Explain the patients' cells' inability to perform a complete breakdown of glucose to carbon dioxide and water.	E: *mitochondria*	E *Dysfunctioning mitochondria explains lack of aerobic CR (which is breakdown of glucose to carbon dioxide and water).*
	11		Explain the patients' chronic fatigue.	A: *energy release*	A *No aerobic CR means less energy and thus, fatigue.*

Note: The letters A to F refer to the conceptual elements of cellular respiration in Figure 1.

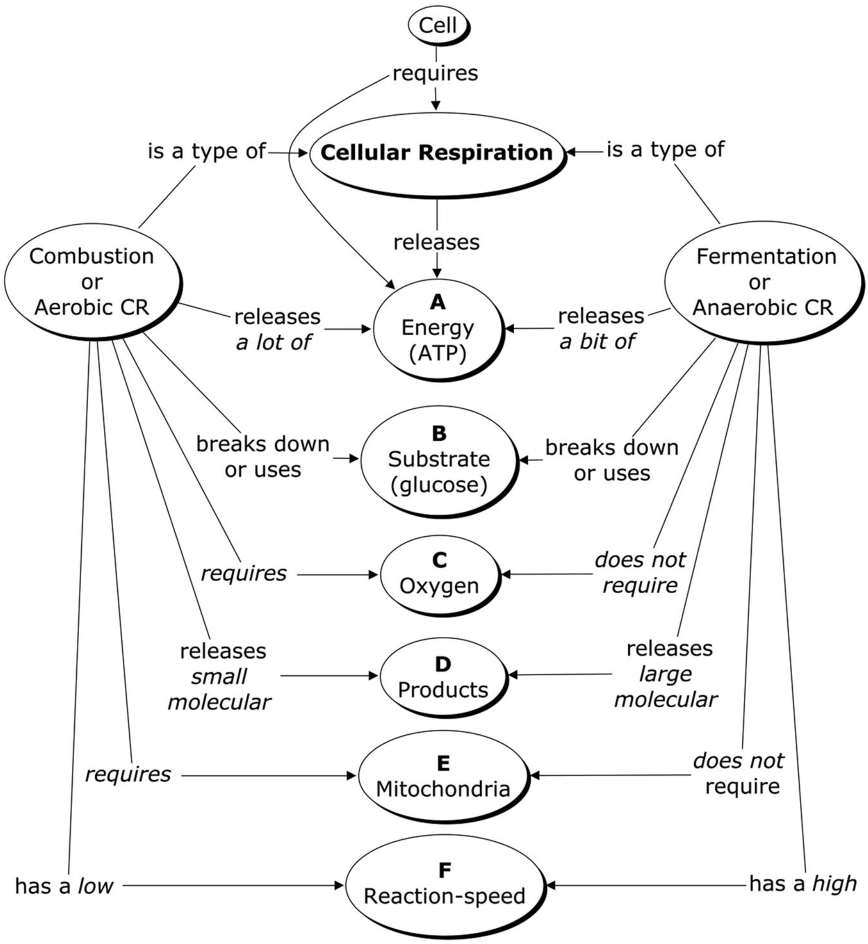

Figure 1. Cognitive elements of cellular respiration.

explaining the differences in the muscular structure and function between different athletes requires a far more detailed understanding of cellular respiration. Among other aspects, one needs at least some understanding of its function in energy supply, the products released by its aerobic and anaerobic variants, and the differences in the speed between these processes. This perspective led to the identification of six conceptual elements of cellular respiration, described in Figure 1.

The instrument decomposes the concept of cellular respiration into six 'conceptual elements' used to define and categorise the different variants of the process. Element A relates to the core function of cellular respiration: releasing energy from energy-rich substances and the differences in the amount of energy released between aerobic and anaerobic cellular respiration. Element B pertains to the substrate for cellular respiration (with glucose as a prototypical example) and use of this substrate in aerobic and anaerobic cellular respiration. Element C pertains to the requirement of oxygen in aerobic cellular respiration and the lack thereof in anaerobic cellular respiration, while element D represents its by- or waste-products and the differences between aerobic and anaerobic cellular respiration. Element E pertains to the mitochondria as the organelles responsible for a complete and aerobic breakdown of substrate.[2]

A more detailed description involving mitochondrial enzymes and membranes, and their involvement in oxidative phosphorylation and the citric acid cycle could provide a more accurate description of the required structures for aerobic cellular respiration and would improve students' understanding of the process. However, such explanations would demand a highly detailed understanding of (sub-) molecular interactions not available to, or expected of, all students in Dutch biology classes at this level of secondary education. The final element F is the only element that is not incorporated in the syllabus for biology education, but was considered to be crucial for a proper understanding and use of cellular respiration in the context of exercise physiology.

The core idea of cellular respiration that was intended for the students to grasp during the lesson module was the idea that the breakdown of energy-rich (organic) molecules releases energy. This idea can be described as the core of the cellular respiration concept and combines the conceptual elements A, B and D.

These conceptual elements were used to identify the aspects of cellular respiration that students used in their concept maps and their answers to the items of the recontextualising test. Categories for a coding scheme were developed using an inductive approach, informed by the data from the first design cycle and guided by the preliminary learning and teaching strategy and lesson module. This process involved several cycles in which coding categories were devised, revised and discarded, before a preliminary coding scheme, including detailed descriptions of each element, was prepared. Next, all concept maps and data from the recontextualising test were coded separately by two researchers in biology education, according to the preliminary coding scheme. Each coded fragment was discussed until inter-subjective agreement was reached (Patton, 2003; Smaling, 1992). Finally, the final coding scheme was determined for use in the second research cycle. The final coding scheme was further discussed with two other researchers, one a biology education researcher and another a pedagogy researcher specialised in activity theory for education.

3.3.1. Analysis of the concept maps

All concept maps were analysed by two researchers with the final coding scheme and the Cohen's kappa were calculated (Table 4). Cohen's kappa scores are a coefficient for the

Table 4. Values for Cohen's kappa for the analysis of students' concept maps.

	A Energy	B Substrate	C Oxygen	D Products	E Mitochondria	F Speed
Kappa 1	0.53	0.21	0.68	0.68	0.59	0.63
Category	Moderate	Fair	Substantial	Substantial	Moderate	Substantial
Kappa 2	1.00		0.79	0.72	0.77	0.72
Category	almost perfect		substantial	substantial	substantial	substantial

Notes: The kappa 1 values pertain to the correct inclusion of a cognitive element, independent of whether or not it also differentiated between aerobic and anaerobic respiration; the kappa 2 values refer to the concept maps that differentiated between aerobic and anaerobic cellular respiration, whether or not the differentiation was correct. The letters A through F depict the conceptual elements for describing aerobic and anaerobic respiration. These were identified as part of our analysis instrument (see Figure 1). Element refers to the amount of energy released (A), the substrate used (B), the need for oxygen (C), its chemical products (D), the role of mitochondria (E) and the speed of the process (F). There is no kappa 2 given for element B, because it did not differentiate between aerobic and anaerobic respiration.

inter-rater reliability. In this case, they reflect the extent to which both researchers agreed on the conceptual elements displayed in each concept map. The values for category relate to particular categories for kappa values described in Altman (1991). The Cohen's kappa for concept maps that differentiated correctly between aerobic and anaerobic respiration was calculated separately and varied from substantial to almost perfect. The conceptual elements described in Figure 1 were used to analyse the concept maps of both the pre- and post-tests. Thus, Figure 1 can be interpreted as our 'reference concept map' used for describing students' understanding of cellular respiration before and after the lesson module. For a more detailed description of students' expected understanding at both times, we refer to the description of the lesson module in a previous article (Wierdsma et al., 2015).

3.3.2. Analysis of the recontextualising test

The final coding scheme was also used to analyse students' answers to the recontextualising test items, and again Cohen's kappa were calculated (Table 5). The values for category relate to particular categories for kappa values described in Altman (1991).

4. Results

4.1. The development of students' ability to recontextualise cellular respiration

To provide an overview of students' development of the ability to recontextualise cellular respiration the following data-sets were analysed: students' concept maps designed in the pre-test, their concept maps designed in episodes 14 and 15, and the concept maps constructed in the post-test (see Table 1). The values for Cohen's kappa for the analysis of the concept maps (see Table 4) indicate an acceptable inter-rater reliability, suggesting that the coding of conceptual elements that students explicated in their concept maps can be considered reliable. This is especially true for the coding of whether or not a student correctly explicated the difference between aerobic and anaerobic respiration. The results of the analyses are presented in Tables 6 and 7. The tables include the combined data of both case studies.

The results of the pre-test show that most students were able to correctly connect glucose to the combustion process (element B). The important function of energy release for combustion (element A) was described in about half the concept maps, and about the same percentage indicated the necessity of oxygen for combustion. In only a small percentage of concept maps, the distinction between aerobic and anaerobic respiration (Table 7) was made.

Table 5. Values for Cohen's kappa (kappa) for the analysis of students' answers to recontextualising test items.

	A Energy	C Oxygen	D Products	E Mitochondria	F Speed	Core
Kappa	0.77	0.63	0.78	0.90	0.62	0.68
Category	Substantial	Substantial	Substantial	Almost perfect	Substantial	Substantial

Notes: The values pertain to the correct use of an element in an answer. Element B is not included here, because it did not differentiate between aerobic and anaerobic respiration.

Table 6. The percentage of concept maps that correctly included a conceptual element for cellular respiration in the pre-test (T0), the implemented curriculum (T1 and T2) and post-test (T3).

T	Data-set	A Energy %	B Substrate %	C Oxygen %	D Products %	E Mitochondria %	F Speed %
T0 ($n = 38$)	Pre-test	52.6	76.3	55.3	26.3	23.7	0.0
T1 ($n = 22$)	Ep. 14	77.3	86.3	95.4	77.2	72.7	22.7
T2 ($n = 19$)	Ep. 15	100	100	94.7	94.7	73.7	15.8
T3 ($n = 23$)	Post-test	91.3	78.3	100	4.3	82.6	13.0

The results of episodes 14 (T1) and 15 (T2) show that most concept maps included elements A–E, but that most concept maps did not include element F. Furthermore, most concept maps differentiated correctly between aerobic and anaerobic respiration.

To illustrate students' development of cellular respiration, Figures 2–5 show the concept maps constructed by two students (Miranda and Roelof[3]) during the pre-test (Figures 2 and 3) and post-test (Figures 4 and 5), in case study 2. Miranda's pre-test concept map (Figure 2) describes the process as combustion, with a focus on the cell as the biological object where it takes place. Her concept maps states that glucose and oxygen enter the cell, which extrudes energy and carbon dioxide. It also appears to locate metabolism inside the cell and the mitochondrion as part of a cell, but since these connections lack a description, we cannot be sure about this. In terms of the analysis instrument used for describing students' use of cellular respiration (Figure 1), her pre-test concept map uses parts of the conceptual elements A (energy release), B (breakdown of a substrate), C (need for oxygen) and D (products) without making a distinction between aerobic and anaerobic respiration. Miranda's post-test concept map (Figure 4) only clearly displays the elements A, B and C, but now describes how elements A and C can differ between aerobic and anaerobic respiration. Judging by his pre-test concept map (Figure 3), Roelof appears to also grasp the basic concept of combustion, but he does not connect the different labels with each other that much. His concept map does mention glucose as the substrate to be combusted. It shows carbon dioxide as a 'waste product from energy', which seems to illustrate that this student does not have a clear idea yet of how carbon dioxide and energy are connected. In terms of the conceptual elements in Figure 1, Roelof's pre-test concept map partially displays the elements A, B, C and D. After following the lesson module, Roelof constructed his post-test concept map (Figure 5), which displays the same conceptual elements as the pre-test and now, like Miranda's, distinguishes between aerobic and anaerobic respiration. Also, Roelof's post-test concept map adds element E (aerobic respiration requires mitochondria) to further differentiate between aerobic and anaerobic respiration.

Table 7. The percentage of concept maps that correctly differentiated between aerobic and anaerobic respiration for a conceptual element in the pre-test (T0), the implemented curriculum (T1 and T2) and post-test (T3).

T	Data-set	A Energy %	C Oxygen %	D Products %	E Mitochondria %	F Speed %
T0 ($n = 38$)	Pre-test	0.0	18.4	0.0	0.0	0.0
T1 ($n = 22$)	Ep.14	40.9	90.9	77.3	54.5	22.7
T2 ($n = 19$)	Ep.15	94.7	84.2	94.7	63.1	15.8
T3 ($n = 23$)	Post-test	73.9	100	4.3	56.5	13.0

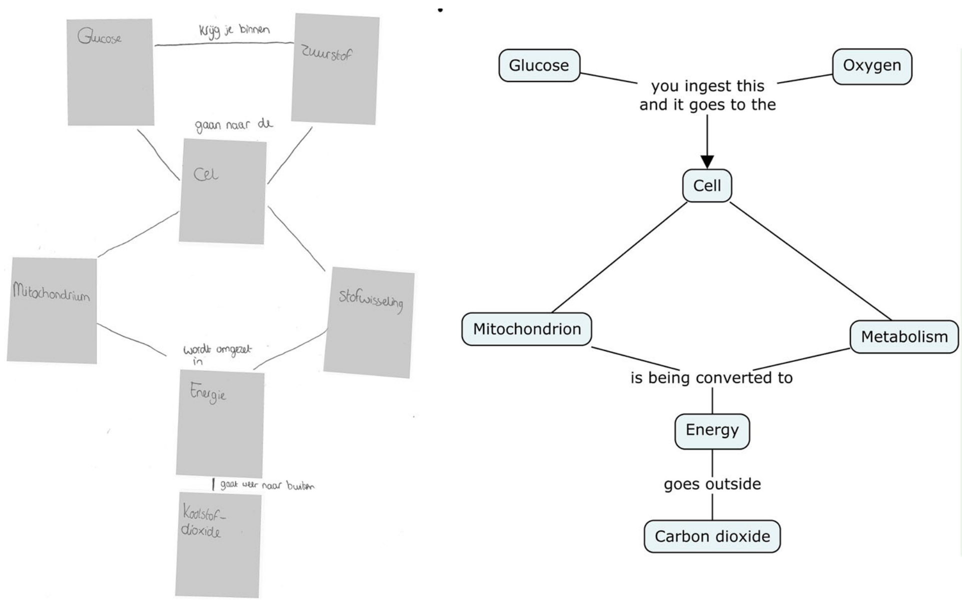

Figure 2. Pre-test concept map by Miranda (case study 2). The image on the left shows the original concept map in Dutch, with its English translation at the right.

If we compare the results from the post-test with those from the pre-test for all students, it can be concluded that most students correctly used elements A, B and D and that a large number of students correctly used conceptual elements to make distinctions between aerobic and anaerobic respiration. Element F was hardly used with success, which is not very surprising since a comparable result was recorded for T1 and T2 (see Tables 6

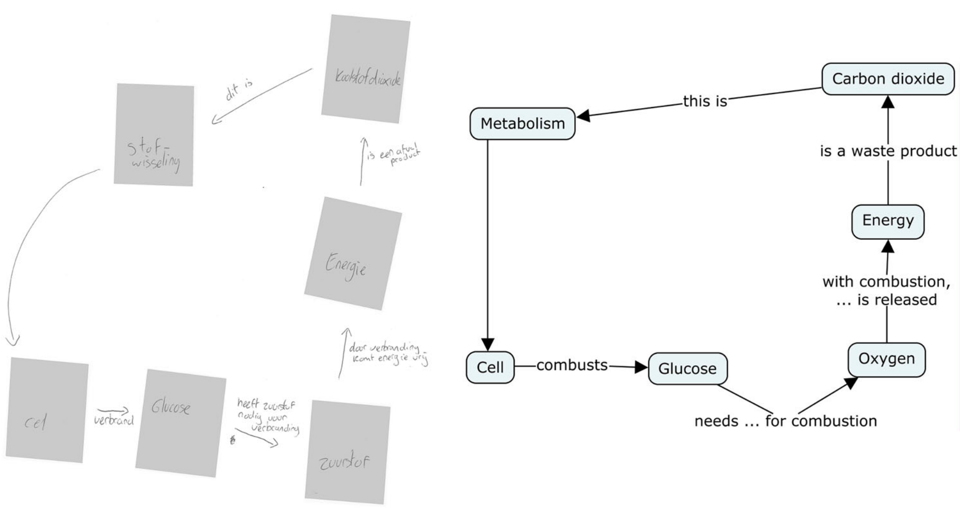

Figure 3. Pre-test concept map by Roelof (case study 2). The image on the left shows the original concept map in Dutch, with its English translation at the right.

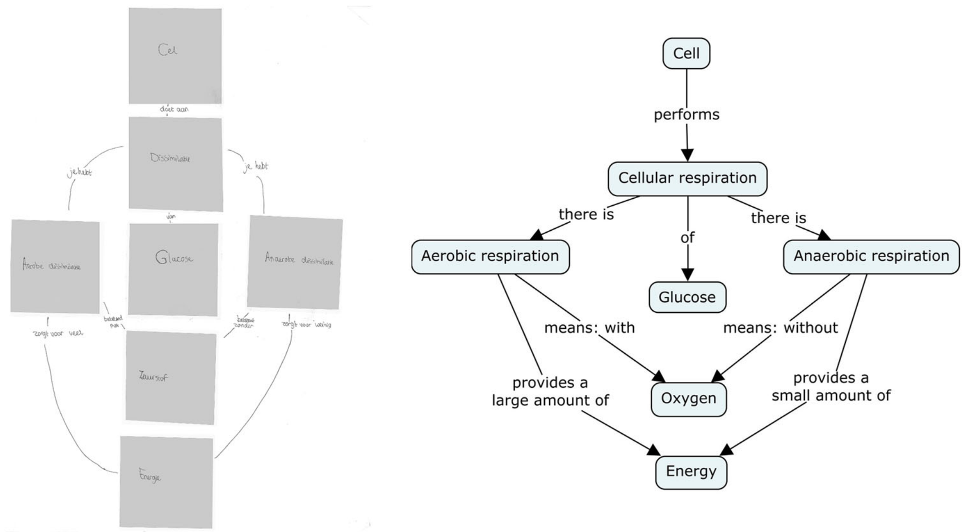

Figure 4. Post-test concept map by Miranda (case study 2). The image on the left shows the original concept map in Dutch, with its English translation at the right.

and 7). What is surprising, however, is the low percentage of concept maps that included component D, compared with the percentages from T1 and T2. This remarkable low percentage may be explained by the omission of the label 'carbon dioxide' in the post-test, which might also explain the lack of that element in student Miranda's post-test concept map (Figure 1), although she did incorporate it into her pre-test concept map (Figure 4). However, the results T1 and T2 indicate that most students were able to distinguish the products in aerobic respiration from the products in anaerobic respiration

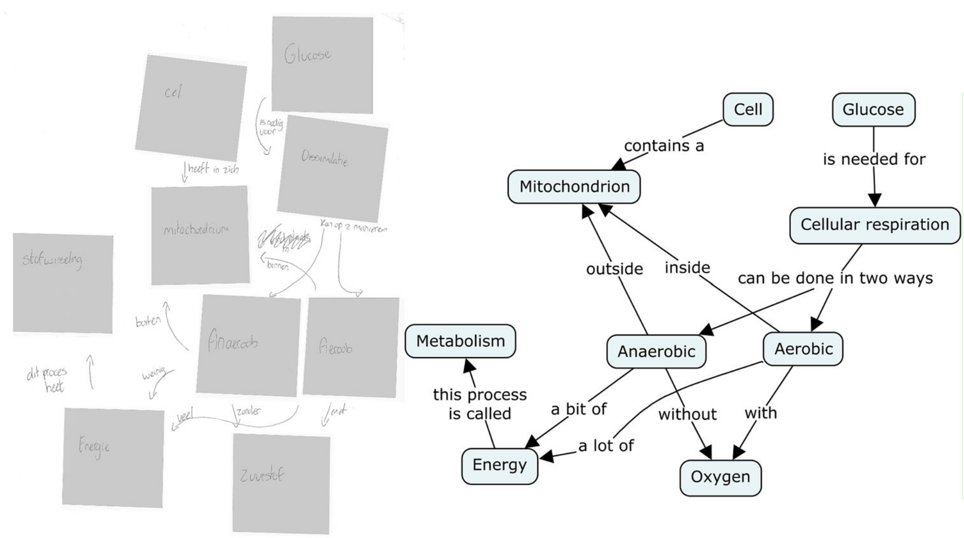

Figure 5. Post-test concept map by Roelof (case study 2). The image on the left shows the original concept map in Dutch, with its English translation at the right.

Table 8. Number and percentage (between brackets) of conceptual elements used in the recontextualising test per item by students from both cases ($n_{1/2} = 44$).

Item	Object (context)	Question	A Energy	C Oxygen	D Products	E Mitochondria	F Speed
1	Yeast (yeast)	Select aerobic CR	23 (52.3)	9 (20.4)			
2 + 3	Humans (muscle cells)	Explain differences between athletes	24 (54.5)	19 (43.2)	14 (31.8)	17 (38.6)	14 (31.8)
4	Yeast (wine)	Explain need for anaerobic CR		12 (27.3)	31 (70.5)		
5		Name gas from anaerobic CR		0 (0.0)	23 (52.3)		
6	Bacteria (bacteria)	Explain lack of aerobic CR				9 (20.4)	
7		Predict consequences of no CR	5 (11.4)				
8	Bacteria (waste water)	Explain need for aerobic CR	5 (11.4)	3 (6.8)	10 (22.7)		
9		Select aerobic CR	2 (4.6)	1 (2.3)	9 (20.4)		
10	Humans (patients' cells)	Explain lack of aerobic CR				8 (33.3)	
11		Explain lack of aerobic CR	16 (66.7)				

Notes: Items 10 and 11 were only included in the test in the second case study ($n_2 = 24$). Only the conceptual elements that are needed for a correct answer to a particular test item are included.

in their concept maps. This indicates that the students did not include D in their concept maps, simply because the label was not prescribed.

4.2. Results of the recontextualising test

Table 8 summarises the results of students' use of conceptual elements for both case studies in the recontextualising test. Only those elements that are needed for a correct explanation are included in Table 8. These values can be considered fairly reliable, based on Cohen's kappa values for the analysis of the recontextualising test in Table 5. The numbers represent the number and percentages of students that correctly used an element in their answers to the test items.

Table 8 presents that most students still had quite a lot of trouble with using cellular respiration in unfamiliar contexts, after having explored the concept in three different contexts during the 9–10 lessons that preceded the recontextualising test.

4.3. Interpreting the results of the recontextualising test

In order to discuss these differences in more detail, it should be remembered that items 2 and 3 were included in the test to allow comparison with the results from the analysis of the concept maps, since the context of these items is the same as the exercise physiology context in the lesson module (see Table 3). A comparison with the results from the concept maps (Tables 6 and 7) reveals that the percentages for items 2 and 3 are rather low and therefore suggest an underestimation of students' understanding of cellular respiration. This assumption is supported by the high percentages of element D for items 4 and 5 (70.5% and 52.3%); consequently, the percentages for element D for items 4 and 5 are probably a better representation of the students' understanding.

Table 8 also presents that students appeared to have the least problems with relating cellular respiration to familiar, yeast-related contexts in comparison to the other contexts in the recontextualising test. These differences are now discussed in more detail to find possible explanations of the differences between the results from items dealing with different contexts.

The first comparison is between muscle cells and the two contexts with yeast as the biological object of focus. The percentage of students that answered items 1, 4 and 5 correctly is high, although not as high for elements A and C. This result is not unexpected, since both contexts were expected to be quite familiar due to their strong relation to the biotechnology context in the lesson module. Therefore, we can conclude that recontextualising cellular respiration to a familiar, yeast-related context was not very problematic for many students.

Comparing the results between the two yeast contexts, we can see that students do perform better for item 4 (focused on the production of wine) than item 1 (focused on the production of yeast). A possible explanation for these differences could be whether or not a biological object is part of the objective (as in the production of yeast) or just a tool (as in the production of wine) in a given context. Yeast's role as a tool only requires a superficial understanding of the concept yeast. A view of yeast as an ingredient for wine production (that can easily be obtained from supermarkets or specialised brewery suppliers) is probably enough to come to a proper solution in this context. In contrast, the context of item 1 involves the explicit manipulation of yeast itself, and as such requires a more complex view of cellular respiration and yeast. It involves the view that yeast needs to obtain energy from food to sustain its needs, and that anaerobic conditions are far from ideal with regard to its reproduction, which requires far more energy than merely sustaining its basic functions.

A comparison between the bacteria-related contexts and students' use in items 2 and 3 indicate that recontextualising cellular respiration to bacteria-related contexts caused more problems than the yeast-related contexts. Although many students correctly used element A for describing differences between athletes in exercise physiology, only a very small number of them also used these in a correct answer to the test items in bacteria-related contexts. Similar results can be seen for the other elements needed for correctly answering these items. The results indicate that most students had problems with recontextualising cellular respiration in bacteria-related contexts and that bacteria-related contexts were not very familiar to the students. This could be due to any difficulty with understanding bacteria as self-organising entities. In addition, the context of a dentist and a biological engineer of items 6 and 7 pertained to bacteria living in a symbiotic relationship with humans. This context requires a detailed view of the bacteria as self-organising entities, as well as their capability and need to perform cellular respiration. Here, the bacteria are the object(s) being manipulated (quite literally, in biological terms). In the context of cleaning waste water (items 8 and 9), the view on bacteria is much simpler, since they are just tools for cleaning waste water.

If we compare the results for bacteria-related contexts with yeast-related contexts, it is evident that a lower percentage of students adequately answered items about bacteria-related contexts, which may indicate that bacteria did present a difficulty for students when trying to recontextualise cellular respiration.

To compare bacteria-related contexts with human-related contexts, the results of items 10 and 11 are compared with the results of items 6 and 7. Items 10 and 11 were added to mirror items 6 and 7. Both items 6 and 10 required an understanding that without any mitochondria cells do not have the ability to use aerobic respiration. The results from these test items are similar not only when compared with each other, but also when compared with the results from items 2 and 3. This indicates that it was not the differences between the contexts, but students' understanding of element E that was the problem here. However, items 7 and 11 yielded very different results. Although the results from these items may indicate bacteria as the problem, students' difficulties with recontextualising in item 7 might also be explained by other differences between both items. One other important difference between both items is the type of explanation that is needed from students to give a correct answer. In item 7, students were asked to explain what would happen to bacteria if they lost the ability to respire glucose altogether. In other words, the cause (no respiration) is given and students need to come up with a possible effect (death) through element A (a lack of energy). In item 11, students are asked why patients with dysfunctional mitochondria often feel tired. Here, both cause (dysfunctional mitochondria) and effect (tired patients) are given, and students are only asked to explain their connection through element A (a lack of energy). This difference may also be an explanation for the differences between students' performance for items 7 and 11. Again, these results are not conclusive as to whether it was a difference between the biological object of focus between these contexts, or other differences between the items.

4. Conclusions and discussion

To answer the first research question 'to what extent do students develop the ability to recontextualise cellular respiration?', the analysis of students' concept maps showed that most did develop a conception for cellular respiration that correctly included elements A–D. Roughly half of the students did correctly understand the need for mitochondria in aerobic respiration. As for the difference in speed, most of the students did remember its significance, but did not connect it directly to the process at the cellular level of biological organisation. To test their ability to recontextualise, a recontextualising test was developed that invited students to answer questions that referred to cellular respiration in different contexts. The results of this test showed that most students still had trouble with using cellular respiration in unfamiliar contexts, after having explored the concept in three different contexts during the 9–10 lessons that preceded the recontextualising test. They appeared to have the least problems with relating cellular respiration to yeast-related contexts in comparison to the other contexts. However, the test also shows that recontextualising an abstract and complex concept like cellular respiration in biology classes is possible.

In order to answer the second research question, an explanation of students' ability to recontextualise is required. That requires an interpretation of the results of the recontextualising test. The analysis suggested that differences in students' performances for different items and contexts in the recontextualising test may be explained by the following variables:

- The *biological object of focus* in the different contexts, in particular the s*tudents' familiarity* with the biological object.
- *The role of a biological object in an activity, that is whether it is a part of the objective in an activity or used as a tool or instrument.*
- *Students' performance for different cognitive elements in the previous lesson module.*

Our finding that students' familiarity with a biological object of focus (such as the organism, type of cell or ecosystem) in a context has a strong impact on their use of cellular respiration corresponds to findings from research on assessment instruments for evolutionary reasoning (Nehm & Ha, 2012; Nehm, Beggrow, Opfer, & Ha, 2012; Opfer, Nehm, & Ha, 2012). These studies showed that students were more inclined to use key concepts for evolution (such as variation, differential survival and heredity) when asked to explain evolutionary changes in a familiar species than unfamiliar species. In our theoretical framework, we described conceptual understanding in close relation to perception of objects and events and their use in goal-oriented activities (Novak, 1990; Novak & Cañas, 2004, 2007; van Oers, 2001). Students' unfamiliarity with specific organisms or taxa might prevent them from linking a problem to a specific concept. For instance, when looking at the results from the recontextualising test in this study it may be the case that students who do not perceive bacteria as self-organising entities in need of energy cannot be expected to connect their perception of bacteria with cellular respiration. As such, they are unable to perceive and use cellular respiration as a tool for understanding and solving the problem presented to them. Nehm and Ridgway (2011) showed similar results for the concept of evolution and students' perception of problems that differed in context-specific features. In another study, Opfer et al. (2012) showed how students had difficulty solving problems with the concept evolution where the familiarity of taxa was manipulated. Along with our findings, these studies suggest that the issue of familiarity with organisms or taxa is an important factor in conceptual understanding and worthy of our attention in future research regarding students' understanding and use of biological concepts in varying contexts.

This means that designers of LT activities and assessment instruments should take these surface features into account. For instance, we might take students' (expected) familiarity with a particular object of focus into account when grading their performance in assessment tasks and design LT activities that allow students to familiarise themselves with a larger variety of biological objects such as plants, bacteria or specific cell types. Both these studies on evolutionary concepts (Nehm & Ha, 2012; Nehm et al., 2012; Opfer et al., 2012) and cellular respiration illustrate how understanding of a biological concept is context dependent and not easily transferred from one context to another. When confronted with novel contexts involving unfamiliar organisms as object of focus, students appear to fall back on other reasoning patterns instead of mechanistic reasoning patterns that can be helpful in finding biological explanations. It might be possible that a strong focus on the biological object involved hinders sufficient explication of the concept and how it is used to explain a specific phenomenon, leading to students connecting a concept with a specific object of group of similar objects and not to others. When asked to explain a phenomenon in another, more unfamiliar or apparently unrelated biological object, it appears that many people tend to fall back on other concepts or explanations that they are more familiar with, instead of using a concept that is relatively new from their perspective and does not appear to be related to the object or phenomenon presented in a new context. Similarly, the role of a biological object of focus as a tool in a context appears to induce a superficial understanding of cellular respiration, only focusing on those elements that are directly related to the specific goals in a context. A final possible explanation for the differences in student performance in different contexts can be interpreted as the influence of prior knowledge. In other words, if students have shown to correctly understand and use a conceptual element during LT activities, they are more likely to correctly use the element in another context during assessment.

The results of the analysis of the concept maps and recontextualising test also contribute to improvement of the learning and teaching strategy. Improvement seems desirable, not only of the available lesson module, but also in a wider scope. Considering a desirable improvement of the available lesson module, the results indicated that improvement of the last part of the strategy is required, in particular for element F. The available strategy was developed with the assumption that coverage between the conceptual content and learning objectives would be required, and that students should have the opportunity to develop all conceptual elements. Therefore, it may be supposed that a more stepwise introduction of element F would be desirable. A second improvement might be to include a recontextualising test in the design of the lesson module and to round it off with a plenary reflection where the recontextualising test and the outcomes are discussed. This can expose students to other contexts and biological objects in which the concept can be used to solve certain types of phenomena and allow them to develop a more flexible understanding of that concept. Recontextualising cellular respiration (or any other concept) in a large variety of contexts probably requires more focus on it in different contexts; reflection certainly contributes to that (e.g. van Oers, 2001).

The results of the recontextualising test also indicate that to recontextualise cellular respiration in a variety of contexts, students should be given more time to focus on that concept. The interpretation of the results suggested that students' familiarity with objects of focus and actions shapes their perception of possible concepts as tools for understanding. This may be an important factor in students' efforts to recontextualise. Consequently, to improve the results it may be necessary to pay attention to the development of students' familiarity with a diversity of objects and actions. That requires an analysis of the objects and actions that determine the desired variability to recontextualise cellular respiration. It certainly also requires more learning time, and it seems questionable whether this familiarity can be acquired in the same learning and teaching sequence, and if it is not recommendable to extend the ability to recontextualise the concept in a sequence of lesson modules, with opportunities to familiarise with other objects and actions in between. Unfortunately, the new biology examination programmes do not offer the opportunity to spend so much time on the development of just one concept. Eventually, in the future, when more studies on recontextualising are available, and if there is broad support for it, it might be necessary to make a choice between learning to apply a small number of concepts in a large diversity of contexts (including a diversity of objects and actions), or to restrict the diversity of contexts for a larger diversity of concepts. With respect to recontextualising and transfer, the first of these options is preferable. This would allow students to develop the ability to recontextualise scientific concepts, which can help them to transfer their understanding of this and other concepts to other practices. In addition to this preparation for future learning (Bransford & Schwartz, 1999) by developing the ability to recontextualise, students can be expected to develop a deeper understanding of a concept since they can devote more time and attention to this specific concept. In order to achieve such a focus on a smaller number of concepts, it is necessary to identify core concepts for – in this case – biological understanding. Current secondary school curricula are often filled with so many different concepts that many students fall back on rote learning strategies instead of deepening their understanding of them. Of course, identifying the concepts that are central to biological understanding will also require policy makers to make a conscious choice for a restricted set of concepts, which may represent an even greater challenge than identifying core concepts.

Because of its detailed and mostly qualitative nature, our study involved a small number of students in just two different schools in the Netherlands and did not produce enough quantitative data to allow for a definitive conclusion as to the success of the described LT strategy. However, this study offers a fruitful approach for viewing the transfer problem for a specific biological concept from a cultural-historical perspective. By focusing in detail on the process of recontextualising, we have shown how such a perspective can help in understanding how people develop a concept during a series of LT activities and how this aided and hindered them in recognising that concept's use in other contexts. Of course, a lot more research on how people recontextualise a concept is necessary in order to provide a sufficient description of affordable actions involved in recontextualising, which teachers can use to intervene in students' learning process as needed. An important avenue for future study lies in the outcomes of an improved strategy for cellular respiration. Adaptations of the recontextualising test, of different versions of it, may result in confirmation of the suggested explanations for the differences between the results on different items. Data for such a study may be supplemented with a number of student interviews. Another line is to broaden the debate by focusing on other concepts. For example, the concept ecosystem may be an interesting example, because it can be expected to be applied differently in a variety of contexts. And finally, it appears fruitful to focus on the variables that may explain differences in students' performances with explanations in different contexts.

Notes

1. The terms 'upper general secondary education' and 'pre-university education' reflect different levels of education in the Dutch secondary school system where students are separated according to their cognitive level after year 6 (student-age 11–12) of compulsory education. Upper general education can best be compared with years 10 and 11 (student age 16–17) of compulsory education in other countries, while pre-university education can be compared with years 10, 11 and 12 (student age 16–18).
2. This is not entirely accurate since some bacteria *are* able to respire aerobically without mitochondria. In fact, the widely accepted theory of endosymbiosis *requires* the existence of such bacteria before they were incorporated as mitochondria.
3. In order to preserve the privacy of the students in this study, the names used here are aliases.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Bert van Oers http://orcid.org/0000-0001-9371-9126

References

van den Akker, J. J. H., Gravemeijer, K. P. E., McKenney, S., & Nieveen, N. (2006). Introducing educational design research. In J. J. H. van den Akker, K. P. E. Gravemeijer, S. McKenney, & N. Nieveen (Eds.), *Educational design research* (pp. 3–7). London: Routledge.

Altman, D. G. (1991). *Practical statistics for medical research*. London: Chapman & Hall.

Beach, K. (1999). Consequential transitions: A sociocultural expedition beyond transfer in education. *Review of Research in Education*, *24*, 101–139.

Binkley, M., Erstad, O., Herman, J., Raizen, S., Ripley, M., Miller-Ricci, M., & Rumble, M. (2011). Defining twenty-first century skills. In P. Griffin, B. McGaw, & E. Care (Eds.), *Assessment and teaching of 21st century skills* (pp. 17–66). Dordrecht: Springer Netherlands.

Boersma, K. T., van Graft, M., Harteveld, A., de Hullu, E., de Knecht-van Eekelen, A., Mazereeuw, M., … van der Zande, P. A. M. (2007). *Leerlijn biologie van 4 tot 18 jaar vanuit de concept-contextbenadering* [Biology curriculum for ages 4 to 18 based on the concept-context approach]. Utrecht: Commissie Vernieuwing Biologie Onderwijs.

Bransford, J. D., & Schwartz, D. L. (1999). Rethinking transfer: A simple proposal with multiple implications. *Review of Research in Education*, *24*(40), 61–100.

Dyson, A. H. (1999). Transforming transfer: Unruly children, contrary texts, and the persistence of the pedagogical order. *Review of Research in Education*, *24*, 141–171.

Engeström, Y. (1991). Non scolae sed vitae discimus: Toward overcoming the encapsulation of school learning. *Learning and Instruction*, *1*(3), 243–259.

Engle, R. A. (2006). Framing interactions to foster generative learning: A situative explanation of transfer in a community of learners classroom. *Journal of the Learning Sciences*, *15*(4), 451–498.

Greeno, J. G. (2006). Authoritative, accountable positioning and connected, general Knowing: Progressive themes in understanding transfer. *Journal of the Learning Sciences*, *15*(4), 537–547.

Kay, K., & Greenhil, V. (2011). Twenty-first century students need 21st century skills. In G. Wan & D. Gut (Eds.), *Bringing schools into the 21st century* (pp. 41–65). Dordrecht: Springer.

Klaassen, C. W. J. M. (1995). *A problem-posing approach to teaching the topic of radioactivity* (Doctoral dissertation). Utrecht University. CD-β Press.

Kozulin, A. (2001). *Psychological tools: A sociocultural approach to education*. Cambridge, MA: Harvard University Press.

Kozulin, A. (2003). Psychological tools and mediated learning. In A. Kozulin, B. Gindis, V. S. Ageyev, & S. Miller (Eds.), *Vygotsky's educational theory in cultural contexts* (pp. 15–38). New York, NY: Cambrdige University Press.

Lijnse, P. L. (1995). "Developmental research" as a way to an empirically based "didactical structure" of science. *Science Education*, *79*(2), 189–199.

Lin, C., & Hu, R. (2003). Students' understanding of energy flow and matter cycling in the context of the food chain, photosynthesis, and respiration. *International Journal of Science Education*, *25*(12), 1529–1544.

Lobato, J. (2006). Alternative perspectives on the transfer of learning: History, issues, and challenges for future research. *Journal of the Learning Sciences*, *15*(4), 431–449.

Marton, F. (2006). Sameness and difference in transfer. *Journal of the Learning Sciences*, *15*(4), 499–535.

Nehm, R., Beggrow, E., Opfer, J., & Ha, M. (2012). Reasoning about natural selection: Diagnosing contextual competency using the ACORNS instrument. *American Biology Teacher*, *74*(2), 92–98.

Nehm, R., & Ha, M. (2012). Item feature effects in evolution assessment. *Journal of Research in Science Teaching*, *48*, 237–256.

Nehm, R., & Ridgway, J. (2011). What do experts and novices 'see' in evolutionary problems? *Evolution: Education and Outreach*, *4*, 666–679.

Novak, J. D. (1990). Concept maps and Vee diagrams: Two metacognitive tools to facilitate meaningful learning. *Instructional Science*, *19*(1), 29–52.

Novak, J. D., & Cañas, A. J. (2004). *Building on new constructivist ideas and CmapTools to create a new model for education*. Paper presented at the concept maps: Theory, methodology, technology. Proceedings of the 1st international conference on concept mapping. Pamplona, Spain: Universidad Pública de Navarra.

Novak, J. D., & Cañas, A. J. (2007). Theoretical origins of concept maps, how to construct them, and uses in education. *Reflecting Education*, *3*(1), 29–42.

van Oers, B. (1998a). The fallacy of detextualization. *Mind, Culture, and Activity*, *5*(2), 135–142.

van Oers, B. (1998b). From context to contextualizing. *Learning and Instruction*, *8*(6), 473–488.

van Oers, B. (2001). Contextualisation for abstraction. *Cognitive Science Quarterly*, *1*(3), 279–305.

Opfer, J., Nehm, R., & Ha, M. (2012). Cognitive foundations for science assessment design: Knowing what students know about evolution. *Journal of Research in Science Teaching*, *49*(6), 744–777.

Patton, M. Q. (2003). *Qualitative research and evaluation methods* (3rd ed.). London: Sage.

Prins, G. T., Bulte, A., & van Driel, J. H. (2008). Selection of authentic modelling practices as contexts for chemistry education. *International Journal of Science Education*, *30*(14), 1867–1890.

Royer, J. M., Mestre, J. P., & Dufresne, R. J. (2005). Framing the transfer problem. In J. P. Mestre (Ed.), *Transfer of learning from a modern multidisciplinary perspective* (pp. vii–xxvii). Greenwhich, CT: Information Age Publsihing.

Schönborn, K. J., & Bögeholz, S. (2009). Knowledge transfer in biology and translation across external representations: Expert views and challenges for research. *Journal of Research in Science Teaching*, *7*(5), 931–955.

Smaling, A. (1992). Varieties of methodological intersubjectivity — the relations with qualitative and quantitative research, and with objectivity. *Quality and Quantity*, *26*(2), 169–180.

Songer, C., & Mintzes, J. J. (1994). Understanding cellular respiration: An analysis of conceptual change in college biology. *Journal of Research in Science Teaching*, *31*(6), 621–637. 621.

Ummels, M. (2014). *Promotong conceptual coherence within biology education based on the concept-context approach* (Doctoral dissertation). Radboud University Nijmegen.

Ummels, M. H. J., Kamp, M. J. A., de Kroon, H., & Boersma, K. Th. (2014). Designing and evaluating a context-based lesson sequence promoting conceptual coherence in biology. *Journal of Biological Education*. http://www.tandfonline.com/doi/pdf/10.1080/00219266.2014.882380

Van Mil, M. H. W., Boerwinkel, D. J., & Waarlo, A. J. (2011). Modelling molecular mechanisms: A framework of scientific reasoning to construct molecular-level explanations for cellular behaviour. *Science & Education*, advanced online publication, 1–26. doi:10.1007/s11191-011-9379-7

van Weelie, D. (2001). Contextualizing biodiversity. In O. De Jong, E. Savelsbergh, & A. Alblas (Eds.), *Teaching for scientific literacy: Context, competency, and curriculum* (pp. 99–116). Utrecht: Utrecht University, Centre for Science and Mathematics Education.

van Weelie, D. (2014). *Recontextualiseren van het concept biodiversiteit* [Recontextualising the concept biodiversity] (Doctoral dissertation). Utrecht University. Utrecht: FIsme scientific library.

van Weelie, D., & Wals, A. (2002). Making biodiversity meaningful through environmental education. *International Journal of Science Education*, *24*(11), 1143–1156.

Wenger, E. (1999). *Communities of practice: Learning, meaning, and identity*. Cambridge: Cambridge University Press.

Westbroek, H. B., Klaassen, C. W. J. M., Bulte, A., & Pilot, A. (2005). Characteristics of meaningful chemistry education. In K. T. Boersma, M. J. Goedhart, O. de Jong, & H. M. C. Eijkelhof (Eds.), *Research and the quality of science education* (pp. 67–76). Dordrecht: Springer.

Wierdsma, M. (2012). *Recontextualising cellular respiration* (Doctoral dissertation). Utrecht University. Utrecht: FIsme scientific Library.

Wierdsma, M., Knippels, M. C., Van Oers, B., & Boersma, K. (2015). Recontextualising cellular respiration in upper secondary biology education. Characteristics and practicability of a learning and teaching strategy. *Journal of Biological Education*. doi:10.1080/00219266.2015.1058842

Yin, R. K. (2003). Designing case studies. In R. K. Yin (Ed.), *Case study research. Design and methods* (Vol. 2, pp. 19–53). London: Sage.