Recontextualising Cellular Respiration

Designing a learning-and-teaching strategy for
developing biological concepts as flexible tools

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Dissimilatie Recontextualiseren

Het ontwerpen van een onderwijsleerstrategie
voor het ontwikkelen van biologische concepten
als flexibel gereedschap

(met een samenvatting in het Nederlands)

Proefschrift

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door

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Voor Loes en Tjitte

Thesis Contents

Chapter 1

Introduction

1.1 Scope of the research project and main research question

A major theme in educational research is the transfer of knowledge: the use of knowledge in situations other than the situation where it was learned or developed. In fact, knowledge-transfer appears to be a prime objective of (senior general) secondary education, which aims to enable students to develop a large body of knowledge that they are expected to use during their future professional and personal lives. This idea of knowledge-transfer between situations has been around for more than a century and seems to be something that takes place on a regular basis with most people (see the review by Lobato (2006) for a history on transfer research). However, it is very hard to attain intentionally in education or find proof of its occurrence in education research. Fuelled by disappointing results from previous research on transfer, a number of different researchers proposed a change of perspective on the phenomenon (Beach, 1999; Bransford & Schwartz, 1999; van Oers, 1998a). From a cultural-historical perspective on learning, van Oers (1998a; 1998b) proposed the idea of *recontextualising*. This idea is based on activity theory and views concepts as tools for use in activities (contexts). Within this view, to use a concept in a new and different context means to use such a tool in a different manner. By doing so, we change our perspective on that concept as well as the meaning of the concept, which can be redesigned to better fit its new purpose. Eventually, this can allow us to develop a concept as a flexible tool that can be used in a variety of different contexts, and even be redesigned if necessary.

In 2013, a new biology curriculum will be introduced for senior general (HAVO) and pre-university (VWO) secondary education in the Netherlands. This new biology curriculum has its basis in the concept-context approach for biology education, which is in turn partially based on activity theory and the idea of recontextualising (Boersma & Schermer, 2001; Boersma et al., 2007). One of its explicit objectives is to enable students to be able to recontextualise their knowledge from one context to another. Here, context is defined as a social practice: the culturally defined practice of a key activity by people with related goals, motives, and who use a common set of tools (for instance: concepts). The concept-context-approach intends for students to develop biological knowledge in relation to the social practices in which this knowledge is used (Boersma, Kamp, van den Oever, & Schalk, 2010). From a perspective of knowledge (such as concepts) as tools that are used in activities, it seems reasonable to assume that students can best develop this knowledge by using these tools (Bennett, Lubben, & Hogarth, 2006; van Aalsvoort, 2004). In other words: by exploring or simulating social practices that use biological knowledge. By allowing students to explore and use a biological concept in different social practices, they may see how its meaning can change with different use and purpose, and develop a concept as a dynamic and flexible tool. In other words: students should be able to recontextualise this concept for use in a new context. Previous studies in context-based biology education did aim at students developing biological concepts by exploring it in different contexts (van Weelie, 2001; van Moolenbroek 2012). However, these studies did not aim specifically at the problem of recontextualising a concept. Currently there are no empirically tested learning-and-teaching[1] (LT-) strategies for context-based biology education that specifically aim for students to develop a concept for flexible use.

Therefore: the *main objective* for this research project is to develop an LT-strategy for learning and teaching biological concepts for flexible use.

An answer to this question requires a detailed look at the process of recontextualising, as well as an instrument for determining students' ability to recontextualise a concept across different contexts. A suitable research strategy for attaining these objectives is developmental or design research (Lijnse, 1995; van den Akker, Gravemeijer, McKenney, & Nieveen 2006). This is a common research tradition at (among other institutes) the Freudenthal Institute for Science and Mathematics Education (FIsme). Design research aims to develop and test educational interventions (such as LT-strategies) in an iterative design process. With each cycle or iteration, an LT-strategy (or part thereof) is tested in (a) classroom practice(s). The resulting LT-process and its learning outcomes can be observed, recorded and analysed in detail by comparing it with a hypothesised learning trajectory or scenario. Reflections on the LT-process and its outcomes, as well as on the design-process itself, may allow for a more detailed perspective on (in this case) recontextualising and contribute to transfer research from a cultural-historical perspective. Therefore, this research project adopts a design-research strategy and aims at answering the following research question:

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[1] Although the common abbreviation is 'TL-' (teaching-and-learning), the term for his thesis is 'LT-' (learning-and-teaching). This is to emphasise the central activity of *learning* in educational practices. From a broad perspective, *teaching* can be viewed as a *specialised* function within the activity of learning.

Research Question (RQ)	How can a learning-and-teaching (LT-) strategy, aimed at the flexible use of biological concepts through recontextualising, be structured?

The term 'structure' should here be interpreted in a broad sense: it includes a content-specific sequencing of LT-activities. This research question was further detailed in four sub-questions, which are summarised below and indicated with RQ I to IV in this thesis. The rationale behind these research questions will be further elaborated in chapter 2.

RQ I Which design criteria for an LT-strategy for recontextualising biological concepts can be identified from an empirical and theoretical exploration of recontextualising?

RQ II Which design criteria for an LT-strategy for recontextualising cellular respiration can be identified from a theoretical exploration of cellular respiration?

RQ III How can we determine students' ability to recontextualise cellular respiration to other contexts?

RQ IV To what extent can the LT-strategy be considered adequate for promoting students' understanding of cellular respiration and their ability to recontextualise cellular respiration to other contexts?

The following sections of this chapter describe the theoretical framework for this research project and provide a description of the concept of cellular respiration for purposes of this research project on recontextualising.

1.2 Concepts, Contexts, and Recontextualising

Transfer revisited

Within studies of knowledge construction, the transfer of knowledge has been studied intensively (Beach, 1999; Billing, 2007; Bransford & Schwartz, 1999; Dyson, 1999; Engeström, 1991; Engle, 2006; Greeno, 2006; Kneppers, van Boxtel, & van Hout-Wolters, 2009; 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. The idea was first proposed by Thorndike at the start of the twentieth century to challenge the traditional educational practices that centred on rote-learning strategies (Lobato, 2006). With learning and knowledge construction being primarily viewed as a cognitive activity, the focus was on knowledge construction 'in' or by individuals.

While this cognitive view does acknowledge the influence of culture and social interaction on knowledge construction and transfer, their part in an individual's cognitive construction is mostly ignored or treated as an independent variable. This isolated, cognitive view on transfer made the phenomenon hard to study and even harder to intentionally bring about in students.

By the end of the last century, a number of different 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; van Oers, 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: a complicated network of past and present social interactions. These authors argued that transfer was not rare, and that the main failure in transfer research was the view on transfer itself. It was supposed that knowledge cannot directly be applied to a new situation because the meaning of this knowledge is context-dependent. This means that previously learned knowledge has to be adapted to fit the new situation, thereby changing the new situation as well. Where previous perspectives on transfer approached it primarily as a spontaneous occurring phenomenon, these new perspectives emphasize a more active process of adapting knowledge for using it in another situation. Bransford and Schwartz (1999) took a more cognitive view on the matter and described their perspective as a 'preparation-for-future-learning'. From this perspective, knowledge acquisition is not done for the sake of the knowledge in itself, but to prepare people for better learning in the future. Instead of focusing on the direct application of developed knowledge in new situations, they argued that researchers and teachers should focus on how these experiences help people to better interpret future situations and determine what knowledge they already have and what they still need to develop. For yet another perspective, Beach and van Oers took a closer look at social processes and activities involved in transfer. Beach (1999) uses the term 'consequential transition' to refer to the transfer of knowledge from one social practice to the next. These consequential transitions always involve some change in the developing relation between individual and one or more social activities. This relationship changes through change in the individual, the activities, or (most of the time) both. By conscious reflection, the transition changes one's sense of self and social position. This change is what makes the transition *consequential* for the individual. In essence, transfer becomes a transitional problem instead of a simple application of knowledge. Van Oers (1998a; 1998b) uses the term ‘recontextualising’ to refer to the transfer process. His view seems similar to Beach’s consequential transitions. In fact, both terms seem to relate to the same process. The difference between the two terms seems to be in the kind of transfer that occurs. Consequential transitions refer to changes of perspective that bring about a significant, personal change in a person’s role and personality. Most of the time, this involves transitions in which people become part of a new social practice, learn a new profession or a new way to practice their profession. Recontextualising refers to changes in activity; these can but do not need to involve strong personal consequences. The idea of recontextualising focuses on the process of change, rather than its (personal) consequences. Thus, one can say that a consequential transition always involves recontextualising, but not the other way around.

Context

Most theories on transfer acknowledge that this process is dependent of the content of the knowledge to be transferred (domain specificity) and the manner in which this knowledge is initially learned (situatedness). The term ‘context’ is often used to depict one or both of these aspects of knowledge. Several authors have tried to define the concept of context. For instance, van Oers (1998b) reviews several interpretations of context, such as: context as mental surroundings, as meaningful social situations, and as activity. Similarly, Gilbert (2006) distinguishes four models for context used in chemistry education and focuses on the relation between concepts and contexts (pp. 966-971). His descriptions of different meanings of context seem to increase in complexity from a direct application of concepts in different situations, to social activities that shape, and are shaped by the concepts used in these activities. With his fourth model that describes context as the social circumstances, he refers to activity theory and the description by van Oers (1998b).

In activity theory and van Oers’ descriptions of recontextualising, an activity is a psychological unit used for analysing human behaviour. In these perspectives, the activity forms the context (van Oers, 1998a; van Oers, 1998b): people engage in 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: social practices (Wenger, 1999). In other words, social practices are formed by practitioners participating in a central activity, which is shaped by the cultural history of that activity and its practitioners, and can involve several activities that differ between practitioners. Since the idea of recontextualising is based in activity theory, the following example is included to clarify the perspective on activities and social practices in activity theory. Imagine, for example, a small-town bakery with two practitioners: a baker and a shop-assistant. Both share a common *motive* to make money, which stems from their *need* to support their personal lives and cultural *rules* such as the use of money to buy goods and services. They hope to satisfy their common motive by engaging in the shared, *central activity* of *selling bread*. The *object* in this activity is *bread*, and *sold bread* is its *goal*. Although the baker and the shop-assistant are engaged in the *central activity* of selling bread, they are each engaged in entirely different activities; in activity theory, this is called the *division of labour*. For instance: the baker's main activity will be *baking bread,* while the shop-assistant is engaged in the actual selling of the bread. To perform these specialised activities, both have their own collection of (conceptual) tools. The baker for instance, needs to know how to use the different instruments and ingredients in his bakery in order to make different types of bread. The shop assistant in turn, needs to know the process for the different types of bread by heart and has probably a number of different ways of dealing with specific customers. Tools that they both use, especially those needed for communicating about their activity, will have *shared meanings*. Examples of such tools are: the different types of bread and the names they use for those, a shared idea for fresh or stale bread, money, working hours, etc. The activity gives meaning to all of its components (i.e.: the motives and goals, the rules, tools and instruments, participants, etc.). At the same time, the different components provide meaning to the activity: due to differences between activities, the meanings of these components differ between activities. For instance, the baker will probably have different concept of 'fresh' than a fisherman, because both use the concept in relation to different objects.

A description of *context* for this thesis

Where activity is the context in van Oers' descriptions of recontextualising; the focus of the concept-context approach for secondary biology education is on the definition of context as a social practice. However, during the explorative phase of this research project it became apparent how this definition of context as an entire social practice can lead to 'over-contextualisation’ and the introduction of too many concepts at the same time (see chapter 3). Therefore, this thesis refers to a context as follows:

A context is the focus on a specific part or *key activity* in a social practice: an activity that aims at solving a specific problem or question that arises from the central activity in a practice. Without removing the entire practice from view, this interpretation means to emphasise the need for focusing on a part of a social practice instead of the practice as a whole, while still allowing a view on how a specific problem is embedded within a social practice.

Concept

Based on insights from both Novak (Novak, 1990; Novak & Cañas, 2004; Novak & Cañas, 2007) and van Oers (2001), a concept can be defined as the *perception* of a regularity or pattern in objects or events, based on a generic principle or model. 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. Activity is embedded and shaped by the culture and history of its participants and because concepts are an integral part of activity, concepts are similarly embedded.

In individuals, concepts might be described as the complex interplay of cognitive processes within the dynamic system that is the combination of one’s mind and body, in relation to its surroundings (Smith & Thelen, 2003; Smith, 2005). Although this perspective focuses on an individual’s perspective on conceptual development, it is not meant to imply that people develop concepts in isolation. In fact, this perspective of an individual mind as a dynamic system in interplay with its *surroundings* should be interpreted to include the physical, as well as social surroundings of that system. Within such a system, new conceptual networks (not to be confused with neuronal networks) might be rather unstable at first, but these can get stabilised when used more often. Just like the repeated use of a physical tool such as a hammer can improve a person’s ability with that tool, people’s ability to use a concept can also improve by using it repeatedly. Using a concept in different contexts can increase the (personal) body of knowledge that is structured with the concept, and enhance its general applicability.

In social practices, concepts are used to communicate and structure the knowledge within and between practices. The knowledge in these practices is developed by the application of ideas to explain patterns or regularities in the world, which in turn gives rise to new ideas. Those ideas and labels that most comprehensively and efficiently help in this perception and explanation will be used more often than others. Most concepts are traditionally described in definitions, which focus on the relations between phenomena that a concept refers to. These definitions help us to set these phenomena apart from other phenomena referred to by other concepts and provide a social, common ground for communicating our thoughts and ideas related to specific phenomena. However we must take care not to view these definitions as the concepts themselves, lest we risk viewing concepts as stable entities in and of themselves. Any definition of a concept is essentially created for purposes of communication. It is a product of activity and strongly connected to the social practice(s) that needed the definition. This means that – although definitions are valuable for and have a purpose in communication – education should not be merely about teaching definitions. It should instead 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 ability of defining, rather than (just) the product of this activity (a definition).

A description of *biological concept* for this thesis

Based on the concept-context approach a number of central concepts were defined that structure large amounts of biological knowledge (Boersma, Kamp, van den Oever, & Schalk, 2010). Staying close to that description, this thesis adopts the following description of biological concepts:

A biological concept is a tool that is used for understanding living systems; a collection of rules, observations, experiences, etc. that is structured under a common label with a shared meaning across most biological practices. It structures a significant amount of theoretical knowledge and provides a biological perspective to activities in social practices.

Recontextualising

Van Oers (2001) describes how a concept can be 'abstracted' or generalised from context-specific meanings by contextualising a concept in different contexts. This is an on-going process of redefining one's activities by recounting past experiences and selecting and adjusting the tools from these past experiences. Ideally, this process of continuous, progressive recontextualising should have two important learning outcomes for the individual. First, a generalised – biological – meaning of the concept becomes a tool that students can use to solve problems in several contexts. Second, a student becomes more and more practised in interpreting different contexts and solving problems from the perspective provided by the concept, while at the same time allowing the different contexts to reshape his or her view on the concept. In other words: students develop the ability to recontextualise a concept, allowing for a flexible use of that concept in a variety of contexts. In a commentary on two recent studies on transfer (Engle, 2006; Marton, 2006), Greeno (2006) identified two important aspects involved in transfer and recontextualising. The first is the development of *conceptual agency* in a domain by students through exploration of the similarities *and* differences between activities embedded in practices. Greeno describes acting with conceptual agency in a domain as treating the concepts, methods, and information of the domain as resources that can be adapted, evaluated, questioned and modified. Second, Greeno hypothesizes that for students to learn to act with conceptual agency, learning environments should be structured to position students as authoritative and accountable for their own learning and products. This means that LT-activities must be structured in such a way that students can be held accountable for the problems they explore and the answers to the problems they produce.

Recontextualising in the concept-context approach

The concept-context approach for biology education aims at enabling students to be able to recognize and use biological concepts as tools for making sense of the world. Students should understand the use of concepts in different life-world, professional, and scientific practices. Life-world practices are social practices that are part of people’s personal lives, while professional practices are geared towards the production of goods and services to fulfil needs of other social practices. Scientific practices are professional practices as well, but where life-world and professional practices produce and describe knowledge in service of their specific goals, scientific practices seek to produce knowledge for its own sake. Concepts that are used by one social practice have their meaning changed when adopted by other practices. Although most biological concepts have similar meanings in different biological practices, the differences between these meanings can generate difficulties for students when trying to use a concept in different contexts. This description of recontextualising in the concept-context approach is different from van Oers' descriptions of recontextualising in that it focuses on social practices and the differences in a concept's use between practices. This means that in the concept-context approach, recontextualising occurs when an LT-process moves from the exploration of one social practice to another. Van Oers on the other hand, describes recontextualising in terms of differences between activities, which implies that recontextualising can also occur when moving from one activity to another *within* the exploration of the same social practice.

In addition to this horizontal change of meaning between social practices, many biological concepts refer to different levels of biological organisation and change their meaning vertically with each step up or down along these levels of biological organisation. In order to be able to navigate among these different meanings successfully, students need to engage in a process of continuous, progressive recontextualising (van Oers, 2001) and generalise their knowledge by using this while engaging in or exploring different social practices. In addition, this might open them up to the idea that they are acquiring knowledge that is of actual use in their current and/or future lives, providing possible motives for learning. 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 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; van Weelie, 2002), provide an example of how students develop this concept by reviewing and reformulating its definition for different contexts, i.e. by recontextualising biodiversity.

A description of *recontextualising* for this thesis

In conclusion, this thesis adopts a broad description of recontextualising, referring to the descriptions of context and concept described in this section:

Recontextualising is the process of people re-evaluating and changing their perspective on a concept, instigated by using it in another context (i.e.: by viewing the other context from the perspective of the concept). It can also be instigated by changes in the 'original' context that require a different perspective due to, for instance: unexpected observations, changes in rules, or changes in the level of biological organisation from which a problem is viewed. During this process, new perspectives (i.e.: possible meanings and uses) are added to the set of rules, observations, experiences, etc. that form the concept. As this collection of perspectives grows, the need for communication drives people to define concepts that have shared meanings in more generalised descriptions that they can agree upon. Although the resulting definitions do have their use, it is the activity of creating these generalised descriptions that allows people to build and structure different perspectives in one or more concepts. A larger collection of possible uses and meanings for a concept enables people to see other possible uses more easily and successfully use it in other contexts.

1.3 Defining cellular respiration

Having established a theoretical description of the problem of transfer and recontextualising in the previous section, this section provides a description of the concept that was chosen as a vehicle for this research project on recontextualising biological concepts: *cellular respiration*. This concept was chosen as the main vehicle for this research project during its first, explorative phase (see chapters 2 and 4). The choice for this concept was inspired by an empirical exploration of a context-based lesson module in practice, and confirmed with a theoretical investigation of biology and biology education research literature. This exploration revealed important learning difficulties for students with regard to this concept. In addition, cellular respiration structures a significant amount of biological knowledge and can be regarded as an important concept in biology; it refers to processes that are crucial for all living organisms. Finally, the concept has been given an undeservingly low amount of attention from education research practices in comparison to other biological concepts. These statements ask for a more detailed explanation, which is provided in the fourth chapter of this thesis.

Although the use of a single label (i.e.: cellular respiration) may suggest that the concept refers to a single and clearly defined biological or biochemical process, in reality it refers to a lot of different biochemical processes, with variations within and between types of organisms and biological circumstances. In addition, the concept is used by many different social practices, each with its own interpretation of the concept (see section 1.2). In order to avoid confusion as to the meaning of the concept for purposes of this research project, a clear definition is required.

The description of cellular respiration in this thesis is based on descriptions of cellular respiration from two prominent biology textbooks for university level education (Campbell & Reece, 2005; Mader, 2003), and several education research articles (Sanders, 1993; Seymour & Longden, 1991; Songer & Mintzes, 1994). The textbooks for biology education provide distinct descriptions of the concept in definitions, whereas the perspective used in education research articles is implied in their descriptions of learning problems and students' conceptions of cellular respiration. Further comparison of these different perspectives on cellular respiration revealed important differences between them.

The education research articles generally base their analysis of learning problems and students' conceptions on an all-encompassing view on (cellular) respiration, including both the aerobic and anaerobic (fermentative) processes. This is reflected in the authors' judging of certain statements as correct or incorrect, such as the following two statements from education research articles. The first statement is taken from a list of 'misconceptions' from Seymour and Longdon (1991), while the second is marked as a correct description of the process by Sanders (1993):

Statement 1: *"No living things can respire in the absence of oxygen." (Seymour&Longdon, 1991: table 3, p.182)*

Statement 2: *"Respiration: a chemical process occurring in all organisms all the time, to break down energy-rich compounds to provide energy for all metabolism." (Sanders, 1991: fig.1, p.924)*

The following description is taken from Campbell and Reece's "Biology"' and also reflects the view in Mader's "Inquiry into Life", which excludes anaerobic respiration from its definition:

Statement 3: "(…) metabolic pathways that release stored energy by breaking down complex molecules are called catabolic pathways. One catabolic process, ***fermentation****, is a partial degradation of sugars that occurs without the use of oxygen. However, the most prevalent pathway is* ***cellular respiration****, in which oxygen is consumed as a reactant along with the organic fuel. In eukaryotic cells, mitochondria house most of the metabolic equipment for cellular respiration." (Campbell, 2005: p 161)*

Clearly, statement 3 reserves the term “cellular respiration” for the aerobic process, while the term “catabolism” is used to also include fermentation. In contrast, the first two statements include both the aerobic and anaerobic variants when speaking of (cellular) respiration. While this may seem trivial, it is crucial in any analysis of students’ conceptions or determination of so-called ‘misconceptions’. A person with a view on cellular respiration based on prominent biology textbooks (statement 3) would probably mark statement 1 as correct, while this is noted as an important misconception of cellular respiration in the education research literature. Without noting either of these views as correct or incorrect, this clearly makes a case for providing a clear definition of the concept for purposes of any education research project. Additionally, any definition for this research project in Dutch biology education should – where possible – reflect the views in Dutch biology education as well. This requires a consideration of the Dutch terminology: a literal translation of the term "cellular respiration" does exist (“celademhaling”), but is rarely used in biology education. A more prevalent term is “dissimilatie” [dissimilation] which in contrast seems to be known but not widely used in the English (biological) language, which frequently uses the term “catabolism”. A distinction between aerobic and anaerobic cellular respiration is made by adding these two terms as adjectives: “aerobe dissimilatie” [aerobic catabolism] versus “anaerobe dissimilatie” [anaerobic catabolism]. Since it reflects the Dutch description and is consistent with descriptions in biology textbooks, the English term “catabolism” could be a good candidate for our description of the concept used in this thesis. Obviously, we have not opted for this term. Despite of its apparent good fit, education-research literature that uses the term “catabolism” commonly incorporates a molecular or even sub-molecular (atomic) view on the process, including detailed descriptions of the chemical reactions involved in glycolysis, oxidative decarboxylation, the citric-acid cycle, oxidative phosphorylation, and the fermentation steps following glycolysis. Such a detailed view does not reflect the necessary detail for Dutch senior general secondary biology education. For this level of education, no molecular detail beyond the overall chemical reactions of the aerobic and anaerobic is required and thus does not have to be included in this LT-strategy[2]. To reflect the common view on the process in education-research literature, and to contrast this overall view with a more detailed molecular view, the term of choice for this thesis is “cellular

[2] The design was in fact open to such detailed descriptions, if it was believed to be instrumental in improving students’ understanding of the overall process.

respiration". The difference between the aerobic and anaerobic variants is made using the terms "aerobic respiration" and "anaerobic respiration" or "fermentation".

Having explained the first, major choices in defining "cellular respiration" for purposes of this research project, we can now produce a description of the concept as it is used in this thesis. Box 1.1 provides such a description, which is consistent with the conceptual elements of cellular respiration as described in chapter 2 and figure 2.7. The choices reflected in this definition are based on the design criteria for recontextualising cellular respiration developed during this research project (see chapter 4), the required level of detail prescribed for Dutch senior general secondary biology education, and contextual aspects of the concept.

Box 1.1: A general definition of cellular respiration within this research project

Cellular respiration: the collection of metabolic pathways that release stored energy by breaking down complex molecules, like glucose, into smaller and less complex ones. It can occur with the use of oxygen (aerobic respiration), but also without (anaerobic respiration or fermentation). The latter is a fast, but partial breakdown process, while the former employs oxygen for a more complete, but slower breakdown. Different organisms can use different kinds of anaerobic respiration; alcoholic and lactic acid fermentation are well-known and representative variants. In eukaryotic cells, mitochondria house most of the metabolic equipment for aerobic respiration while the first part of this process is performed in the cytoplasm, as is anaerobic respiration. Both processes consist of a series enzyme-mediated chemical reactions which, using glucose as exemplary fuel source, can be represented by the following chemical formulas:

Aerobic respiration:

glucose	+ oxygen	→ carbon dioxide	+ water	+ *energy*
$\mathbf{C}_6H_{12}O_6$	+ 6 O_2	→ 6 $\mathbf{C}O_2$	+ 6 H_2O	+ (*32-36*) *ATP*

Anaerobic respiration:

Alcoholic fermentation:

glucose		→ carbon dioxide	+ alcohol	+ *energy*
$\mathbf{C}_6H_{12}O_6$		→ 2 $\mathbf{C}O_2$	+ 2 $\mathbf{C}_2H_5OH$	+ *2 ATP*

Lactic acid fermentation:

glucose		→ lactic acid		+ *energy*
$\mathbf{C}_6H_{12}O_6$		→2 $\mathbf{C}_3H_6O_3$		+ *2 ATP*

The description in this chapter of the recontextualising process and the view on concepts as tools in activity mentions how any definition for a concept is part of the activity in which it was created. It is therefore *contextualised* within the activity of defining the concept, which is – in turn – part of a social practice. Examples of such defining-activities can be found in many educational and scientific practices, in attempts to structure the bodies of knowledge developed in these practices. Due to this inherent connection to the activity in which a definition was created, one definition can probably never encompass all possible contextualised perspectives on a concept. The definition created for purposes of this research project should be viewed similarly. It is intended to describe a perspective on the concept that is based on education research literature and text books for biology education. Since this research project focused on senior general education (see also: chapter 2), the description used in this thesis strongly reflects descriptions related to this concept in the attainment targets for this level of education (CEVO, 2007b).

1.4 Thesis outline

This thesis reports on the design research project for developing an LT-strategy for recontextualising biological concepts, and cellular respiration in particular.

Chapter 1 (this chapter) describes the scope of this research project and summarises the research questions. The theoretical framework introduces the idea of recontextualising as an alternative perspective on the use of concepts in different contexts. In addition, it describes how the concept of cellular respiration is defined for purposes of this research project, and finishes with this thesis overview.

Chapter 2 provides an overview of the methodology and design of this research project and the research questions that guided its explorative and design-research phase. It then continues with a detailed description of the research settings and data collection during each phase of the research project. In addition, it describes the research instruments that were developed for testing and determining students' ability to recontextualise cellular respiration. In that sense it provides a partial answer to RQ III.

Chapter 3 describes the development of design criteria for an LT-strategy aimed at recontextualising biological concepts. These criteria were developed during the explorative phase of this research project (see figure 2.1), and are based on empirical and theoretical notions. The chapter finishes with an answer to RQ I, by summarising design criteria for an effective LT-strategy for recontextualising biological concepts.

Chapter 4 provides an argumentation for the choice for cellular respiration as the concept of focus in this research project. It describes common problems with learning and teaching the concept that were derived from science education literature. It also provides a description of how the concept is approached in Dutch textbooks for biology education. Finally, the chapter provides an answer RQ II with a set of design criteria for an LT-strategy that aims at students to develop the concept of cellular respiration.

Chapter 5 starts with a discussion of three specific, social practices that were chosen as a basis for contexts in the design of a preliminary LT-strategy. It continues with a description of the intended learning trajectory for the LT-strategy, followed by a summary of the findings from its enactment in case studies α1 and α2 (design-research cycle 1). The chapter concludes with a summary of redesign considerations for the LT-strategy that were derived from these findings, and a brief description of the redesigned LT-strategy.

Chapter 6 describes the results from the second design research cycle (case studies β1 and β2), during which the redesigned strategy was tested in practice. It starts with a description of results from the analysis of a pre-test for determining student's prior knowledge of cellular respiration before the start of the first lesson. It then continues with a description the enactment of the LT-strategy in case studies β1 and β2 (design-research cycle 2), and the results from a post-test that was similar to the pre-test for assessing students understanding of cellular respiration after taking part in the LT-activities that make up the LT-strategy. It continues with a description of the results from a recontextualising-test that was designed to determine if and how students were finally able to use cellular respiration in other contexts. This chapter finishes the description of the two design-research cycles by providing an answer to research questions IV and V.

Chapter 7 discusses the findings from both research-cycles and returns to the main research question. It reflects on the designed LT-strategy for recontextualising cellular respiration and generalises it structure by identifying a LT-structure for recontextualising biological concepts in general. In addition, this chapter discusses how the developed research instruments may be generalised, and how these can provide insights in the process of recontextualising. As a part of this reflection, possible theoretical outcomes from this research project will also be discussed. Finally, this chapter finishes with possible implications for education and suggestions for future research.

Chapter 2

Methodology

This chapter describes the methodology for this entire design research project and includes a detailed description of the data collection and analysis instruments that were used during the explorative and design research phases. The first section (2.1) provides an overview of the design for the entire research project. Section 2.2 continues with a description of the research settings, data collection and analysis for the two empirical case studies that were part of the explorative phase of this research project. The research settings and data collections during the two design research cycles are respectively described in sections 2.3 (cases α1 and α2) and 2.4 (cases β1 and β2). Section 2.5 is a detailed description of the analysis instruments that were developed for assessing students' conceptual development of cellular respiration, as well as their ability to recontextualise this concept to other contexts.

2.1 Overview of this design research project

Background of this research project and main research question

This research project is set within a research tradition for science education common at the Freudenthal Institute for Science and Mathematics Education (FIsme) at Utrecht University. A number of other research projects for biology education at this institute have been based on, and have shaped ideas in the concept-context approach. These aimed at developing (context-based) LT-strategies for specific biological problems, such as modelling ecosystems (Westra, 2008), ethical and emotional decision making in the context of genetic testing (van der Zande, 2011), and the study of animal behaviour (van Moolenbroek, 2012). Other research projects in biology education from this institute were not as explicitly context-based, but also aimed at developing LT-strategies for specific biological problems, such as relating the different levels of biological organisation (Knippels, 2002) or biological system's thinking (Verhoeff, 2003). Aside from research in biology education, similar research projects for chemistry and physics education have provided insights in the use of a problem-posing structure for science education (Klaassen, 1995), and the selection of social practices for context-based science education (Prins, Bulte, & van Driel, 2008; Westbroek, Klaassen, Bulte, & Pilot, 2005). Together, these projects have led to a number of LT-strategies that can be used for designing context-based biology education. However, no LT-strategies were available at the start of this research project (in 2007) that aimed at *recontextualising* concepts, and biological concepts in particular. Therefore, the research question for this design research project was:

Research Question (RQ)	How can a learning-and-teaching (LT-) strategy, aimed at the flexible use of biological concepts through recontextualising, be structured?

In order to answer this question, this research project adopted an educational design research approach (Lijnse, 1995; van den Akker, Gravemeijer, McKenny, & Nieveen, 2006). Educational design research strategies aim at the design and redesign of interventions in an iterative design process (van den Akker *et al.*, 2006). These research strategies all aim at solving a specific education problem with a specially designed intervention, based on theory and empirical research. Such interventions are usually designed in an iterative process involving several cycles of design, empirical testing, redesign, etc. At FIsme, there is a tradition of design research that does not only focus on the design of a specific intervention, but rather on the development of theoretical insights in an educational problem (Boersma & Waarlo, 2009; Lijnse, 1995). This type of design-research has also been described as *developmental research*. The research project described here uses a similar approach with the development and redesign of a learning-and-teaching-strategy (LT-strategy) for recontextualising biological concepts. The emphasis of this project was as much on gaining a better understanding of the process of recontextualising as on developing an LT-strategy. This emphasis on developing a domain-specific theory touches on a description by Lijnse (1995) of a similar research approach. He uses the term 'developmental research', and emphasizes the development of domain-specific theory as part of the design-research process.

General structure for this research project

During the research project described in this thesis, there was a continuous dialogue between the (fledgling) theory of recontextualising biological concepts, the practical innovation represented in an LT-strategy with its scenario, and analysis of empirical results from testing the LT-strategy in classroom practices. The process itself can be viewed as a process of (re)constructing and recontextualising theory in various (domain-specific) classroom practices. Figure 2.1 shows the overall structure of this research project, which aims to combine both practical innovation and theory development. The explorative phase led to the development of an LT-strategy for recontextualising cellular respiration, which was tested and redesigned during the first design cycle. The second cycle aimed at guiding and analysing students' ability to recontextualise cellular respiration to a variety of contexts.

The project started with an explorative phase (see figure 2.1) for identifying design criteria for an LT-strategy that aims for students to develop and recontextualise biological concepts. This phase included an exploration of literature on transfer and recontextualising, and an empirical exploration of lesson modules for context-base biology education in two explorative case studies (Yin, 2003). The effectiveness of any LT-strategy for recontextualising can be highly specific for a concept, especially within the view on recontextualising described in chapter 1. This view emphasizes the recursive relation between the meanings of concepts and contexts. Thus, for any LT-strategy developed as part of this research project to be considered effective, a focus on a specific concept was necessary. After considering several possibilities, the concept of *cellular respiration* was chosen to be the central concept for the LT-strategy. Chapter 4 of this thesis, which describes design criteria for an LT-strategy for recontextualising that are specific for cellular respiration, also provides an argumentation for the choice for this concept in this design research project.

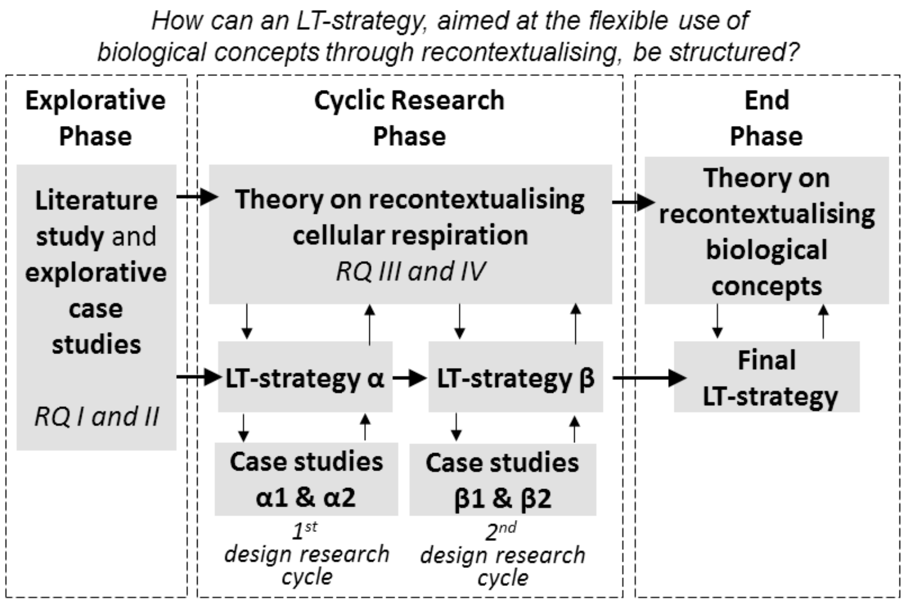


Figure 2.1. Structure of this design research project. Horizontal arrows depict the development and (re)design of a theory on recontextualising. Downward arrows depict the elaboration of a theory on recontextualising in an LT-strategy and case-specific LT-materials. Upward arrows indicate the reflection on the LT-strategy and theory, based on results from the case studies.

Specified for cellular respiration, the sub-questions for the explorative phase were:

RQ I Which design criteria for an LT-strategy for recontextualising biological concepts can be identified from an empirical and theoretical exploration of recontextualising?

RQ II Which design criteria for an LT-strategy for recontextualising cellular respiration can be identified from a theoretical exploration of cellular respiration?

During the design cycles an LT-strategy was designed and tested in an embedded case study structure (Yin, 2003). In the first (α) research cycle, a preliminary LT-strategy for recontextualising cellular respiration (see figure 2.1) was developed and tested in two subsequent case studies (cases α1 and α2). Similarly, the second (β) research cycle also comprised two case studies (cases β1 and β2).

The first cycle aimed at the development of an effective sequence and structure of LT-activities, based on design criteria developed during the explorative phase, as well as LT-structures from literature. This preliminary design was tested in two subsequent case studies (α1 and α2) during the first design research cycle (Yin, 2003). The findings from these two case studies were used to identify strengths and weaknesses in the preliminary LT-strategy. Additionally, an analysis instrument was developed for interpreting student answers and explanations in terms of using and recontextualising cellular respiration. This proved to be quite a challenge, with very few footholds from available literature on recontextualising and cellular respiration. Therefore, an analysis instrument for determining students' ability to recontextualise the concept in a variety of contexts was designed in relation to the LT-strategy and RQ III:

RQ III How can we determine students' ability to recontextualise cellular respiration to other contexts?

During the second research cycle, emphasis shifted towards further refinement of the preliminary analysis instrument from the first cycle and the explanation of possible learning outcomes from the LT-strategy: how students developed and used a conception of cellular respiration during the lessons and how they used this concept in other contexts. With an assessment- and analysis instrument for determining students' developing understanding of cellular respiration, as well as for determining their ability to recontextualise the concept to other contexts, the effectiveness of the LT-strategy in allowing students to do so can be assessed:

RQ IV To what extent can the LT-strategy be considered adequate for promoting students' understanding of cellular respiration and their ability to recontextualise cellular respiration to other contexts?

An answer to RQ III will allow for an indication of the effectiveness of the LT-strategy for recontextualising biological concepts in terms of promoting students' ability to recontextualise cellular respiration in a variety of contexts (RQ IV). The answers to these four sub-questions provide an answer to the main research question for this project. This answer is described and discussed in the final chapter in this thesis, in relation to the practical and theoretical insights gained from this research project and possibilities for generalising this LT-strategy for recontextualising other biological concepts.

2.2 Research methods in the explorative research phase

The explorative phase of this research project started with an exploration of the literature with a focus on transfer, recontextualising (activity theory), conceptual development, and context-based biology education. Additionally, an explorative empirical investigation of two different, context-based lesson modules was conducted; these theoretical and empirical explorations of recontextualising aimed at answering RQ I and RQ II:

RQ I Which design criteria for an LT-strategy for recontextualising biological concepts can be identified from an empirical and theoretical exploration of recontextualising?

RQ II Which design criteria for an LT-strategy for recontextualising cellular respiration can be identified from a theoretical exploration of cellular respiration?

The research settings for the two explorative case studies are described in table 2.1. Each of these case studies explored a context-based lesson module in practice; both lesson modules were designed by teachers. Module 1 (explorative case study 1) was designed by a teacher who participated in a preliminary design-team for designing exemplary lesson modules according to the guidelines from the new curriculum for biology education. Module 2 (explorative case study 2) was designed by a teacher who did not participate in this design team, but instead was working on a PhD research project involving the learning and teaching of animal behaviour (van Moolenbroek, 2012). It was expected that because these lesson modules were designed by teachers, an exploration of these could provide practical insights for structuring an LT-strategy not described in the literature.

Explorative case studies: lesson module 1 and lesson module 2

Both modules were designed for and carried out in senior general secondary education in two different schools. The basic characteristics of both these explorative case studies are summarised in table 2.1.

Table 2.1
Basic characteristics of both explorative case studies

	Explorative case study 1	Explorative case study 2
Biological subject area	Photosynthesis Cellular respiration Genetic modification Ecosystem research	Animal behaviour Hormonal regulation
Contexts	Brewing wine Crop farming	Caring for pets Caring for livestock
Designer	Teacher in a design team for the new context-based curriculum.	Teacher/PhD-student involved in development of a context-based LT-strategy for animal behaviour.
Year	10 (senior general secondary education)	10 (senior general secondary education)
Students	Mixed gender, ages 15-16 n= 17	Mixed gender, ages 15-16 n=22
Teacher	Same as designer (9 years of experience)	Other than designer (15 years of experience)
# lessons	21	12

The first module (1) was chosen for its innovative structuring of contexts in comparison to other structures used in the design teams. It primarily involved an exploration of photosynthesis and cellular respiration in a number of different contexts, such as agriculture and wine production. Module 2 was chosen because it was representative for the structure used by most designing teachers, although its designer was not a part of the aforementioned design-team.

Developing design criteria for recontextualising cellular respiration

Based on the explorative literature survey, extensive discussions with experts in biology education (teachers, teacher educators, and researchers), and observations in both explorative case studies, a set of criteria for effective learning and teaching of recontextualising was defined to serve as a basis for the analysis of the lesson modules. Figure 2.2 is a schematic representation of this iterative process.

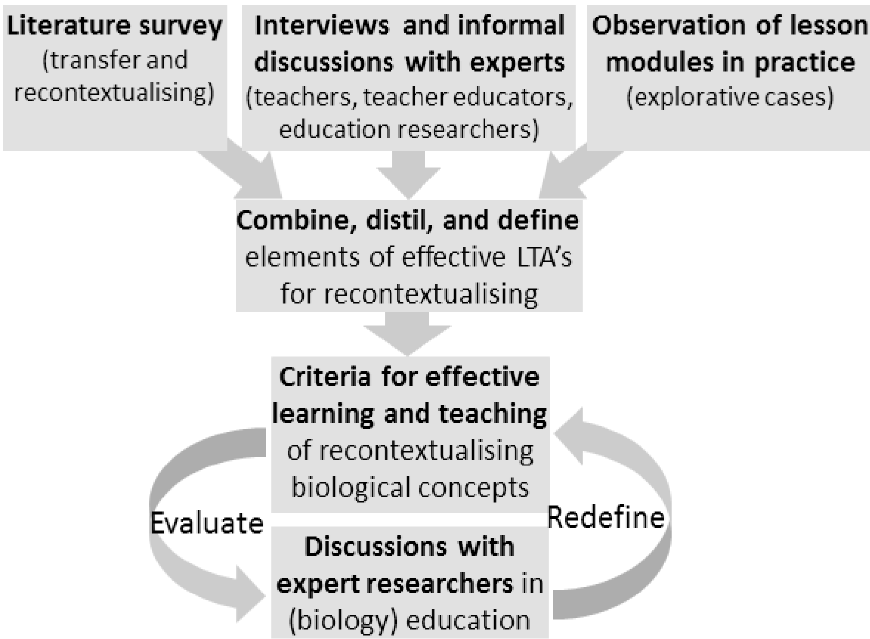


Figure 2.2. Development of criteria for analysing lesson modules in the explorative phase. Potentially effective LT-activities were identified from the literature, interviews with experts in (biology) education and observations of context-based lesson modules in practice.

The preliminary set of criteria was quite extensive with considerable overlap among criteria. Discussions with three expert researchers in biology education served to evaluate and redefine these criteria until agreement on two sets of criteria and their descriptions was reached.

Module 2 was designed by a researcher at FIsme who had elaborated the expected actions of students and teacher during each LT-activity in a scenario. A scenario is a detailed description of the expected actions of students and the teacher during enactment of the LT-activities and is a commonly used research and design instrument at this institute (Lijnse, 1995).

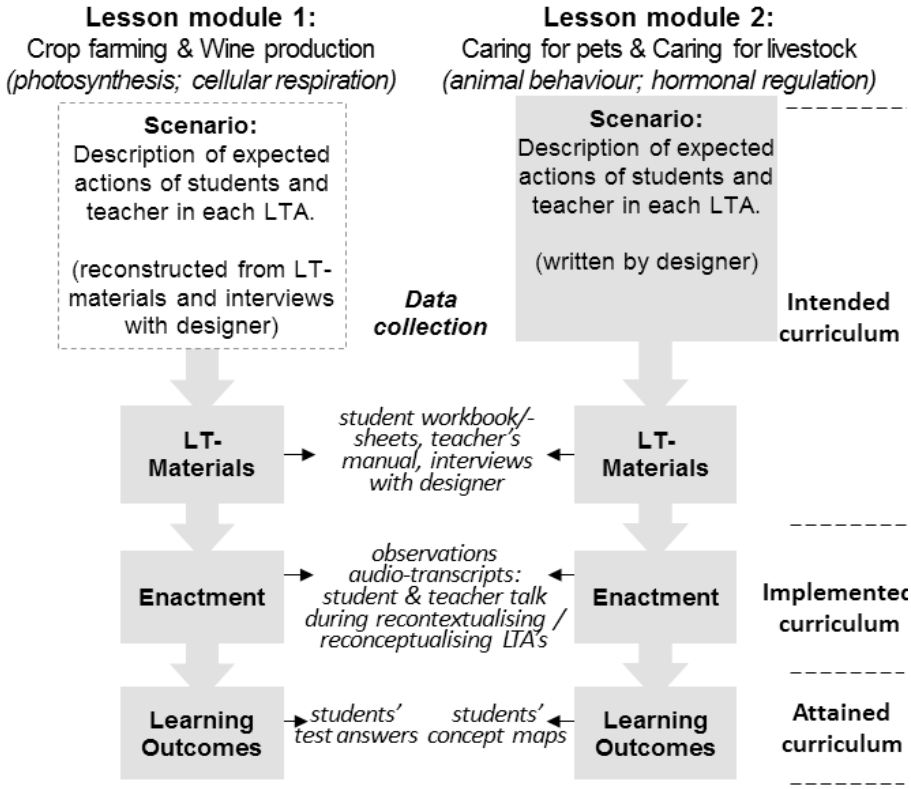


Figure 2.3. Data collection for both explored lesson modules. The scenario and LT-materials were used to gain a view on the intended learning trajectories for these lesson modules. In case of the first lesson module no scenario was present and had to be reconstructed before analysis.

In order to explain the differences between the learning goals and outcomes for each lesson module, the curricular levels of representation provided by Goodlad, Klein, and Tye (1979) were used to guide the collection and analysis of data. In terms of these curricular representations, the scenario, LT-materials in the module, and interviews with the designer provided a view on the *intended curriculum*. In case of the first lesson module (1), the designer was not a researcher at FIsme and had not developed a scenario prior to designing this module. For a proper view on this module's intended curriculum, a scenario was reconstructed based on interviews with the designer and the LT-materials. There can be quite a difference between the design and enactment of a lesson module (implemented curriculum), thus data on the enactment of both modules were collected as well, such as: observations of enacted LT-activities by the researcher, and transcripts of student and teacher talk during recontextualising or conceptualising LT-activities. These served to reconstruct the implemented curriculum in both lesson modules. As with the intended curriculum, the reconstruction of the implemented curriculum could then be compared to the analysis criteria. Although this description suggests a judgement on the effectiveness of the both lesson modules for recontextualising, this was not the aim of this explorative study. Instead, the analysis served to identify promising LT-activities and ways for structuring LT-activities and contexts in an effective strategy for recontextualising. The collection of data and specific research questions for this empirical investigation have been summarised in figure 2.3.

The insights gained during these investigations served both to further refine the criteria developed from the literature and as a source of inspiration for the design of the LT-strategy during the main, cyclic research phase of this research project. The development of design criteria for recontextualising are described in chapter 3 of this thesis; those that relate to cellular respiration are described in chapter 4. The arguments supporting the choice for cellular respiration as a topic for this research project will be also discussed in the fourth chapter of this thesis.

2.3 Research methods in the first research cycle (cases α1 and α2)

The cyclic design phase of this research project aimed at the design of an LT-strategy for recontextualising. As a vehicle for investigating the phenomenon of recontextualising, the concept of cellular respiration was chosen as the topic for the designed LT-strategy. This phase was primarily guided by research questions III and IV:

RQ III How can we determine students' ability to recontextualise cellular respiration to other contexts?

RQ IV To what extent can the LT-strategy be considered adequate for promoting students' understanding of cellular respiration and their ability to recontextualise the concept to other contexts?

Outline of the first design cycle

The LT-strategy was developed for students in senior general secondary education (ages 15-17) and used three main contexts in which students explored cellular respiration during a lesson module that consisted of 8-10 lessons, followed by a recontextualising-test. This test was designed for two purposes: as a series of LT-activities in which students could test their understanding of cellular respiration, and a research instrument for testing their ability to recontextualise cellular respiration to other contexts. Prior to and after the lesson module, concept-mapping assignments (including written instructions and an example using 'furniture') served as a pre- and post-test; these asked students to connect and describe a set of nine terms (labels) related to cellular respiration. This provided a view on students' conceptions of cellular respiration before and after participating in the lesson module. Figure 2.4 provides an overview of the LT-strategy during this first design research cycle. Further details of the design and differences between its α- and β-versions (see figure 2.1) will be elaborated and explained in following chapters.

The lesson module started with an introduction in the sports physiology context, focusing on differences in muscular structure and function between power- and endurance-focused athletes.

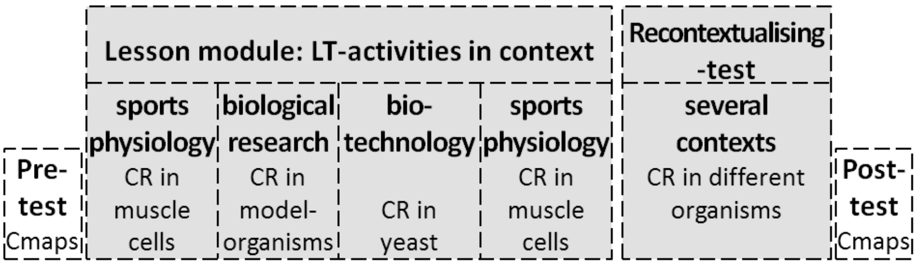


Figure 2.4. Structure of the LT-strategy (filled blocks). The recontextualising-test was intended to be a part of the LT-strategy, in contrast to pre- and post-test. The pre- and post-tests were not included in case study α1. CR = cellular respiration; Cmaps = concept maps.

After exploring muscular physiology down to the cellular level of biological organisation and having identified cellular respiration as the key process for providing energy to a cell, the students moved on to the context of a biological engineer for a further exploration of cellular respiration. This new context illustrated how cellular respiration is used in breeding yeast cells with more efficient respiratory capabilities (a 'super-yeast'). Following this detailed exploration of aerobic and anaerobic cellular respiration in yeast cells, students finally returned to the context of sports physiology to explain the differences in the muscular structure and function between power- and endurance-focused athletes. A third context (biological research) served to connect the sports physiology and biotechnology contexts through the introduction of yeast as a model organism for exploring cellular respiration in human muscle cells. Centred on the changes in contexts were LT-activities that explicitly aimed at recontextualising cellular respiration. Data from the enactment of these LT-activities in the lesson module were collected for describing students' learning trajectories during each case. These are described and explained in detail in chapter 5.

Development and validation of a recontextualising-test

The recontextualising-test consisted of a collection of test-items related to contexts different from those explored during the lesson module. The pre- and post-test concept-map data and the results from the recontextualising-test were intended to provide an indication of the attained curriculum: the learning outcomes for students in terms of their understanding of cellular respiration and ability to recontextualise the concept to other contexts. Figure 2.4 already depicts the recontextualising-test and pre- and post-test concept maps as part of these two case studies. However, the pre- and post-tests were not included in the first case study (α1) and the recontextualising-test changed considerably between both case studies. These two research instruments were still in development during this first design research cycle. The results from these tests were used to validate and redesign these tests during this cycle. These results were not used in the assessment of students' understanding of the concept and their ability to recontextualise it to other contexts in case studies α1 and α2. Therefore, these results are not described in detail in this thesis. Insights from these two case studies are included in the description of the recontextualising-test in section 2.5.

Implementation of the LT-strategy and data collection in case studies $\alpha 1$ and $\alpha 2$

The LT-strategy was implemented in two subsequent case studies in two different schools in the Netherlands. Both case studies involved classes in senior general secondary education, and were chosen because of the teachers' availability and willingness to take part in this project. Although this method does not ensure the selection of cases that are representable for all Dutch schools for senior general secondary education, a random selection of schools and classes would not have been possible. After all: any selection depends on the availability and willingness of teachers to cooperate and devote a significant amount of their time to this research project. Despite the fact that the two schools were chosen using a convenient sampling method (Denscombe, 2007), personal observations in these two schools during both case studies indicated that they can be considered as not atypical examples for education practices in Dutch, senior general secondary education. In addition, both schools were located in two different parts of the country and although both are described as urban, also had quite a population of students from smaller communities nearby. Therefore, the two schools and classes that were used in case studies α1 and α2 can be considered as typical practices in Dutch, senior general secondary education. The relevant information for each case is presented in table 2.2.

For each case study, the LT-strategy was described in a case-specific scenario, which is a detailed description of the expected teacher and student behaviour during each LT-activity (see figure 2.5). This scenario was then used to develop LT-materials such as a workbook or worksheets for students, and a teacher's guide. A part of this scenario has been translated from Dutch and is included in appendix II of this thesis. Together, these documents provide a view on the *intended curriculum* of the LT-strategy.

Table 2.2
Basic characteristics of case studies α1 and α2 in the first research cycle

	Case study α1	**Case study α2**
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=36 *(2 classes: 13 and 23 students).*	Mixed gender, ages 15-16, n=31 (31 students in one class).
Teacher	10 years of experience	6 years of experience
# lessons	9 (50 min./lesson)	9 (45 min./lesson)

The implemented curriculum was described using transcripts of teacher-student and student-student talk during the LT-activities, students' written answers in their workbooks or -sheets, collaborative concept maps, and the researchers' observation notes from the enactment of the lesson module. Finally, students' concept maps and written answers from the pre- and post-test gave an indication of the learning outcomes of the LT-strategy, although these were primarily used to validate and redesign these tests for assessing students' development of cellular respiration.

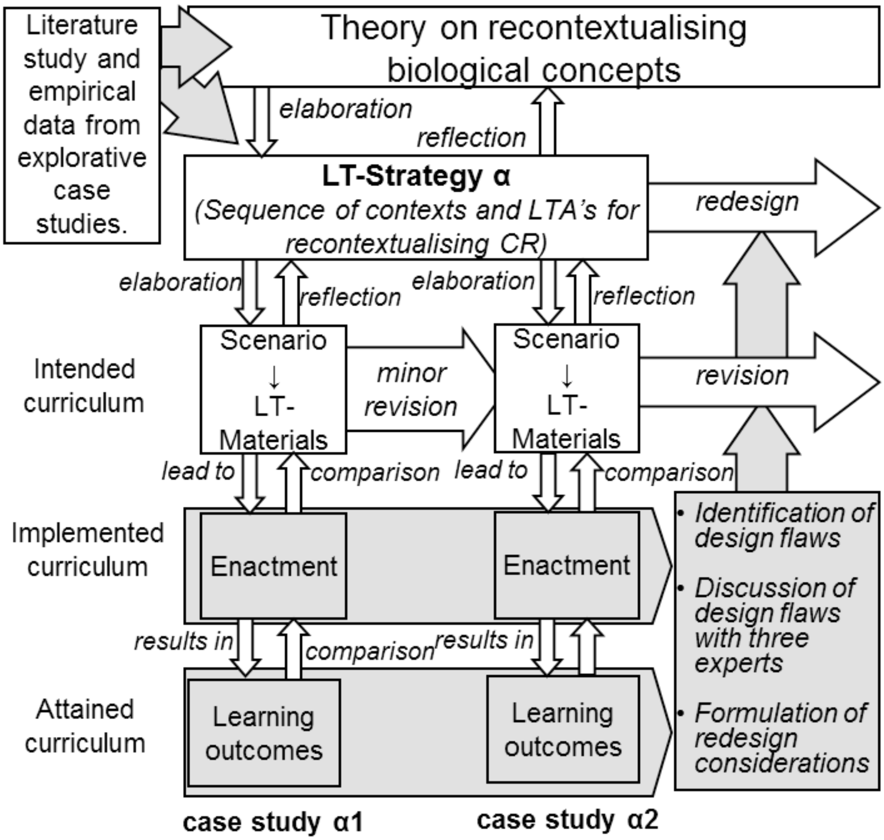


Figure 2.5. Structure of the first design cycle within this project. Information from the explorative phase led to the development of a preliminary theory on recontextualising biological concepts as well as a preliminary LT-strategy α.

Because of the objective of optimising and redesigning the LT-strategy (consisting of the lesson module with context-based LT-activities, and the recontextualising-test), the analysis was limited to the identification of remarkable episodes during enactment of the lesson module that indicated strengths and weaknesses in the design. These were then summarised and supported with relevant examples from the data, followed by detailed discussions with three other experts in (biology) education. These discussions yielded redesign considerations which were used to redesign and re-sequence the relevant LT-activities in the lesson module, as well as to redesign the recontextualising-test. Other changes were mainly due to practical considerations from the teacher or the school's timetable. The recontextualising-test was redesigned between cases, along with the other LT-activities in the LT-strategy. For instance, the results from the tests in this cycle led to a number of unanswered questions and unforeseen problems in the design of some test items and apparent interpretation by students that prompted revision and addition of several test items. These design choices are motivated and described in more detail in chapter 5 of this thesis.

In addition to optimising the LT-strategy, research cycle α aimed at the development of an analysis instrument for determining students' ability to recontextualise cellular respiration to other contexts. This is instrument was also used to describe students' developing conceptions of cellular respiration during the lesson module in the second design research cycle (RQ III). While the initial development of this analysis instrument took place during this first research cycle, it was refined during the second research cycle. Because of this, and the instrument's central role in the analysis of the second research cycle, the instrument and its development will be described separately in the final section of this chapter. The following section describes the research methods and data collection in the second design cycle (cases β1 and β2).

2.4 Research methods in the second research cycle (cases β1 and β2)

Similar to the previous design cycle, this one was guided by RQ III and RQ IV. With an optimised strategy and an instrument for analysing students' written answers, concept maps, and discussions during LT-activities, this cycle focused on explaining the differences between the expected and actual learning outcomes of the LT-strategy. The questions central to this second and final research cycle were:

RQ III How can we determine students' ability to recontextualise cellular respiration to other contexts?

RQ III-a Which elements of cellular respiration do students use and develop during the lesson module?

RQ III-b Which elements of cellular respiration do students use when answering questions or solving problems in other contexts?

RQ III-c How can students' use of conceptual elements of cellular respiration in other contexts be explained?

RQ IV To what extent can the LT-strategy be considered adequate for promoting students' understanding of cellular respiration and their ability to recontextualise the concept to other contexts?

The three questions RQ III-a, III-b, and III-c refer to the identification of specific elements for the concept of cellular respiration. The identification of these 'conceptual elements' for use as an analysis instrument is described in section 2.5, which details the research instruments that were used for assessing students' development of cellular respiration and their ability to recontextualise this concept in other contexts.

The LT-strategy, optimised as a result of the previous research cycle, was enacted again in the second design cycle in two similar case studies (β1 and β2) involving the same teachers and schools as those in the previous cycle. These case studies took place approximately one year after case studies α1 and α2, during the school year that ran from September 2009 to August 2010. With the exception of three students (two in case β1 and one in case β2) who repeated year 10 for senior general secondary education, the students in both case studies were different from the students in case studies α1 and α2. The basic characteristics of these cases are summarised in table 2.3.

A major advantage of having the same teachers during this second cycle was that both had experience with the LT-strategy from the previous cycle. It was expected that this experience would enable them to better improvise on to students' remarks or questions during the LT-activities, while keeping the main structure and sequence of the LT-activities in the strategy intact. The collection of data in this second cycle (cases β1 and β2) was very similar to that of the previous cycle (cases α1 and α2), although the objective had shifted somewhat.

Table 2.3

Basic characteristics of case studies β1 and β 2 in the second research cycle

	Case study β1	Case study β2
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 in one class.	Mixed gender, ages 15-16 n=24 students in one class
Teacher	11 years of experience	7 years of experience
# lessons	9 (50 min./lesson)	9 (45 min./lesson)

As with cases α1 and α2 in the previous cycle, the case-specific scenarios and their related LT-materials provided a detailed view on the intended curricula for cases β1 and β2. The data collected for determining the implemented and attained curricula are summarised and related to the LT-strategy in figure 2.6. The implemented curriculum was brought into view with descriptions of the learning trajectories for the whole class, focusing on moments when students were expected to recontextualise cellular respiration and moments when they did so unexpectedly. This detailed description is based on data from the enactment of the LT-strategy: students' written answers in workbooks or -sheets, their collaboratively constructed concept maps during specific LT-activities, and transcripts of student- and teacher-talk during LT-activities aimed at conceptualising and/or recontextualising cellular respiration. The attained curricula were determined by analysing and comparing students' individual concept maps from the pre- and post-tests, and their written answers to the recontextualising-test-items. Both these tests are described in detail in the following section in this chapter.

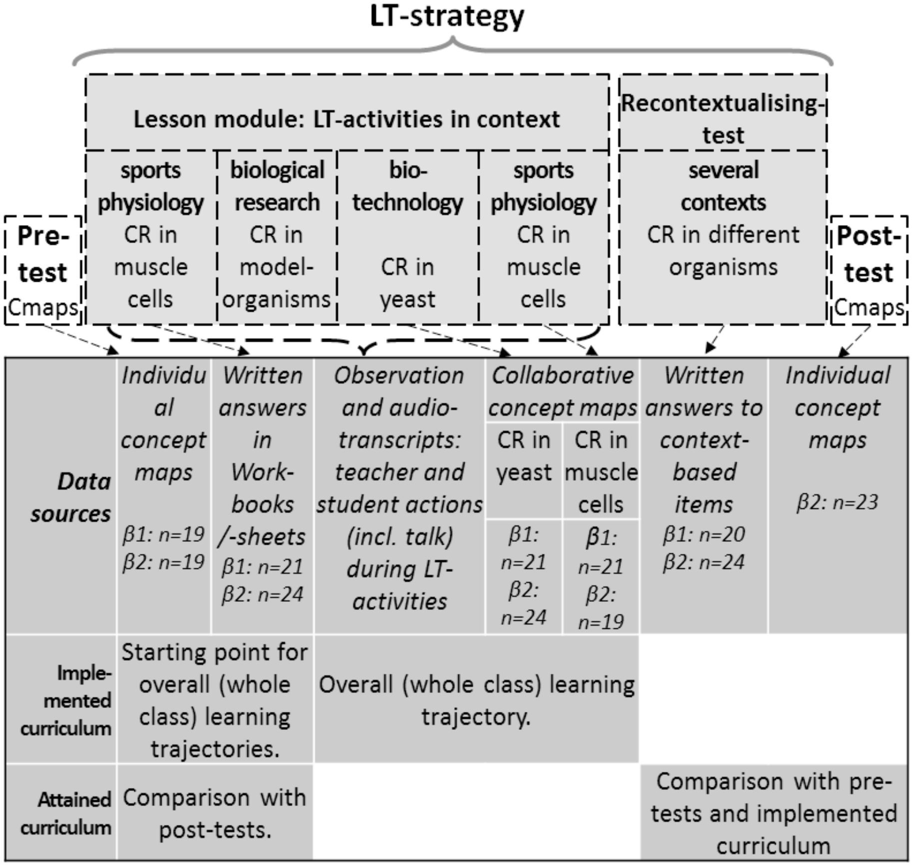


Figure 2.6. LT-strategy and data sources for case studies β1 and β2 in relation to the LT-strategy and the ‘implemented’ and ‘attained’ levels for curricular analysis. CR = Cellular Respiration

Although it may be expected that optimisation of the LT-strategy will lead to smaller differences between the design (intended curriculum) and enactment (implemented curriculum) of the LT-strategy, such differences can never be fully eliminated. Therefore a comparison of the scenario and implemented curricula was necessary to provide possible explanations for differences between students’ expected and actual use of cellular respiration in the recontextualising-test. The data sources described in figure 2.6 can provide a detailed view on the implemented and attained curricula for this lesson module. The teacher’s guide and learning materials for the lesson module were presented to the teachers before the start of the first lesson in the lesson module, to give them time to prepare and make any necessary last-minute changes based on schools’ timetables. At regular intervals (usually once a week), the researcher and the teacher discussed the enactment of previous lessons as well as the intended curriculum for lessons in the following week. Most lessons were observed by the researcher who noted students' and the teacher's behaviour during the LT-activities. Practical limitations prevented the observation of two lessons in case study β2. Observation of one of these lessons was done by another researcher at FIsme. The lack of observation of the other lesson was compensated with summary of that lesson by the teacher and an interview with the teacher based on that summary. This unobserved lesson did not involve LT-activities deemed crucial for recontextualising cellular respiration.

Audio-recordings of the lessons were made with three separate recording devices. One of these was given to the teacher and recorded all the remarks from the teacher during the LT-activities. The other two recorders were placed on the tables of two students, who were chosen because they were expected to provide an active contribution during whole class discussions and other LT-activities. These expectations were based on the teachers' impressions of these students' participation during previous lessons. Although the recorders were placed on the tables of these students, they were not used for a detailed description of individual students' learning trajectories. It was expected however, that the placement of these recorders with the same (actively participating) students during each lesson would provide a consistent view on the learning trajectory for most students in a class. The audio-recordings, notes from the observations of the lessons, recordings of discussions between the researcher and the teachers, and students' written answers on worksheets were combined to assess the actual enactment of the lessons and provide a view on the implemented curriculum. This could then be compared to the scenario.

Having described the general collection and analysis of data during this second and final research cycle of this research project, what is still needed is a more detailed description of the pre- and post-tests and the LT-activities used for determining students' individual and whole-class learning trajectories. The LT-activities will be described in chapter 5 (designing an LT-strategy for recontextualising cellular respiration) with the other LT-activities that made up the lesson module. The recontextualising-test formed an integral part of the LT-strategy, but primarily served as a test for determining the learning outcomes of the LT-strategy and finding explanations for students' (in-) ability to recontextualise cellular respiration.

The design of this recontextualising-test and the pre-and post-tests are described in the following section of this chapter.

2.5 Research instruments for describing students’ use of cellular respiration

This section describes the research instruments that were developed during the first design-research cycle, and used during the second cycle for assessing students’ understanding of cellular respiration before and after their participation in the LT-strategy, as well as if and how they were able to recontextualise the concept to other contexts. Before moving on to a description of the recontextualising-test and assignments for concept-mapping in the pre and post-test, this section starts with a description of the coding scheme that was developed and eventually used to determine if and how students used the concept in their concept maps and written answers to the recontextualising-test. In addition to its use in the analysis of these tests, these conceptual elements are also referred to in the descriptions of the learning trajectories during the two case studies (β1 and β2) in the second design research cycle (see chapter 6 of this thesis).

Conceptual elements of cellular respiration: a coding scheme

Although a simple determination of whether or not students provided a correct answer to a particular question in the recontextualising-test might suffice for determining the strategy’s success, this would not provide any indication of *how* they recontextualised and used the concept. To understand *why* students used the concept in one context, but not in another, it was necessary to develop an instrument that would provide a more detailed view on the matter, by confronting students with context-based problems that require them to use the concept. An instrument for assessing students’ use of a concept in different contexts had not been developed previously and thus no suitable examples could be obtained from literature on transfer or recontextualising. In biological literature, the concept is usually described in an all-encompassing manner: all its aspects or elements are described as a logical and interconnected whole, without clearly separating these elements such as the substrate used for respiration, the resulting products or the amount of energy that is released. Although such generalised descriptions can be quite suitable for the objectives with which they are developed, these do not allow for a proper view on the differences between students’ use of the concept between contexts. During the first research cycle and the process of designing the LT-strategy, it became apparent that with different contexts, different aspects of the concept become 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, explaining the differences in the muscular structure and function between different athletes requires a far more detailed understanding. Among other aspects, one needs at least some understanding of cellular respiration’s function in energy-supply, the products released by its aerobic and anaerobic variants, and the differences in the speed between these processes. This perspective, primarily developed during the first research cycle, led to the identification of six conceptual elements of cellular respiration, which are described in figure 2.7.

The instrument decomposes the concept of cellular respiration into six distinct ‘conceptual elements’ that can be used to define and categorise different variants of the process, and to separate it from other biochemical processes. Although the six categories were developed to cover students’ required understanding of cellular respiration in senior general secondary education, this instrument does not provide an exhaustive or final definition for the concept; different research perspectives or other LT-strategies than described in this thesis may result in the identification of other or more detailed conceptual elements for cellular respiration. The first of the six elements (A, in figure 2.7) relates to the core function for cellular respiration: releasing energy from energy-rich substances and the differences in 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 the by- or waste-products of cellular respiration 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. This is not entirely accurate: some bacteria *are* of course able to respire aerobically without any mitochondria. In fact, the widely accepted theory of endosymbiosis *requires* the existence of such bacteria before they were incorporated as mitochondria.

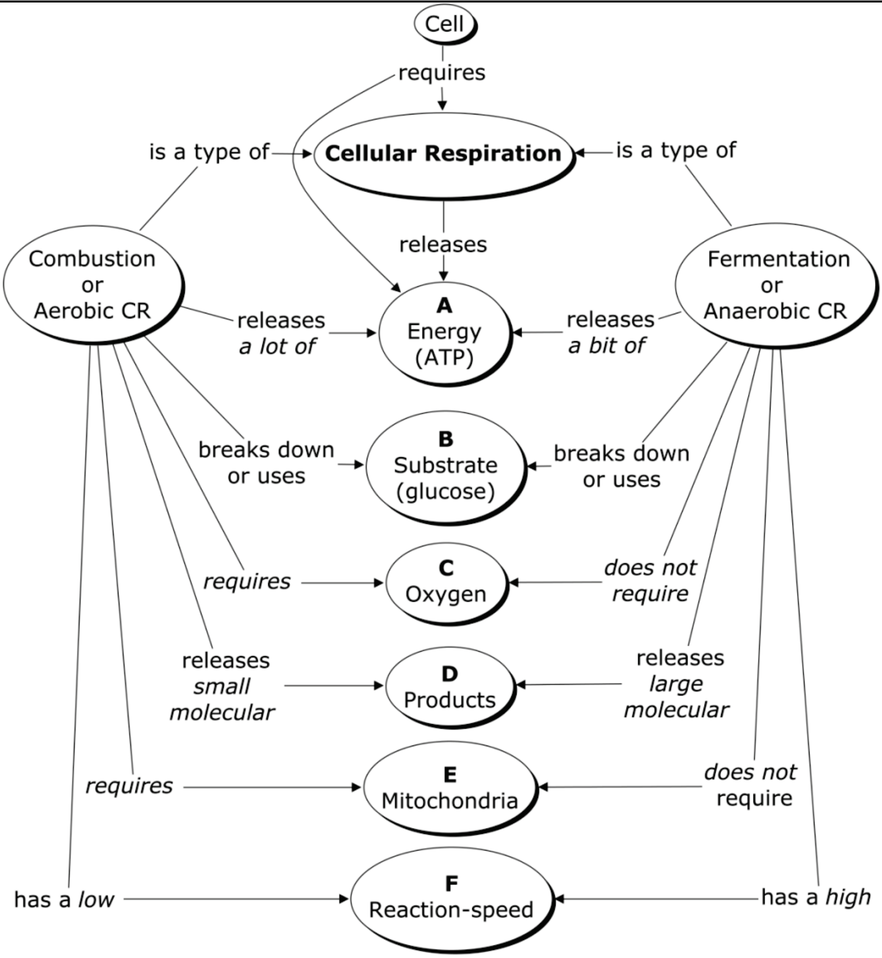


Figure 2.7. Conceptual elements of cellular respiration.

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 a typical Dutch biology class at this level of secondary education. The final element F (reaction speed) is the only element that is not incorporated in the Dutch curricular demands for biology education (see chapter 4), but was considered to be crucial for a proper understanding and use of cellular respiration in the context of sports physiology. Chapter 4 explores the concept of cellular respiration in detail and also discusses the motives for incorporating this element into the LT-strategy and its related analysis instrument.

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 several of the conceptual elements in figure 2.7: elements A, B and D. Element A represents the primary function for cellular respiration in organisms and the differences between the amount of energy released in aerobic and aerobic respiration can be explained by combining elements B and D. Although element 'B' refers to the use or breakdown of glucose in cellular respiration, whether this breakdown is partial or complete can only be determined by combining this element with the differences between the products from aerobic and anaerobic respiration: element D.

These conceptual elements were used to generate detailed descriptions for each context in the lesson module (see chapters 5 and 6), and the final recontextualising-test (see section 2.5). The identification of the conceptual elements that were made available to, and were used by students during LT-activities was done to explain students' performance during the recontextualising test. This was based on the rationale that any elements not introduced or not explicitly used during the lessons, would probably not be available to students by the time they participated in the recontextualising-test. An inductive approach for developing categories (Patton, 2003; Schönborn & Bögeholz, 2009) was used for identification and separation of the conceptual elements, informed by the data from the first design-cycle and guided by the designed LT-strategy and lesson module. This process is illustrated with figure 2.8. This process involved several cycles in which coding categories were devised, revised, and discarded. Eventually, each element was described in detail for each context, test-item and applicable levels of biological organisation.

The first iterations in this process were performed by the author of this thesis, which resulted in a preliminary set of codes along with their detailed descriptions (figure 2.8-I). These were then given to another biology education researcher along with the post-recontextualising-test data from the final case study.

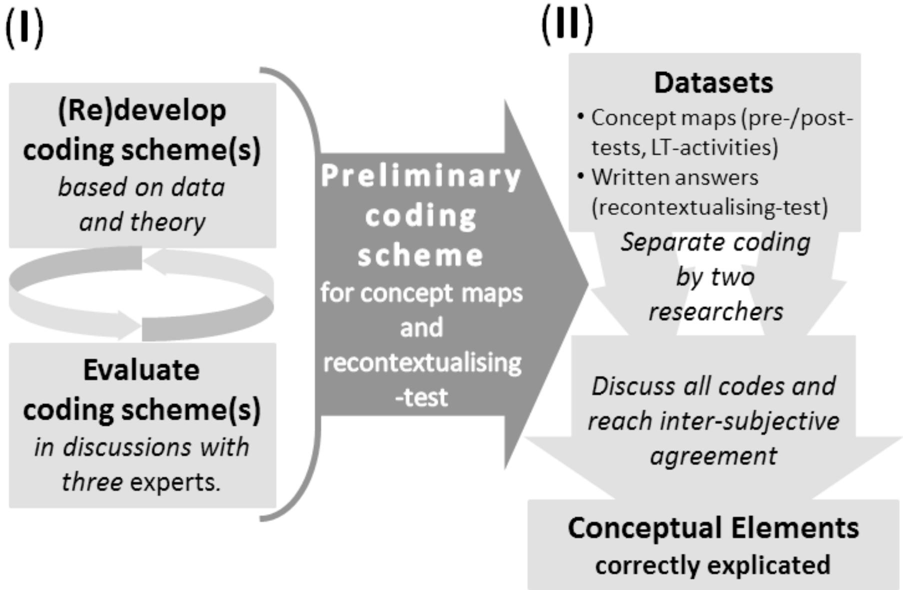


Figure 2.8. Development of coding schemes (I) for determining the conceptual elements explicated by students (II) in their concept maps and written answers, which were obtained from the pre- and post-tests, and LT-activities.

Both the second researcher and the author used the preliminary codes to code the dataset before they sat down together to discuss both the code set as well as the coding of each answer in the dataset. They discussions served to come to an inter-subjective interpretation of the coding categories in relation to the dataset (see figure 2.8-II). The final, inter-subjectively agreed coding categories were then adapted for use with students' concept maps (constructed during the pre- and post-test as well as during specific LT-activities in the module, see also figure 2.6). All data from the recontextualising-test and pre- / post-test concept-maps in the second research cycle was coded by two researchers. They each analysed the data separately according to the preliminary coding schemes before they sat down and discussed each coded fragment until inter-subjective agreement was reached (Patton, 2003; Smaling, 1992).

Determining the reliability of the final coding scheme

The final coding scheme that resulted from the inter-subjective agreement between both researchers was assessed by having both researchers use it to code approximately 25% of the data from case studies β1 and β2 again. This recoding of data took place approximately one year after the original coding sessions and discussions that had resulted in the final coding scheme. The results from these were used in an analysis of the reliability of the coding scheme and will be described in chapter 6 with the other results from the recontextualising-test, and the pre- and post-tests.

Pre- and post-test: concept mapping assignments

Before students can be expected to be able to recontextualise a concept, they should first develop it. Therefore, aside from the recontextualising-test for determining students' ability to recontextualise cellular respiration to other contexts, a pre- and post-test was developed for determining if and how students developed the concept during the LT-strategy, which is reflected in RQ III-a:

RQ III-a Which elements of cellular respiration do students use and develop during the lesson module?

These pre- and post-tests made use of individual concept-mapping assignments (Novak, 1990; Novak & Cañas, 2007) in which the students were given a set of nine or ten concept labels and were asked to construct a concept map using these labels. Table 2.4 provides an overview of the concept map labels given to the students in each case and test.

Table 2.4

Concept labels provided during the pre- and post-test concept-mapping assignments in case studies β1 and β2. The solid grey coloured cells indicate the use of a label in each test.

Label	**β1 pre-test**	**β1 post-test**	**β2 pre-test**	**β2 post-test**
Glucose	■	■	■	■
Oxygen	■	■	■	■
Carbon dioxide				■
Cell	■	■	■	■
Cellular respiration	■	■	■	
Anaerobic respiration	■	■	■	■
Aerobic respiration	■	■	■	■
Energy	■	■	■	■
Metabolism	■	■	■	■
Mitochondrion	■	■	■	■

Both the pre- and post-test 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. It was expected that the combination of students' concept maps and their descriptions of terms would provide a detailed view on students' understanding of these terms.

During case study β1, this post-test was eliminated due to time-limitations and incompatibility with the school's timetable. Also, due to a researcher's mistake during the final case (β2), the label 'cellular respiration' was replaced by 'carbon dioxide' in the post-test. However, this pre- and post-test were meant to provide an additional view on students' understanding of cellular respiration, next their concept maps constructed during two LT-activities and the recontextualising-test. The labels 'aerobic cellular respiration' and 'anaerobic cellular respiration' ensured the inclusion of labels for cellular respiration and it could be expected that students that 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 case β2 are still useful for this purpose. Because most students had not encountered the process labelled as 'cellular respiration' before, but were already familiar with the term 'combustion', the labels 'glucose', 'oxygen', and 'energy' were added to provide students with a means of describing 'combustion'.

A test for recontextualising cellular respiration

In the entire lesson module, the main objective for students was to develop a flexible conception of cellular respiration (see section 1.1) that they would be able to use in contexts they had not yet encountered before. In order to challenge students to do so, the recontextualising-test was developed as part of the LT-strategy (see also: figure 2.6). This test served two functions. First of all, the recontextualising-test was intended as an LT-activity that provided students with a chance to test their conceptions of cellular respiration by using it to solve problems set in contexts different than those they had explored during the lesson module. As such, the recontextualising-test was intended to be as much a part of the students' learning process as the LT-activities in the lesson module. Secondly, the recontextualising-test served as a research instrument: as a test for determining students' ability to use cellular respiration in different contexts and possibly improving our understanding of *how* students use their conceptions of cellular respiration and connect them to new, context-related information. Thus, the recontextualising-test aimed at RQ III-b, and RQ III-c.

RQ III-b Which elements of cellular respiration do students use when answering questions or solving problems in other contexts?

RQ III-c How can students' use of conceptual elements of cellular respiration in other contexts be explained?

In case study β2, the recontextualising-test was administered before the concept-map post-test, shortly after the last lesson in the module. For the design of the recontextualising-test, the literature provided a disappointingly small amount of valuable information. Although there is lot of transfer-related research literature available, many research articles do not specify the kind of test (-items) used in analysis. Any details of test-items that are available seem either to centre on a single context, which is explored in detail and possibly requires the use of various concepts, or on a biological object such as a (type of) cell, organism, or ecosystem, without clearly explaining the context in which the object is manipulated. While a detailed exploration of a single context requiring students to connect numerous different concepts in a coherent whole can be valuable for creating coherence between concepts, the objective for this test was to gain a view on students' use of a single concept (cellular respiration) in different contexts. Therefore, this test should provide students with various context-related problems or questions, preferably in a number of different contexts. With this objective in mind, different context-related test items were developed over the course of the four cases in the two research cycles.

The test was administered as an individual paper-and-pencil test and was also used by the teachers for a summative assessment of students' progress. Similar tests are also part of the national exams, making it reasonable to incorporate such a test in this LT-strategy. The objective of understanding *how* students used their conceptions of cellular respiration in different contexts also determined the type of questions used in the test. The different items were designed in such a way, that they each required different conceptual elements as part of a correct answer or solution. Multiple choice questions are not an effective tool for gaining such detailed information and additionally, such items would provide restraints and suggestions for students to connect the contextual information with their conceptions of cellular respiration. Thus, the test-items were designed as open-ended, context based questions. English translations of these items as they appeared in the recontextualising-test can be found in appendix I of this thesis.

Each context was introduced with an introductory 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. There is always a tension between clarity and confusion in choosing the amount of information provided in such a description and it should be noted that the descriptions in this recontextualising-test do not allow students to fully acquaint themselves with a social practice. Such full and extensive descriptions of a social practice and context can be fruitful if the objective is to have students make complex, highly situated decisions using a variety of different (biological and other) concepts (van der Zande, 2011). However, the aim of this research project required the use of several and differing contexts in the recontextualising-test and problems centred on the use of cellular respiration. This, combined with the amount of time available for administering the test forced a limitation on the length of the descriptions.

Table 2.5 describes the contexts, expected activities, and the conceptual elements needed for a complete answer to the different items in the recontextualising-test. All contexts and test-items were designed specifically for this research project, although one context (no. 4, see table 2.5) was inspired by exam questions from Dutch national exams for pre-university secondary education (Cito, 2008). Table 2.5 shows the contexts and test-items that were part of the final recontextualising-test. Case study β1 included contexts 1-5 (items 1-9, see table 2.5); the final case study (β2) consisted of 11 questions distributed along 6 items and contexts. The rightmost column in table 2.5 contains the key cognitive elements needed for a complete answer. The results from the first design-cycle had already shown that many students tended to provide incomplete descriptions of their reasoning. Many written answers implied the use of certain elements, but did not explicitly describe these. Therefore, it was decided that for reasons of determining whether or not a written answer could be interpreted as a result of successful recontextualising, not all the elements described in the rightmost column of table 2.5 were needed. The elements that were eventually needed as proof of successful recontextualising will be provided in the following individual descriptions for these test-items.

Table 2.5

Summary of contexts and items in the recontextualising-test as it was used in the final case-study (β2). The rightmost column describes the conceptual elements for cellular respiration needed for providing a correct answer or solution to each test-question. The letters A through F correspond to the letters used to denote conceptual elements of cellular respiration in figure 2.7.

Context no.	Item no.	*[Social practice]* Context	Expected activity performed by the student answering the test item	Conceptual element(s) needed for a complete answer
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)*
2	2	*[Sports 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 sprint- and marathon runners.	A: *energy release* B: *substrate (glucose)* C: *oxygen requirement* D: *waste products* E: *mitochondria* F: *speed*
	3		Explain and describe the differences in energy use and supply between white and red muscle fibres.	
3	4	*[Amateur Vintner]* Produce wine.	Explain the need for an anaerobic environment in wine production.	C: *oxygen requirement* D: *waste products*
	5		Name the gas that is released during the production of wine.	
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*
	7		Explain what would happen to (these) bacteria if they had no ability to break down glucose.	A: *energy release*

Table 2.5 – (Continued)

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)*
	9		Choose and explain a suitable method for cleaning wastewater using bacteria (aerobic or anaerobic).	
6	**10**	*[Medical professionals in an expertise centre for chronically fatigued patients]* Care for chronically fatigued patients.	Explain the patients' cells' inability to perform a complete breakdown of glucose to carbon dioxide and water.	E: *mitochondria*
	11		Explain the patients' chronic fatigue.	A: *energy release*

Using the distinction of cognitive elements for cellular respiration (see also: figure 2.7), the answers students provided to the recontextualising-test items were coded according to the (correctly described) cognitive elements used. During the development of the recontextualising-test for use in case studies β1 and β2, the results from the first design cycle (see also section 2.2) and the test-items themselves were discussed in detail with a second expert researcher in biology education and redesigned according to the outcomes of these discussions. The final part of this section describes the items in the recontextualising-test in more detail. English translations of these items are provided in appendix I of this thesis.

Recontextualising-test, context 1: The production of yeast

This context included only one item, which was also the first item in the recontextualising-test. After a short introduction to the practice of a yeast producer, it invited students to make a choice between an aerobic and anaerobic environment for reproducing yeast. The description included an emphasis on the large energy requirement in reproduction, which is closely linked to the element of *energy release* (element A in figure 2.7), and its differences between aerobic and anaerobic cellular respiration. An ideal answer should link the elements of energy release, substrate (element B), and waste products (element D) to describe the conceptual core: full vs.

partial breakdown of the substrate in aerobic vs. anaerobic cellular respiration. The element of energy release (A) was determined as a minimal requirement for successful recontextualising.

Recontextualising-test, context 2: sports physiology

The second context in the recontextualising-test resulted from a need for more data on students' use of cellular respiration in the context of sports physiology, adding to data from the concept-mapping assignments; both from the pre- and post-test, as well as from LT-activities (see figure 2.6). Student's familiarity with this context should allow them to use cellular respiration without recontextualising and thus, no minimal requirement for *recontextualising* was determined for these items. However, any conceptual elements used and explicated by students in their answers to these two items can indicate how students have understood and contextualised cellular respiration within the context of sports physiology and inform any expectations of their use of conceptual elements in other contexts. In other words: can we expect students to ***re****contextualise* cellular respiration if they have not properly or completely *contextualised* it for the original context? Because of the importance of this question in the interpretation of the results from the recontextualising-test, chapter 6 of this thesis returns to this question with a description and discussion of the results. An ideal answer to the first question in this context (item no.2) should include differences in the number of mitochondria between red and white muscle fibres (or cells) as well as differences in the size and number of microfilaments between these types of fibres. The differences in microfilaments should then be connected to the differences in contractile power or strength between these cells. Differences in the number of mitochondria should ideally be related to the differences in fibres' capability to perform aerobic cellular respiration (element E in figure 2.7) for a steady and efficient source of energy (elements A and B). From here, an ideal reasoning pathway should step up to an organ- and organism-level description of the differences in number of muscle fibres between muscles in both types of athletes.

Item 3 invited the students to further detail the differences between aerobic and anaerobic cellular respiration in muscle cells and explain why anaerobic cellular respiration can provide energy much faster than aerobic cellular respiration, and why aerobic cellular respiration is a (far) more steady and efficient source of energy than anaerobic cellular respiration.

Such an explanation should ideally involve all conceptual elements A through D and F (figure 2.6).

Recontextualising-test, context 3: producing wine

Context 3 invited students to explain the need for an anaerobic environment in wine production (item 4) and name the gaseous waste product from (alcoholic) fermentation in yeast (item 5). While students had studied anaerobic cellular respiration in comparison to aerobic cellular respiration *in yeast* during the lessons, they had not yet done so within the context of wine production. Both items required students to use their knowledge of the waste products in anaerobic cellular respiration (alcohol and carbon dioxide; element D in figure 2.7) which connects to the need for alcohol in wine and the use of a 'water-lock' to seal off the fermentation bottle.

Recontextualising-test, context 4: Genetic modification of lactic acid bacteria

Context 4 (items 6 and 7) in the recontextualising-test invited students to explain what would happen to bacteria without any capacity for cellular respiration. Both the context and item 6 were taken from a Dutch exam for pre-university education (Cito, 2008). For this recontextualising-test, the context description and the wording of the item were changed to fit the senior general level of secondary education. Item 7 was added to test students' ability to understand that the lactic acid production by these bacteria is a consequence of (anaerobic) cellular respiration. Where the previous items were designed to test students' ability to recontextualise cellular respiration in contexts similar to the context studied during the lessons (all using yeast for different purposes), these two items were set in a context very different from what the students had encountered before. It involved a type of organisms (bacteria) that students had not yet studied in detail before. To complicate matters even more, these bacteria live in symbiosis with other organisms (humans). These differences from previously encountered contexts formed a main reason for incorporating this context in the recontextualising-test. Any ideal answer to item 6 should include the fact that these bacteria have no mitochondria (element E in figure 2.7) and thus are not able to perform aerobic cellular respiration, which is required for a complete breakdown of glucose (element B) to carbon dioxide and water (element D). Item 7 should ideally be answered with the observation that the lack of any type of cellular respiration prevents an organism from releasing energy (element A) from food substrates and thus results in the death of an organism, or to be more precise: it would probably never have lived.

Recontextualising-test, context 5: Cleaning wastewater with bacteria

Context 5 (items 8 and 9) involved bacteria used in the cleaning of wastewater. Its description did not make any distinction between specific types of bacteria or aerobic and anaerobic strains. This context was similar to the first context in the recontextualising-test, which asked students to choose between an aerobic and anaerobic environment for producing yeast. The items in this context invited students to make a similar choice, but now in a context involving bacteria and with a different goal in mind: the complete breakdown of organic waste. Item 8 invited students to provide an explanation for using an aerobic cleaning phase for cleaning wastewater. Ideally, an answer to this item should involve a combination of the differences in oxygen requirement (element C in figure 2.7) and complete vs. partial breakdown (core) of the substrate between aerobic and anaerobic cellular respiration. For proof of successful recontextualising, this core could also be substituted with an observation of the differences in products between aerobic and anaerobic cellular respiration (element D) and the observation that carbon dioxide and water are the more desired end products compared to alcohol or lactic acid. An alternative explanation could have included element A: differences in amount of energy released between aerobic and anaerobic cellular respiration, combined with the observation that with the larger amount of available energy from aerobic cellular respiration, the bacteria are better able to multiply or reproduce; more bacteria then result in better cleaning. Both explanations were marked as examples of proper recontextualising although an explication of element C was not required, which has been explained in the first part of this section describing the recontextualising-test in general. Item 9 involved a similar line of reasoning, but now included with a choice for an aerobic or anaerobic cleaning phase in the design for a new wastewater cleaning facility.

Recontextualising-test, context 6: Explaining the symptoms of chronically fatigued patients

These final two items in the recontextualising-test were designed to mirror items 6 and 7 in context 4. Item 6 invited students to explain bacteria's inability to respire aerobically. In contrast, item 10 invited students to explain a lack of aerobic respiration in the cells of chronically fatigued patients. The context description clearly mentioned the lack of (functioning) mitochondria meant to activate students' knowledge of mitochondria as important structures for performing aerobic cellular respiration (element E in figure 2.7). Items 11 and 7 were similarly mirrored: both invited students to name the lack of energy released in absence of cellular respiration (element A). However, there was one important difference between both questions which should be taken into account when comparing the results from these items in an analysis. In item 7, students were invited to explain the need for *cellular respiration (either aerobic or anaerobic)* at the cellular level of biological organisation. Item 11 on the other hand, invited them to explain patients' symptoms arising from a shortage of *aerobic respiration* due to dysfunctioning mitochondria (i.e.: to explain a phenomenon at the organism and organ levels of biological organisation with knowledge that refers to the cellular level of biological organisation).

Now that the research methods and instruments for this design research project on recontextualising cellular respiration have been described in detail, the following two chapters describe the outcomes of the explorative phase of the design research project. The aim for this phase was to identify design criteria specific for recontextualising biological concepts, and for learning and teaching the concept of cellular respiration. Chapters 5 and 6 continue with a description of the design of the LT-strategy, and results from implementation during design research cycles α and β. Finally, chapter 7 discusses and generalises the findings for this design research project, and provides suggestions for future research.

Chapter 3

Exploring Recontextualising

The aim of the explorative phase was to identify characteristics for LT-activities and contexts that can be effective in a LT-strategy for recontextualising, and how such LTA's and context can be structured. This is also described in RQ I, repeated here:

RQ I Which design criteria for an LT-strategy for recontextualising biological concepts can be identified from an empirical and theoretical exploration of recontextualising?

This chapter describes design criteria for an LT-strategy for recontextualising biological concepts, not specified for cellular respiration. The first section (3.1) describes the structure and topics of the two lesson modules that were a part of the explorative case studies. It also summarises the design criteria that were developed during the explorative phase. The following three sections (3.2 to 3.4) each describe the development of one of these design criteria in relation to theoretical and empirical sources that led to its development. Finally, section 3.5 provides an overview of the design criteria for recontextualising.

Before moving on to a description of design criteria, it should be noted that any descriptions of inconsistencies in the design and implementation of the lesson modules that were part of this explorative study is in no way intended as a critique on the designers and teachers of these lesson modules. These inconsistencies were brought into view through the observation and analysis of these lesson modules from an education research perspective, with a focus on recontextualising biological concepts. Teachers have a different perspective. Although this is not intended to imply that teachers do not reflect on and improve on their teaching practices, it does mean that they have other concerns and cannot be expected to devote the same amount of time and resources to such detailed analyses of this phenomenon. In fact, inconsistencies similar to those described in this chapter were observed by the author in his own education practice as a biology teacher in secondary education (personal observation), even when already involved in this design research project.

3.1 Structuring contexts in two context-based lesson modules

The two lesson modules observed in this exploration were investigated in two explorative case studies (see also table 2.1). The lesson module that was part of the first explorative case study is referred to in this chapter as 'lesson module 1', which aimed at photosynthesis and cellular respiration. The lesson module in the second explorative case study is referred to as 'lesson module 2', and aimed at students to develop concepts related to animal behaviour. A major difference between both lesson modules and a reason for exploring these two, was the sequencing of contexts used in their designs. Figure 3.1 displays the 'standard sequencing' of contexts in most lesson modules that were based on the concept-context approach, developed by a team of teacher/designers (see section 2.2.). Most of these modules started with an exploration of an 'acquisition-context' in which students would study and learn the concepts involved. This was followed by an 'application-context' where students were asked to use their newly developed concepts in another context. Finally, the module ended with one or more 'test-contexts', asking students to use the concepts in again other contexts (see figure 3.1).

Figure 3.1. Standard sequencing of contexts in lesson modules based on the concept-context approach, designed by a team of teachers.

While the designer of lesson module 1 was also a part of a design-team for designing lesson modules based on the concept-context approach (see also: chapter 2), the contexts in that lesson module were structured in an alternating sequence, very different from the 'standard sequencing' (see figure 3.2-I).

In contrast, while the designer of lesson module 2 took no part in such a design-team, the contexts in his lesson module (figure 3.2-II) were structured according to the design-team's 'standard sequencing' (figure 3.1). Lesson module 1 was chosen because of its innovative, alternating sequence of contexts in comparison to the 'standard sequencing', reflected in the structure of lesson module 2.

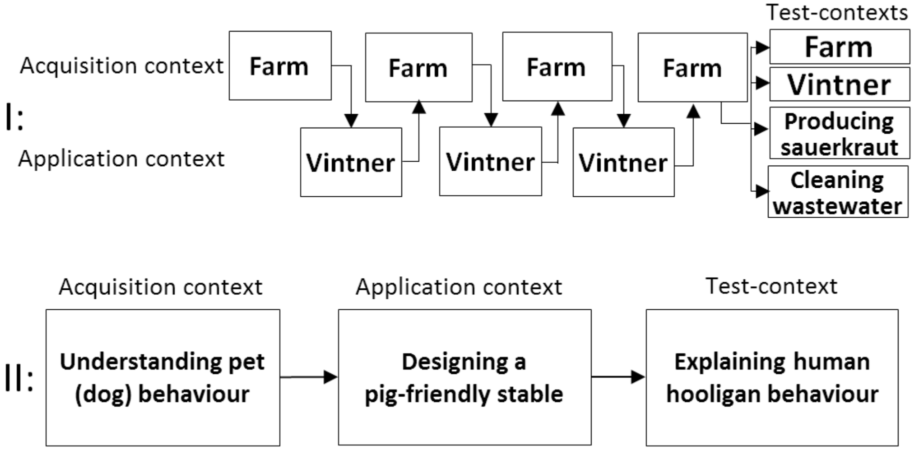


Figure 3.2. Sequence of contexts in lesson module 1 (I) and in lesson module 2 (II). Note that the actual number of switches between the farm- and vintner contexts for lesson module 1 (I) was larger than shown in this schematic representation.

The theoretical and empirical exploration of the recontextualising process resulted in the identification of three design criteria for an effective LT-strategy for recontextualising biological concepts. These criteria apply to important aspects of LT-strategies that need consideration, and how these can be structured effectively to reach specific learning goals. Chapter 2 describes how the explorative phase employed a mixed-methods approach (Denscombe, 2007). It combined methods from *grounded theory* for observation and analysis of context-based lesson modules in practice, with theoretical insights from the literature survey and interviews and informal discussions with experts. The empirical case-studies and the study of the literature occurred simultaneously; each exploration strongly influenced the others while gradually leading to an identification and specification of design criteria. It is impossible to single out the insights stemming from each of these sources and describe them separately. Therefore, the following sections describe the development of these design criteria in relation to empirical and theoretical sources that led to their development.

3.2 Focusing on a concept in context

Concepts and contexts in lesson module 1

The first criterion came to light during the explorative case study of lesson module 1. It was further developed during the exploration of the literature and the second explorative case study (lesson module 2). Lesson module 1 revolved around an exploration of two social practices: the crop farmer and the vintner. The LT-activities in this module frequently switched between the acquisition context of ‘the crop-farmer’ and the application context of ‘the vintner’. Interviews with the designer on the design of the lesson module (see chapter 2) revealed a primarily practical motivation on his part. He had planned for students to brew their own mead (a honey-based wine) as part of the lesson module. But the fermentation processes involved in brewing mead take time: at least 4-6 weeks. Also, aside from the preparation of the mead, most follow-up activities (such as monitoring the fermentation process) were not so extensive that they would fill a six-week period of biology lessons. Therefore, he had decided to frequently switch between vintner-related LT-activities and LT-activities related to another context: the crop farmer. As an added benefit; the designer reasoned that this structure would allow students to first study a single set of concepts. They would be introduced in a context related to the crop farmer, followed by LT-activities in which they could use the same set of concepts in a vintner-related context. Table 3.1 depicts the sequence of farmer- and vintner-related contexts and concepts involved in lesson module 1 (chronological order: from top to bottom). The descriptions of concepts and contexts were derived from the LT-materials, a teacher’s guide and summary of the lesson module provided by the designer. To clarify the type of context involved in each exploration, the first column of table 3.1 also displays the organism that is central in each context (in brackets).

When looking at the sequence of contexts in this lesson module, it becomes clear that the designer interpreted the context of ‘a farm’ in a broad sense: several different types of farms were explored as part of the lesson module, such as an algae farm, potato-farm, orchards, vineyards, etc. Compared to the many different types of farms explored in this lesson module, the context of the vintner was interpreted more consistently and mostly referred to the brewing of mead. But in a number of LT-activities involving the vintner context, an additional context (breeding and producing yeast) was incorporated in the exploration. From the designer’s (biological) perspective, this seemed reasonable because the context of the vintner in itself would not allow for an exploration of the yeast cells at the cellular level of biological organisation.

Table 3.1

Sequence of farming- and vintner-related contexts in lesson module 1 (total: 20 lessons), and the sequence of concepts that were to be developed during the LT-activities in that lesson module (chronologically ordered from top to bottom: F=farm contexts, V=vintner contexts).

Context (biological object)		Concepts
F	Farmer (algae)	Photosynthesis; food; auto- / heterotrophic organisms; assimilation (anabolism); ingredients for mead
V	Vintner (yeast)	
F	Farmer (potatoes)	Breeding and selection; genetic modification
	Farmer (grapes)	
V	Vintner (yeast)	Ingredients for mead; preparing mead
F	Farmer (potatoes)	Breeding and selection; genetic modification
	Farmer (fruit) / Farmer (yeast)	Asexual reproduction; mitosis
V	Vintner (yeast) / Yeast producer (yeast)	Cloning (yeast); breeding a pure culture of yeast cells
F	Farmer (mushrooms)	Food; nutrients; assimilation (anabolism); cellular respiration
V	Vintner (yeast) / Yeast producer (yeast)	Bacteria; breeding a pure culture of yeast cells; contamination
		Food; nutrients; assimilation (anabolism); cellular respiration
F	Farmer (potatoes)	Photosynthesis; food; auto- / heterotrophic organisms; assimilation (anabolism); (a-) biotic factors; ecosystem
V	Vintner (yeast)	Anaerobic cellular respiration
F	Farmer (potatoes)	(a-) Biotic factors; species-tolerance
V	Vintner (yeast)	
F	Farmer (cows; grasses)	Anaerobic cellular respiration; assimilation (anabolism); photosynthesis
V	Vintner (yeast)	
		Population, symbiosis
Test-contexts: Sauerkraut producer (sauerkraut, bacteria) Vintner (yeast) Farmer (algae) Waste water cleaning (bacteria)		All of the above, but with a focus on: cellular respiration (aerobic and anaerobic) photosynthesis assimilation (anabolism)

Aside from the large variation in contexts explored during the lesson module, the number of concepts to be developed during the lesson module (right-hand column in table 3.1) was rather extensive as well. Also, the list of concepts spanned almost all levels of biological organisation; a more detailed analysis of the (intended) LT-activities and LT-materials for this lesson module revealed frequent switches between these levels of organisation within and between LT-activities, moving from a cellular to an ecosystem perspective without clearly connecting these through the intermediate levels of biological organisation.

Several interviews with the designer of the lesson module (see section 2.2) revealed two main reasons for incorporating this many biological concepts. *One*: The lesson module was designed to span approximately twenty lessons over a period of six weeks. Because of this large amount of time needed in relation to the time available for covering the entire biology curriculum for senior general secondary education, the teacher felt it necessary to incorporate more concepts. *Two*: The designer's biological perspective on the vintner and farmer contexts led him to reason that one might describe the yeast culture in a fermentation bottle as a small ecosystem, with one population of yeast cells. Whether or not such a description of yeast cultures as tiny ecosystems is a correct biological description is beside the point here. At the very least, it could be a useful analogy for introducing another perspective on the organism involved (yeast). Judging the analysis of the LT-materials and execution of the LT-activities, this seems to be how the designer intended to use it. But the introduction of this biological perspective actually introduced a new context not mentioned or clarified during the LT-activities: a scientific context of ecological research. Similarly, other vintner-related LT-activities did not involve a vintner's perspective, but that of a modern yeast-producer. To help students manage this large variety of concepts and contexts in the lesson module, the designer had planned a number of LT-activities that were intended for students to reflect on the meaning of the concepts during group- and whole-class discussions. But these activities were limited in their descriptions of conceptual learning goals and placed at irregular intervals, generally after studying a set of concepts in several contexts. The conceptual learning goals were only described with a single label, such as "photosynthesis", and failed to describe how the concept could be interpreted in a specific context. Therefore, there was no description of how students were expected or meant to interpret and describe the concepts during a particular LT-activity, leaving much to the interpretation of the teacher.

The designer of the lesson module 1 was also the teacher during the enactment of these lessons in explorative case study 1. Consequently, most of the LT-activities were enacted as planned by the designer; although a number of reflection LT-activities were skipped due to time limitations. Observations during the enactment of this lesson module revealed how students were initially motivated by the idea of producing their own wine (mead). But as they progressed through the lessons, many students had trouble understanding 'the point' for the entire lesson module. Several students remarked at different occasions that they failed to understand 'what the lessons were all about' and 'what they were supposed to learn'. Frequent switches between different contexts (especially in the case of the farm-related contexts) left little time for proper introductions of these contexts, obscuring the use of a concept in a specific context. For example: the transcript in box 3.1 is taken from of a whole class discussion on the nutrients needed for growing mushrooms during lesson module 1. After taking part in a series of LT-activities related to the production of wine, students were introduced to a practice of a mushroom farm with a newspaper article describing it. After students had read the article individually, the teacher led the students in a whole class discussion on the food or 'ingredients' needed for growing mushrooms. Apparently, this was intended for the development of two biological concepts: cellular respiration and anabolism using contextual information from the article. However, despite the contextualised description of nutrients for mushrooms in the text, the teacher and students mostly used generalised descriptions for the concepts. This discussion is described in box 3.1.

Box 3.1

Transcript of a short whole class discussion from lesson module 1 (lesson no. 8).

This discussion was intended for understanding concepts related to growing mushrooms and took place directly after the students had read a text describing the practice of a mushroom farm.

1.	Teacher	Why do you and why do all the other organisms like the mushroom, need fuel?
2.	Chris	So you can combust it to produce energy.
3.	Teacher	Right. You combust something to get energy. And this combustion of fuels is also named cellular respiration [dissimilatie].
4.	Patrick	Oh, right.

5.	Teacher	That's a new word.
6.	Sibrand	Then what is it?
7.	Teacher	You've already heard another word that's similar to this one.
8.	Chris	Anabolism [assimilatie].
9.	Anna	We've covered that word before.
10.	Hilde	No, assurance.
11.	Anna	Yes we did, in Dutch class.
12.	Teacher	Bastiaan?
13.	Bastiaan	Anabolism.
14.	Teacher	Anabolism, right.
15.	Hilde	No it was here, I'm sure
16.	Gert-Jan	We've also already covered cellular respiration.
17.	Chris	Yes, but we've also covered cellular respiration this year, in biology class.
18.	Teacher	Did we cover cellular respiration already?
19.	Francesc	I have it in my little dictionary; I mean I've got this list of words.
20.	Chris	Yes, I'm sure it's in the dictionary.
21.	Teacher	Then it's a bit of a rerun. Well, those fuels are combusted, like sugars and fats. And later we'll have a look at a very important fuel, that is: glucose. But first this: When an organism has gotten its energy by burning those fuels, then it can grow and recover. And as we've just seen; you now have two words that resemble each other a lot. We've already covered anabolism, and cellular respiration is new. And they are actually each other's opposites. And now we're going to formulate two definitions. If you're ready.
22.	Chris	Yes, go right ahead.
23.	Teacher	Anabolism is the assembly of larger molecules, therefore: anabolism. Anabolism is the assembly of larger molecules, in which energy is stored. So think of photosynthesis: small molecules are being combined to form one large glucose molecule. And within that glucose molecule, there is a lot of energy.
24.	Chris	Oh.
25.	Teacher	Anabolism is the assembly of larger molecules and it requires energy, that process. Cellular respiration is the opposite.
26.	Chris	Right, to make it smaller then.
27.	Teacher	Breakdown people. Breakdown of large molecules, breakdown of molecules that *releases* energy. Sanne, Bastiaan, write that down.

28.	Gert-Jan	Breakdown of?
29.	Chris	Large molecules.
30.	Teacher	Cellular respiration of large molecules.
31.	Chris	Then what happens with glucose in photosynthesis?
32.	Francesc	That releases energy.
33.	Chris	Yes, but what for? The energy used for what? <a buzzer sounds, signalling the end of this lesson>
34.	Teacher	Energy is stored in glucose, so to say.

The transcript in box 3.1 illustrates how students struggled with separating different functions for the food needed for growing mushrooms. They were expected to identify and compare these functions based on their expected prior knowledge of different food categories for humans (as part of the curricula in years 7 and 8 for senior general secondary education). This might have proofed a fruitful comparison, because these three categories are based on the difference between the (main) functions for nutrients in cellular respiration or anabolic processes. However, the teacher explicated and defined these categories before providing students with a chance to do so. An additional LT-activity that would have invited students to remember and describe these categories, could have provided them with a means for connecting this with what they had just read about nutrients for mushrooms. There was no explicit need for them to fully describe and discuss these different functions for themselves. Without the need for an explication, students did not try to define these categories by themselves, let alone to define the related concepts of cellular respiration and anabolism. Furthermore, the teacher (logically) described cellular respiration and anabolism at the cellular level of biological organisation. However, there did not seem to be any explicit steps from the organism to the cellular level of biological organisation during these LT-activities. As a result, students could not be expected to develop these two concepts for themselves. This is illustrated by the comparison of the *label* 'anabolism' [Dutch: assimilatie] with other labels, such as 'assurances' [assurantiën] by Anna and Hilde in remarks 9-11 (box 3.1).

Concepts and contexts in lesson module 2

These observations were discussed extensively with three other experts in (biology) education, strongly influenced by the explorative literature survey on transfer and recontextualising. Thus, the theoretical investigation of the problem of recontextualising and the empirical investigation of lesson module 1 led to the development of a preliminary description of the 'focus' criterion. At this time, the description was not definitive, but it included the following two ideas:

- Any LT-process should *focus* students' attention *on a single concept or limited set of closely related concepts* too avoid confusion, especially in the case of concepts they encounter for the first time.
- Any LT-process should allow for *proper introduction of each context*, focusing on the activities where a concept is actually used and allowing students to see how and why a concept is used in a context.

With these preliminary ideas on focus developed from the first explorative case, attention turned to lesson module 2, which employed a problem-posing approach (Klaassen 1995). The sequence of contexts in this lesson module is displayed in figure 3.2-II at the beginning of this section. In contrast to lesson module 1, the contextual sequence in lesson module 2 reflected the standard sequence as used in many lesson modules from the design-team and clearly separated its contexts by first exploring an 'acquisition-context', followed by an 'application-context', and finally a 'test-context'. The concepts that were to be developed during the exploration of these contexts are listed in table 3.2.

Table 3.2
Concepts explored in the three contexts used in lesson module 2.

Context (biological object)	Concepts
Acquisition: Understanding pet behaviour.	Natural behaviour, stress-related behaviour, chronic stress, coping-styles, hormonal regulation
Application: Designing a pig-friendly stable.	
Test: Explaining human hooligan behaviour.	

Studies concerning the problem-posing approach (Klaassen, 1995; Lijnse, 2007) and its practical translation to lesson module 2 showed how the focus on a particular, context-related problem can help students to develop a motive for learning the concepts and methods used for solving that problem. Such a motive developed from a particular, context-related problem can help students to focus their attention on the specific concepts needed for solving the problem. Other concepts that are related to the context but not to the problem in question can be left out of view for the time being. Lesson module 2 employed two such problem-posing structures concerning two distinct problems involved in studying animal behaviour. It started with a context in which students were asked to explain unexpected and stressful behaviour of pets (dogs). After reflecting on these concepts by constructing a concept-map, a second problem-posing structure concerned the design of 'pig-friendly' (stress-reducing) stables for keeping pigs on an industrial scale. The use of a problem-posing structure stimulated a more precise description of the context-related activity in which a concept is used, which is reflected in the descriptions of contexts in figure 3.2 and table 3.2. The problem of understanding and reducing stress-related behaviour in pets provided a focus on those aspects of keeping pets that are directly related to stress. Although one can easily think of other important aspects involved in caring for a pet (such as feeding it or treating ailments), these were not the focus for the lessons involved. Thus, while these aspects could be expected to be touched upon during the introduction of a context, they did not need any detailed exploration for a solution to the context-related problem. This stands in contrast to more limited or general descriptions of contexts – such as: 'a farm' – that do not specify a context-related problem or activity, leaving it open to a number of different interpretations like the different kinds of farms in lesson module 1 (see table 3.1). These combined observations led to development of two criteria for focus, that will be referred to as criteria 1-1 and 1-2 in this thesis. These two criteria are discussed here.

Two design criteria for focus

The development of the first design criterion of focus that is described in this section, finally led to the following two specifications:

Design criterion 1-1	Focus on a specific context related to the concept in a social practice Any context in an LT-strategy for *recontextualising* a complex concept should allow students properly *contextualise* a concept, i.e.: to see *how and why* a concept is used in a social practice, without requiring them to develop a detailed perspective of other activities in that practice. Therefore, a general orientation should allow students to recognise the social practice and identify themselves with participants

	in that practice. From there, it should zoom in on a specific problem with its related activities: the context. With a specific problem in focus, a problem-posing structure can allow students to develop a *motive for learning the concept by triggering the focus on that concept*.
Design criterion 1-2	Focus on the conceptual elements needed in a context and allow for a stepwise conceptual development. Any LT-strategy aimed at recontextualising a complex concept that structures a large amount of biological knowledge should trigger a *focus* in students on the conceptual elements that determine its contextualised meaning. Introducing these elements in a step-by-step learning process can allow students to connect these elements and *gradually develop the concept* for themselves.

Design criterion 1-1

Design criterion 1-1 describes how a general orientation on a social practice should allow students to identify with participants in that practice, followed by an orientation on a specific context: a specific problem with activities related to solving that problem. The large number of contexts in lesson module 1 and lack of proper introduction to familiarise students with these contexts gave rise to a preliminary description concerning a proper introduction for these contexts. This description became more pronounced with the exploration of lesson module 2, which used problem-posing structures. A process of orientation is intended to focus on the parts of a social practice that can be recognised by students and are related to the concept that is to be developed. This not only involves a focus on the specific problem and activity, it also involves an adaptation of other aspects of the practice, such as translating practice-specific terminology to terminology used in biology education. Similar adaptations of social practices into contexts for an LT-strategy have been elaborated by Prins (Prins, 2010) in a study on modelling in context-based chemistry education. This criterion for focus does not include a full exploration of a social practice, but rather only a part thereof and in this sense is different from the view described by van der Zande (2011) who showed that in order for students (and teachers) to be able to relate to complex decision making processes in genetic testing contexts, they need to be introduced to a lot of different, context-specific information. The goal for this research project however, is to allow students to develop the ability to recontextualise a biological concept to a variety of different practices. However, it does raise an interesting point that in order to successfully use (and thus recontextualise) biological knowledge on genetics, one needs context-specific information as well. This criterion is not meant to not include context-specific knowledge, but it is intended to limit the amount of context-specific knowledge that is introduced as part of the orientation on a specific context.

During the orientation on a particular context, students are expected to focus on a specific problem. This implies the use of a problem-posing structure (Klaassen, 1995; Lijnse, 2007), which was originally designed in research on physics education, but successfully used for biology education as well (for example, see: Knippels, 2002; Verhoeff, 2003). A problem-posing structure aims for students to develop a *motive for learning*, derived from a practice-related problem that they can identify with. This motive can allow students to focus on those aspects of the context that are important in finding a solution (i.e. particular concepts), leaving other contextual aspects out of view. In other words: they should develop a motive for learning the concept *in context*. Although the third design criterion for this LT-strategy (described in section 3.4) explicitly mentions the need for a motive, that criterion pertains to the development of a motive for recontextualising and implies the use of a concept in another context. This motive for learning a concept in context (derived from a problem-posing approach) is not yet a motive for recontextualising. Section 3.4 describes how an LT-strategy for recontextualising should encourage students to further develop this motive for learning into a motive for recontextualising a concept. The *initial development* of a motive for learning or studying the concept stems from the problem-posing structure and is therefore included in this first design criterion. By developing such a motive from a recognisable and practice-related problem, students can be expected to better focus their attention on developing the tools (i.e.: concepts) needed to solve that problem. Although descriptions of the problem-posing approach in research publications provided convincing illustrations of its effectiveness, it was observed in practice in explorative case study 2. The lesson module in that case study used several problem-posing structures to structure its series of LT-activities in different contexts. Chapter 5 of this thesis describes the design process for an LT-strategy for recontextualising and details how an orientation on a social practice was combined with a problem-posing structure to focus students on a specific concept in context.

Design criterion 1-2

The second part of the focus criterion (1-2), was influenced by the large number of concepts in lesson module 1 and students' resulting confusion as to 'the point' of the lessons led to: to limit the number of (complex) concepts to be developed and allow for a stepwise development of those. In addition to this focus on a particular concept that is to be developed, criterion 1-2 also emphasises the need for structuring the LT-activities in such a way that it allows for a stepwise conceptual development of cellular respiration. This means that it should not introduce a complete description of the concept such as the description in chapter 1 of this thesis (box 1.1) when it is first encountered. Instead, students should be allowed to gradually develop their concept of cellular respiration by adding or changing only a few *conceptual elements* in each step. See chapter 2 (figure 2.7) for a description of the conceptual elements for cellular respiration that have been identified for this research project. Relating this criterion to the first focus-criterion (1-1), this means that an LT-strategy should introduce or change these conceptual elements on a 'need-to-know' basis, provided by the focus on a specific context and its problems. The following section moves on to the second criterion for an LT-strategy for recontextualising biological concepts: explication and reflection.

3.3 Explication of and reflection on a concept in context

A lot of studies on learning and teaching have emphasised the importance of students actively constructing new knowledge by expressing and comparing their ideas with others in one way or another (Engle, 2006; Greeno, 2006; Kinchin, De-Leij, & Hay, 2005; Sfard, 2000; Wells, 2001). In addition, studies on the problem-posing structure (Klaassen, 1995; Lijnse, 2007) also emphasised the use of frequent reflection activities. While referring to the acknowledgement of the importance of and methods for reflection in these sources, this criterion specifies reflection activities that are needed to enable students to develop and recontextualise a concept. It also includes the idea that such activities should allow for students to explicate their own views on a concept in context by – for instance – producing written or verbal descriptions of these views. Students should then compare these descriptions and be invited to try and come to a commonly accepted description in cooperation.

The initial development of this criterion was strongly influenced by the (sociocultural) view on learning and recontextualising described in the first chapter of this thesis. This chapter describes concepts as tools for thinking and communicating about (biological) objects and phenomena. Therefore, one can only learn *how* to use such tools if allowed to actually use them as they were intended. Consequently, students should *not only* be invited to use these concepts to think about (biological) objects and phenomena in specific context-related assignments. They should *also* be regularly challenged to express their thoughts and interpretations, allowing them to use and build on each other's interpretations. Ideally, students and teacher in a class should form a community of learners (Crawford, Krajcik, & Marx, 1999). After recontextualising a concept several times, students should be able to act with what Greeno (2006) terms as 'acting with conceptual agency'. According to his description, people that act with conceptual agency in a domain treat the concepts and methods in that domain as resources that can be adapted, evaluated, questioned, and modified to suit one's purposes. This is similar to descriptions of the process of abstraction by van Oers (see chapter 1). He described this as a process of 'continued, progressive recontextualising': an on-going process of recounting past experiences, and selecting and adjusting any tools from these experiences that can be used in a current activity (v Oers, 2001). Thus, any LT-strategy for recontextualising should incorporate frequent LT-activities that invite students to consciously reflect on past (LT-) activities from their current perspective. This can encourage them to select and describe those concepts that are needed in the new activity. This repeated, conscious recontextualising can help students open up to the idea that a concept can change with different goals, allowing them to develop an interpretation of the concept that they are willing to change, if the circumstances would require.

Explication and reflection in lesson module 1

Section 3.1 described how lesson module 1 employed a large variety of contexts to explore an even larger variety of concepts. This was influenced by practical considerations as well as a generalised, biological perspective on the part of the designer and teacher of the lesson module. Such a variety of contexts might have proved useful for allowing students to explore many different, contextualised interpretations of a biological concept, provided they had a chance to reflect on each contextualised interpretation and compare it to interpretations from other contexts. The design of lesson module 1 included a few LT-activities meant for reflecting on the meaning of the different concepts. However, these reflection activities were only included after exploring a number of concepts in different contexts. There were no LT-activities planned for students to reflect on specific, contextualised interpretations of concepts.

The example in box 3.1 (see section 3.1) was intended as a discussion on nutrients for mushrooms, although these organisms were hardly mentioned during this discussion. Additionally, the concepts that needed to be developed during those reflection activities were described in very general terms: most concepts were described by a single label such as ‘photosynthesis’ or ‘cellular respiration’, without specifying them in context-specific descriptions. The example in box 3.2 illustrates how this led to a poor understanding of the concepts that had been introduced during the lessons. The transcript in box 3.2 is taken from explorative case study 1 (lesson module 1). It took place during one of the final lessons (no. 15) of the lesson module, after the teacher had one student explain how her father (a livestock farmer) produced silage to feed his livestock during winter.

Box 3.2

Transcript of a short whole class discussion from lesson module 1 (lesson no. 15).

This transcript follows a whole class discussion in which the teacher invites one of the students to describe how her father (a livestock farmer) produces silage. Silage is produced in many livestock farming practices to feed the animals when there’s no fresh food available (for instance: in winter). It is produced by allowing fresh foods such as grass or corn to be fermented by lactic acid producing micro-organisms. The resulting acidification of the food prevents the growth of other micro-organisms. This traditional method of preserving food is still used in many modern farming practices and provides an example for anaerobic respiration that at least some students in this class[1] can recognise.

1.	Patrick	Lactic acid bacteria. Without oxygen.
2.	Students	<rumour>
3.	Teacher	Those lactic acid bacteria; they actually only grow

[1] Although the school can best be classified as an ‘urban’ (see chapter 2), a substantial number of students come from surrounding villages, which support quite a number of cow and pig farms.

		without oxygen. And that makes them, and there's your next word: anaerobic.
4.	Hilde	Oh, we didn't have that one yet.
5.	Chris	Anaerobic.
6.	Teacher	Anaerobic bacteria.
7.	Students	<rumour>
8.	Chris	Isn't that with oxygen?
9.	Sibrand	Cellular respiration!
10.	Patrick	Oh! I'm good!
11.	Gusta	Cellular respiration.
12.	Teacher	So what exactly do they do?
13.	Gusta	[They] divide.
14.	Chris	[They] respire.
15.	Anna	[They] duplicate.
16.	Gusta	[They] multiply.
17.	Teacher	Yes, they're multiplying.
18.	Patrick	But what does anaerobic respiration mean?
19.	Chris	Combustion without O2.
20.	Teacher	Combustion without O2. Indeed. But what are they combusting?
21.	Chris	How boring.
22.	Patrick	Glucose.

Following this short discussion, the teacher defined cellular respiration and anabolism again, using similar descriptions as in the first episode from lesson 8 described in this section. After that, students started to work on a group assignment in which they were expected to answer a few questions regarding cellular respiration in yeast.

23.	Francesc	What fuel does yeast need?
24.	Patrick	Is oxygen a fuel?
25.	Gert-Jan	I don't know.
26.	Patrick	Sugar.
27.	Francesc	Photosynthesis.
28.	Patrick	What fuel does yeast need?
29.	Gert-Jan	Starch, that's nasty.
30.	Francesc	Tasty!

Having discussed the methods used for producing silage and emphasizing the oxygen-deprived conditions needed for this, the teacher identified the micro-organisms used for fermentation as lactic-acid producing bacteria. He then introduced the concept of anaerobic respiration as another form of cellular respiration. However, when they were asked what it is that the bacteria are doing students replied by saying that they multiply (remarks

12-17). The teacher acknowledged this, possibly allowing students to incorporate the idea of multiplication of organisms as part of their concept for cellular respiration.

Following the first part of this transcription, the teacher defined cellular respiration as well as anabolism again, using similar descriptions as in the first episode described in this section (box 3.1). Because of the similarity between these two whole class discussions, the discussion in lesson 15 is not included here. Instead, the second part of this transcript described a short discussion between three students, which followed after the teacher's descriptions of cellular respiration and anabolism. These two short transcripts (box 3.2) illustrate how students, after being introduced to a large number of new concepts during the lesson module, had trouble to decide if these concepts could be applicable in a specific situation. As for the concept cellular respiration; the example from the small group discussion between Francesc and his classmates shows that they had not yet grasped this concept at this time.

The lack of consistent sequencing of reflection-purposed LT-activities, and the lack of conceptual focus from a student perspective (see section 3.1), resulted in students being either unwilling or unable to describe these concepts for themselves. As a result, during the majority of reflection-purposed LT-activities the teacher provided the students with his own, detailed and generalised definitions for the concepts from a biological perspective (see also: chapter 1). Of course, when students did try to add to the discussion with their interpretation of a concept the teacher let them voice their interpretation, but there was no active invitation to students to do so. This kept the responsibility for correct descriptions of concepts with the teacher. Combined with the confusion brought about by the large number and frequent changes in contexts, this led to most students adopting a passive stance during the LT-process. With no requirement or invitation for actively developing the concepts themselves, the students did not use the concepts as tools for thinking and communicating, leaving most of the thinking and communicating to the teacher.

Explication and reflection in lesson module 2

The design of lesson module 2 included reflection activities after explorations of the acquisition- and application-contexts. Students were invited to develop contextualised descriptions of the concepts involved using concept maps (Novak, 1990), and compare their interpretations among one another. The usefulness of concept-mapping assignments has been described in quite a number of studies (Hay & Kinchin, 2006; Kinchin, 2001; Kinchin *et al.*, 2005; Novak & Cañas, 2004; Novak & Cañas, 2007; Odom & Kelly, 2001; Soyibo, 1995; van Zele, Lenaerts, & Wieme, 2004). An important aspect of constructing a concept-map is the requirement to use propositions for describing *how* two or more concepts are related. This requires one to actively think about how concepts are interrelated instead of simply signifying that they *are* related, which is the case with similar tools for visualising a body of knowledge (such as mind-maps or word-webs). However, this also means that students should be aware of this important difference and be stimulated to try and describe all connections in their map. This was not the case in the enactment of lesson module 2. Although a description of the concept-mapping process was provided in the LT-materials, the teacher failed to stress this point during the concept-mapping activities, and accepted concept maps without any connecting descriptions from the students. As an example, figures 3.3 to 3.6 provide (translated) examples of concept maps from two students.

Figure 3.3 and 3.4 display a concept map made by a student on the left, with its English translations to the right. Figures 3.3 and 3.4 are concept maps constructed by students during LT-activities for reflecting on a context of pet (dog) behaviour.

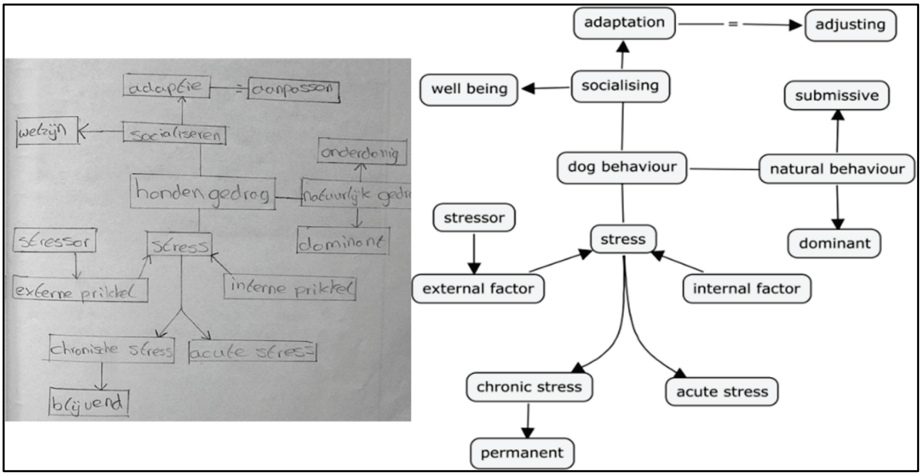


Figure 3.3. Concept-map made by 'student 1' in explorative case study 2 in a context for explaining pet (dog) behaviour.

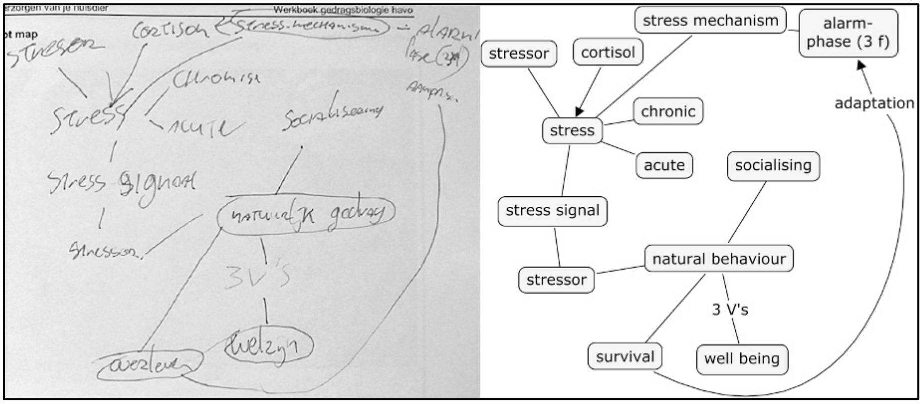


Figure 3.4. Concept-map made by 'student 2' in explorative case study 2 in a context for explaining pet (dog) behaviour.

The first concept map (figure 3.3) depicted is from a student who had produced rather detailed concept maps in comparison to others, while the second concept map (figure 3.4) is an example of a students who did not produce detailed concept maps in comparison to the other students.

The concept maps in figures 3.5 and 3.6 were also created by 'student 1' and 'student 2', respectively (see figures 3.3 and 3.4), this time as part of an LT-activity in the context of designing a pig-friendly stable. These concept maps can be considered as examples that represent the majority of concept maps that were constructed by the students during these LT-activities in case study 2. While they clearly show that the described concepts or labels involved in animal behaviour and these two contexts are connected, these concept maps do not to describe exactly *how* these are connected within a context, and with other context-specific factors.

Aside from the fact that the lack of 'connecting phrases' makes these concept maps harder to interpret, this also makes it impossible to discern any specific contextual perspective from these concept maps. Without any differences of note between the concept-maps made in the different (context-based) LT-activities, students could not be expected to explicate and compare differences and similarities between context-specific uses of the concept(s). Additionally, and similar to the enactment of reflection activities in lesson module 1, time-restraints led the teacher to refrain from any true comparison of students' concept-maps, providing students with generalised, biological definitions of the concepts involved. Finally, despite the LT-activities during which students were asked to construct concept-maps for each context, no comparison of these contextualised descriptions was included in the design of the lesson module.

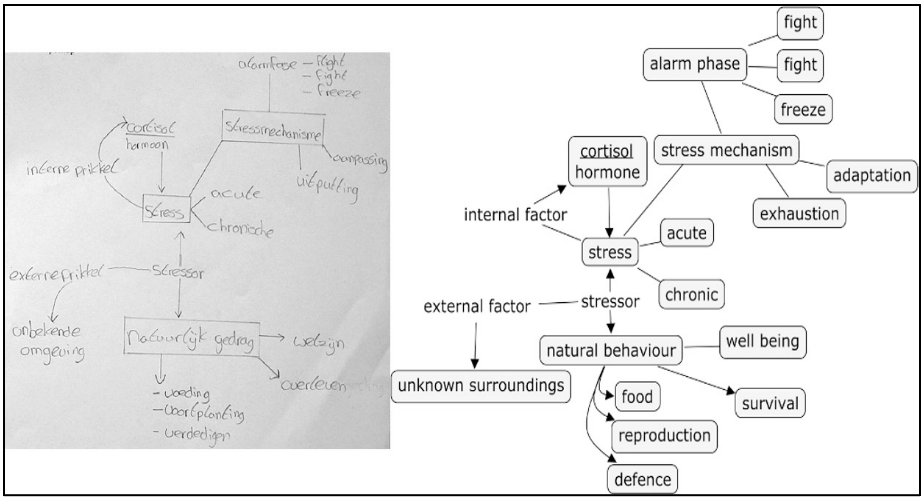


Figure 3.5. Concept map made by 'student 1' in explorative case study 2 in a context for designing a pig-friendly stable.

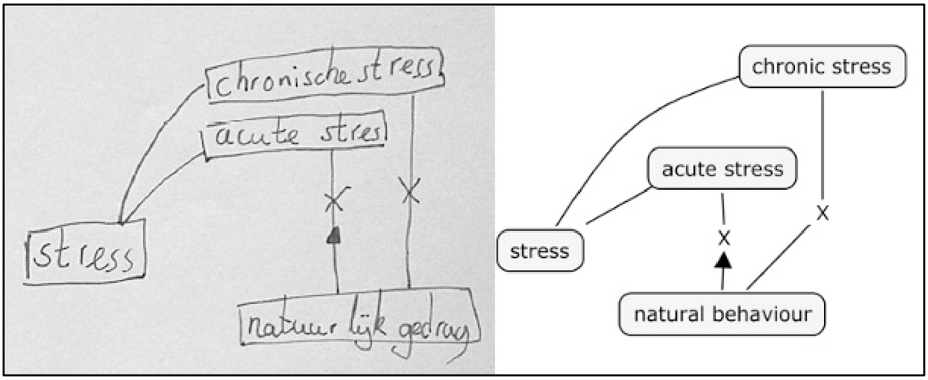


Figure 3.6. Concept map made by 'student 2' in explorative case study 2 in a context for designing a pig-friendly stable.

Two design criteria related to explication and reflection

The design criterion of 'explication and reflection' was derived for a large part from the view on learning and teaching that forms the base for this thesis and is described in chapter 1. This view was developed for a large part through an exploration of literature on learning and teaching, which stresses the importance of allowing students to develop their own interpretations of a concept during LT-activities, in interaction with others.

The design criterion for explication of and reflection on a concept in context can be further detailed as follows:

Design criterion 2-1	Explication of a concept in context. An LT-strategy for recontextualising should employ specific reflection activities that encourage students to identify, explicate and discuss *those elements of a concept that determine its meaning in a context*, allowing them to arrive at a specific, contextualised description (or other representation) of the concept.
Design criterion 2-2	Reflection on a concept in different contexts An LT-strategy for recontextualising should employ specific reflection activities that encourage students to identify, explicate, and discuss the *similarities and differences between different contextualised descriptions (or other representation) of the concept*. This should allow them to identify those conceptual elements that are different and those that are– more or less – stable across contexts.

To encourage students to actively think about (and thus develop) contextualised descriptions of a concept, specific LT-activities are needed that invite them to explicate their views. Furthermore, any LT-strategy for *recontextualising* should allow for LT-activities that invite students to do just that: to consciously compare different, contextualised descriptions of a concept. This can help them to become aware of any similarities and differences between these descriptions, and how they are related to their specific contexts. Observation and analysis of the enactment of LT-activities for reflection in the explorative lesson modules showed how easily such activities – if enacted at all – can result in the teacher providing concept-descriptions, instead of allowing the students to develop their own. While this might suggest that LT-materials or a teacher should never provide such descriptions, that interpretation of the criterion would be too narrow. Of course, biological knowledge was not developed overnight and asking students to develop it by themselves would be extremely inefficient. However, providing students with detailed descriptions of a concept before they have had any chance to develop their own interpretation does not stimulate them to actively construct the concept by themselves. Why should they, if they already have a detailed description provided by experts in the field? Therefore, this criterion refers not only to the timing of such LT-activities to allow students to gradual develop and recontextualise biological concepts. It also emphasises the necessity of designing and enacting them in such a way that student are specifically invited to explicate their own views and discuss them with each other and the teacher, instead of repeating any descriptions initially offered by LT-materials or the teacher. In other words: an LT-strategy aims at students to develop a flexible biological concept, needs to encourage students to engage in activities for defining a biological concept, and not just provide them with ready-made, generalised definitions of that concept.

3.4 Developing a motive for recontextualising a concept in another context

This third and final criterion is strongly tied to the focus criterion and the use of a problem-posing structure to provide the necessary focus, as well as provide them with a possible motive for learning. It was developed at the end of the explorative phase, fuelled by a desire to use a similar, alternating sequence of contexts as in lesson module 1 (see section 3.1), albeit with a more precise interpretation of the contexts.

Motives for recontextualising in lesson module 1

The designer of lesson module 1 had intended the context and its related LT-activities of brewing mead to provide students with a learning motive for studying the concepts involved. Observations of the first lesson in the module (when the teacher introduced this activity) revealed that students were enthusiastic about the assignment at the start, which provided an indication that it could be used to develop a motive for learning. However, this was not enough to keep them motivated throughout the entire, six-week period. This can at least partially be explained by the confusion brought about by the large variety of contexts and the large number of concepts involved. In addition, one could reason that any motive for learning that was derived from brewing mead, would not provide any reason for students to take a different perspective and develop concepts that are not applicable in that context. For example: this happens with concepts strongly connected to ecological research or genetic modification, which are not used by anyone involved in brewing mead or other drinks. In other words, there was no *motive for recontextualising*, causing a break in the consistency of the sequence of LT-activities from the students' perspective.

Aside from a decreased motivation for students to actively participate in the LT-activities, this lack of a motive for recontextualising also appeared to add to their confusion as to the *focus* of the entire lesson module. The designer of the lesson module did see a connection between these concepts; from his perspective there was a consistent connection between most LT-activities in the lesson module. This is that surprising if his generalised biological perspective is taken into account (see section 3.1, and also chapter 1). This is not only the case for developing any concepts that are entirely unrelated to a context, but also for developing concepts in more detail than its use in a context allows for, such as the concept of cellular respiration in a brewer's context. This will be explained in more detail in the next chapter, which discusses important design criteria and considerations for cellular respiration.

Motives for recontextualising in lesson module 2

Similar to lesson module 1, lesson module 2 did not provide a possible motive for recontextualising, at least not one that was derived from the explored contexts. There was no contextual reason or necessity for moving from the life-world context (see chapter 1) of explaining pet behaviour to a professional context of designing a pig-friendly stable. The only motive for changing contexts expressed by both the LT-materials and the teacher in this second explorative case study was the need for students to be able to pass the final test and – eventually – any exams, which required a more detailed perspective on the concepts involved. While such a motive can certainly be effective and is probably always tied to a secondary school setting, the addition of a context-based reason for switching perspective might allow students to develop a stronger, intrinsic motive for recontextualising. In addition, the inclusion of such a motive might also help students to better see how social practices are related with one another through their use of similar concepts (see also chapter 1). A better understanding of this division of labour between social practices might allow them to accept the idea of changing their perspective on a concept with a change in context more easily, and open them up to the necessity of conscious recontextualising as part of their learning process.

A context-based motive for recontextualising

Although the usefulness of a context-related motive for recontextualising is easily argued, finding possible anchors-point for such a motive is not that easy, especially when trying to incorporate multiple contexts in a single (and contextualised) problem-posing sequence. During discussions with other experts in (biology) education, a couple of possible routes were explored. The first of these is similar to the learner's motive in lesson module 2 described above, and connects different contexts through the use of similar concepts. Such a motive for recontextualising would rely heavily on students' personal motives for wanting to understand particular biological concepts.

A second connection might be found in a similar organism or biological object that is manipulated in different contexts. This is closely related to the connection the designer of lesson module 1 possibly made when expanding the context of brewing mead to a context of breeding improved strains of yeast during a number of the LT-activities. With modern yeast producers supplying most vintners with specialised and very reliable strains of yeast, this connection seems obvious. But when focusing on brewing-related problems no obvious problems come to mind that need a biotechnological perspective. One might envision a vintner choosing a suitable strain of yeast for his wine. However, this activity does not require him to do much more than to read descriptions of different yeast strains, which are adapted to a vintner's practice and probably do not require a biotechnological perspective. Therefore, there seems to be no motive to move from a brewing context to a biotechnological context. However, it could be made the other way around, since a yeast producer is involved in developing yeast for brewers and bakers.

A third possible connection that was explored is similar to the first connection described, in that it connects contexts through their shared concepts. However, the difference is in concepts being developed in other contexts, in terms of increasing its complexity with new (scientific) insights. This is for instance, the case with many concepts first developed in an academic setting; most professional or other academic practices develop concepts and related insights and use them for their own purposes. In such practices, the use of a concept can become so automated and 'second nature' to its participants, that it becomes an operation in activity theoretical terms. This is the case in many medical practices, for instance: while a concept like "*heart*" is crucial for many medical practices, its meaning hardly requires any discussion and its use is automated in many activities for doctors and nurses. But they probably did develop a detailed conception of that organ during their medical studies, using information in text-books derived from other practices. This connection might prompt the idea that when trying a problem related to a medical context, one needs a more detailed perspective on a concept that cannot be gained from the context that posed the problem, requiring an exploration of a context where the concept was developed.

A fourth possible connection was found in a common idea in biological research practices: using ‘model-organisms’. In biological practices, the use of so-called ‘model-organisms’ provides obvious examples: due to ethical and practical considerations, it is common to develop insights on biological phenomena by studying organisms that are comparatively easy to study and sacrifice. A motive for recontextualising that is based on the use of ‘model-organisms’ can provide an obvious example of recontextualising by exploring it in a different organism, as part of a different context.

A design criterion related to a motive for recontextualising

Based on the description of its development in this section, the design criterion for allowing students to develop a motive for recontextualising a concept in another context can be described as follows:

Design criterion 3	Develop a motive for recontextualising a concept to different contexts. An LT-strategy for recontextualising should incite students to develop a motive for recontextualising: a reason for changing their perspective on a concept from one context to another. Social practices often use certain aspects of a concept implicitly or do not use all conceptual elements that make up a concept. The contexts that are explored in an LT-strategy can be connected in a *storyline*.

In conclusion, this criterion for developing a motive for recontextualising was strongly influenced by the idea of a ‘motive for learning’ reflected in the problem-posing structure (see section 3.1). It is actually an extension of a motive for learning, which is derived from an exploration of a context-related problem. Although any motive for recontextualising would ideally be derived from a context-related problem as well, finding such a motive suitable for use in an LT-strategy can proof difficult. Any motive for recontextualising is best described in relation to the contexts that are to be explored. Certain context-specific views will not provide a motive for exploring a concept in more detail, and care should be taken to weave different contexts into one, single *storyline*. A storyline that connects different motives for studying a concept in different contexts may enable students to develop a narrative for describing their development of cellular respiration. As such, a motive for studying the concept in another context does not have to stand on its own, but be a part of a broader motive for developing the concept in more detail.

This discussion will be continued in chapter 5, which describes the motive for recontextualising as it was developed for this LT-strategy, in relation to the contexts it intended for students to explore. With the development of three design criteria detailed in this and the previous sections, the final section of this chapter finishes with an overview of these three design criteria in a response to RQ I.

3.5 Design criteria for an LT-strategy for recontextualising a biological concept

RQ I details the need for design criteria to guide the development of an LT-strategy for recontextualising biological concepts. This research question is repeated here for ease of reference:

RQ I Which design criteria for an LT-strategy for recontextualising biological concepts can be identified from an empirical and theoretical exploration of recontextualising?

In response to this question, three design criteria were developed during the explorative phase of this research project. Their development and their relation to theory and practice are described in the previous sections of this chapter.

Design criterion 1-1 Focus on a specific context related to the concept in a social practice

Any context in an LT-strategy for *recontextualising* a complex concept should allow students properly *contextualise* a concept, i.e.: to see *how and why* a concept is used in a social practice, without requiring them to develop a detailed perspective of other activities in that practice. Therefore, a general orientation should allow students to recognise the social practice and identify themselves with participants in that practice. From there, it should zoom in on a specific problem with its related activities: the context. With a specific problem in focus, a problem-posing structure can allow students to develop a *motive for learning the concept by triggering the focus on that concept*.

Design criterion 1-2 Focus on the conceptual elements needed in a context and allow for a stepwise conceptual development.

Any LT-strategy aimed at recontextualising a complex concept that structures a large amount of biological knowledge should trigger a *focus* in students on the conceptual elements that determine its contextualised meaning. Introducing these elements in a step-by-step learning process can allow students to connect these elements and *gradually develop the concept* for themselves.

Design criterion 2-1 Explication of a concept in context.

An LT-strategy for recontextualising should employ specific reflection activities that encourage students to identify, explicate and discuss *those elements of a concept that determine its meaning in a context*, allowing them to arrive at a specific, contextualised description (or other representation) of the concept.

Design criterion 2-2 Reflection on a concept in different contexts

An LT-strategy for recontextualising should employ specific reflection activities that encourage students to identify, explicate, and discuss the *similarities and differences between different contextualised descriptions (or other representation) of the concept*. This should allow them to identify those conceptual elements that are different and those that are– more or less – stable across contexts.

Design criterion 3	Develop a motive for recontextualising a concept to different contexts. An LT-strategy for recontextualising should incite students to develop a motive for recontextualising: a reason for changing their perspective on a concept from one context to another. Social practices often use certain aspects of a concept implicitly or do not use all conceptual elements that make up a concept. Therefore, students need to explore several contexts to develop a sufficiently detailed perspective on the concept that they can recontextualise and use in other contexts. The contexts that are explored in an LT-strategy can be connected in a *storyline*.

The next chapter describes the choice for the concept of cellular respiration as a vehicle for this design-research study on recontextualising and the results of the exploration of this concept in biology education research and practice. It ends with a final description of the design criteria presented in this chapter, specified for the concept of cellular respiration.

Chapter 4

Exploring Cellular Respiration

Chapter 1 (section 1.3) provides a description of cellular respiration from a generalised, biological perspective for purposes of this research project on recontextualising that concept, but it does not detail the argumentation behind this choice. Therefore, the first section of this fourth chapter discusses the arguments for choosing this concept as a vehicle for this research project. Section 4.2 then continues with a review of the education research literature on learning cellular respiration. Section 4.3 describes the learning-goals related to cellular respiration in the Dutch biology curriculum for senior general secondary education, followed by a analysis of the concept in Dutch textbooks. The fourth and final section of this chapter summarises the resulting design criteria that need to be taken into account when designing an LT-strategy aimed at recontextualising cellular respiration in senior general secondary biology education.

4.1 Choosing cellular respiration

The concept of cellular respiration first came into view during this research project with the explorative case study (see chapters 2 and 3) which involved lesson module 1. This lesson module used the production of wine in order to visualise cellular respiration in yeast. Observations of this lesson module in practice showed that students had numerous difficulties with understanding this concept. It should be noted that cellular respiration was not the only concept explored during this lesson module, which also explored concepts like photosynthesis and anabolism (see chapter 3). Although these observations clearly showed that students had difficulty with understanding cellular respiration in several contexts, they were not sufficient to clarify the source of these difficulties. These might have arisen from problems related to specific aspects of the concept itself, but also from the number of new concepts or contexts presented to the students during this lesson module. The eventual choice for cellular respiration was inspired by two considerations regarding cellular respiration as the concept of focus for an LT-strategy for recontextualising biological concepts:

- Cellular respiration plays a crucial role in organisms and can be defined as a 'central' or 'key' concept in biology.
- Cellular respiration seems to have received an undeservingly low amount of education research attention.

Cellular respiration is a central concept in biology

The first of these suggests that cellular respiration is a central concept in biology. Chapter 1 of this thesis defines a concept in biology as structuring a substantial amount of biological knowledge that is generalizable to many different biological systems. Because of this substantial amount of generalizable knowledge structured by a central concept, it can be expected that such concepts are used in a large number of social practices. With use in more practices, such a concept needs to be recontextualised frequently, making it a suitable candidate for researching recontextualisation. But is cellular respiration a central concept in biology? Various sources identify the concept as central to biological understanding (Anderson, Sheldon, & Dubay 1990; Sanders, 1993; Seymour & Longden, 1991; Songer & Mintzes, 1994; Wandersee, Mintzes, & Novak, 1994). Also, cellular respiration processes play a crucial role in all living cells and organisms: it is responsible for providing living organisms with the energy required for all other processes that sustain them. Because of this, requirements for performing cellular respiration have a tremendous impact on the structure and behaviour of cells, organs, organisms and even populations.

Therefore, understanding cellular respiration helps us to understand the structure and behaviour of biological objects. Any biological subject matter involving the concept of energy requires at least a rudimentary understanding of the processes that provide energy by ‘combusting’ or ‘breaking down’ food substances. In addition, cellular respiration incorporates two important aspects identified as possible ‘threshold concepts’ in biology. The term ‘threshold concept’ does not have the same meaning as ‘central concept’, but refers to troublesome content knowledge that provides a ‘new and previously inaccessible’ perspective on something, revealing things previously out of view (Meyer & Land, 2005). For biology, several studies have identified a number of concepts that can be considered as central or crucial to biological understanding (Kamp, 2000; Boersma & Schermer, 2001; Ross et al., 2010; Taylor, 2006). Examples of such concepts include: homeostasis, cellular division, osmosis, cellular respiration, energy (transformation), variation, and thinking at a sub-microscopic level. Since cellular respiration is defined at sub-microscopic levels of biological organisation, is strongly tied to the concept of energy transformation, and explains how all organisms get the energy they need to survive; it is safe to say that this concept is central to biology. It might also include several ‘threshold concepts’ as well.

Cellular respiration deserves more attention

Secondly and unfortunately: although cellular respiration can be identified as a central concept in biology, the learning and teaching of this concept does not seem to have received much research attention (Songer & Mintzes, 1994). To provide another indication of the research attention for cellular respiration in comparison with two other very important concepts in biology, genetics and evolution, table 4.1 shows the number of ‘hits’ in several keyword searches in a specific search engine (Google Scholar). Keep in mind that each number represents the number of research articles that contain a certain keyword within the search’s parameters. The number of actual, peer-reviewed, research articles on subjects relating to that specific keyword can be expected to be smaller than the number of hits listed in table 4.1. Each search was made using the keywords “education”, “biology” and “concept”, in addition to one of the concepts below. The searches were all made on the same date: February 27, 2011. The number of hits listed represents the number of hits in a limited search within the subject areas of

Social Sciences, Arts and Humanities, in combination with Biology, Life Sciences, and environmental education, with no limitation for publication period.

Table 4.1
Results (number of 'hits') for several key word searches in Google Scholar (combined with the keywords "biology" and "education")

Keywords related to genetics	**# hits (x1000)**	**Keywords related to evolution**	**# hits (x1000)**	**Keywords related to cellular respiration**	**# hits (x1000)**
Genetic	54,8	Evolution	58,5	Respiration	9,6
Gene	29,4	Natural selection	17,1	Fermentation	8,0
DNA	23,6	Mutation	17,2	Cellular respiration	**0,63**
Chromosome	16,9	Hereditary	15,7	Anaerobic respiration OR Aerobic respiration	**0,43**

Note. Each 'search hit' does not represent an applicable research article, but just the occurrence of a term in an article. These figures are only meant to indicate differences in research attention between cellular respiration and other important, biological concepts in biology education.

In conclusion: the central and difficult nature of the concept, combined with the low amount of research attention led to the final choice for cellular respiration as the focus for an LT-strategy for recontextualising biological concepts. The following section continues with a review of the research literature related to the learning and teaching of cellular respiration.

4.2 Difficulties in learning and teaching cellular respiration

Although there seems to have been a lot less attention to the concept in comparison to other biological concepts (see section 4.1), the research that has been done on the subject identified a number of learning difficulties related to understanding cellular respiration (Anderson et al., 1990; Sanders, 1993; Seymour & Longden, 1991; Songer & Mintzes, 1994). There are of course, more studies that concentrate on the concept of cellular respiration (C. Lin & Hu, 2003; S. W. Lin, 2004), but many of these have looked at students' understanding of cellular respiration in direct relation to other concepts such as photosynthesis or energy flow. These were deliberately left out from this research, because of a desire to understand students' difficulties with understanding cellular respiration in itself, not in combination with other concepts. Studying cellular respiration combined with photosynthesis in these research articles brings to light interesting problems, such as students viewing both processes as exact opposites, or that plants do not need to respire in daylight. But these concern problems of how students relate these concepts to each other and not the understanding of one of them in their own right. Of course, relating these concepts is very important in understanding energy flow in ecosystems or metabolism in plants and might help students to further distinguish the concept from other bio-molecular concepts. But, for reasons explained in our discussion of criterion 1 (focus: see section 3.5), an understanding of cellular respiration in itself before relating it to other (central) concepts can be fruitful. Chapter 6 will return to this point in the discussion of the possible implications of the outcomes of this research project for learning and teaching other biological concepts. Although not all sources categorise learning problems in the same way, with some categorising alternative- or misconceptions (Seymour & Longden, 1991; Songer & Mintzes, 1994), and others categorising the source of erroneous ideas (Anderson et al., 1990; Sanders, 1993), the major problem categories from these studies can be summarised as follows:

- *Confusions with everyday language*, for instance: the term "respiration" is often confused with breathing.
- *Confusions with everyday ideas about energy*: energy previously stored in organic molecules can be released by breaking them down again into smaller molecules.
- *The concept is biochemical in nature*: it takes place at the molecular level of biological organisation and requires a concept of molecules or particles as the building blocks for matter.
- *The concept is inclusive in nature*: it incorporates different versions of similar processes: the most obvious variations being those between aerobic and anaerobic respiration, and alcoholic and lactic acid fermentation.

The rest of this section discusses each of these issues one at the time, and finishes with a description of possible implications of these with regard to design criteria for an LT-strategy that aims for students to develop this concept.

Confusions with everyday language

The first problem listed that has received quite some attention is the obvious confusion of the terms respiration and breathing, discussed by various authors and focused on in the title of the article by Songer and Mintzes (1994): “Respiration – that’s breathing isn’t it?”. In many life-world, professional, or scientific practices (see chapter 1), the term *respiration* refers to the breathing process. For instance, we speak of a *respiratory system* when we speak of lungs, gills, etc. As a result, the biological view on respiration as a biochemical process is overwhelmed by alternative conceptions or interpretations of respiration. The major problem here seems to be a difference between the levels of biological organisation from which we perceive respiration. Using the term *cellular* respiration to refer to the cellular process helps to clarify this distinction. The problem of confusing *cellular respiration* with *respiration* will not be further explored here because Dutch education makes use of the term *dissimilatie* [dissimilation or catabolism] instead of the also available (but far less common) *celademhaling* [cellular respiration] (see section 4.1). Although our first explorative case study (lesson module 1, see chapters 2 and 3) brought to light a few minor difficulties students had during their initial confrontation with the word dissimilation, the obvious advantage of using such a term that it is uncommon in everyday language, solving the problem of confusions with everyday language.

Confusions with everyday ideas about energy

Other problems related to cellular respiration are not so easily overcome with a little luck in linguistic evolution, and become as apparent in Dutch as they are in the English language. The second problem in our list concerns students’ understanding of energy, or more particular: energy conversions. Although studies shows that energy conversions can be a tricky concept to get your head around in biology (Flores, 2003; C. Lin & Hu, 2003), the author’s experience with students at this level of biology education suggests that they do not seem to have much problem with understanding that every living organism requires energy to stay alive. Additionally, these studies refer to cellular respiration in direct relation to other concepts involving energy conversions, like photosynthesis.

The focus-criterion for recontextualising (see chapter 3) states that an LT-strategy that aims at the initial development of a concept should focus specifically on that concept. Therefore, it seems best to focus the LT-strategy developed in this research project on cellular respiration in heterotrophic organisms and their inclusive levels of biological organisation, avoiding possible confusion with other concepts – like photosynthesis – at this point in students' conceptual development. An exploration of cellular respiration in autotrophs or from an ecosystem or biosphere perspective (which would illustrate the relation between cellular respiration and other concepts) is reserved for LT-strategies that could follow this one. This does not remove the problem of a more general understanding of energy conversions in biology. It does narrow it down to a required understanding that cellular respiration makes chemically stored energy available for powering cellular metabolic processes, and that it does so by breaking down comparatively large, energy rich molecules. Such an understanding is expected to be sufficient for understanding most of the relations between the levels of organisation and is consistent with the required understanding at this level of education. This understanding is in itself again related to the third and fourth problems in our list: the molecular level at which cellular respiration takes place and the inclusive nature of the concept referring to several different versions of the process in different organisms, and its different contextual interpretations.

The process is biochemical in nature

Both the biochemical and the inclusive nature of cellular respiration are referred to as 'abstract' in several of the studies discussed in this review. Because the idea of recontextualising (see chapter 1) is closely related to any notions of abstraction (van Oers, 2001), this section further explores these apparently contradicting 'abstractions' of cellular respiration. A major difficulty here seems to be that describing these different interpretations of cellular respiration as 'abstract', it does not help us any further. Therefore, these different meanings are discussed in more detail here in relation to the idea of recontextualising.

Visualising cells and molecules.

When looking at *the process of cellular respiration*, one can reason that while descending from the organism level of biological organisation down to the cellular and sub-cellular levels, the process apparently becomes more abstract with each level of organisation. In this case, 'abstraction' means that the process under investigation becomes increasingly obscured from direct observation. Although the cellular level can be (partially) brought into view with direct (microscopic) observation of the cell under investigation, the molecules cannot be observed at all; molecules are models.

Understanding the molecular level of biological organisation requires the use of molecular models. Even modern technologies for 'visualising' molecules rely on our interpretations of specific measurements, based on conceptual models that help us explain these measurements. This molecular or biochemical nature of cellular respiration is related to two important problems for learning and teaching the concept (Anderson et al., 1990; Sanders, 1993; Seymour & Longden, 1991; Songer & Mintzes, 1994). The first is the way in which the molecular process is represented and what aspects of the concept a representation focuses on. The second involves the ability to understand how processes on one level of biological organisation are related and can be used to explain phenomena on another level of organisation.

Starting with the problem of representations of sub-cellular or molecular level, we can say that in order to understand cellular respiration; one needs to be able to imagine the molecules (like the exemplary glucose) involved breaking down and releasing energy and relate this to other metabolic processes in the cell. But, due to the fact that not all of the students in a typical Dutch biology class take chemistry as part of their secondary school curriculum, many lack an understanding of the chemical processes involved. Because this can easily pertain to a substantial number of students in a given class, care should be taken in determining how to represent the overall process to students, without sacrificing a focus on the connection between the break-down of energy-rich substances and the release of energy. Because of this lack of understanding, and the ease of describing the process as an overall reaction, it is often first described as a process of 'combustion' of glucose taking place in 'the body', requiring oxygen:

Combustion: glucose + oxygen → carbon dioxide + water + energy

This prior conceptualisation of the concept can make it harder to step down from the organism and organ level of organisation and understand the chemical aspects of the process. Sanders (1993) showed that many teachers neglect to even mention energy as a major 'product' in their word equations of the process, focusing the students on the released products instead of the major function of the process: the utilisation of energy for metabolic process. Although this study dates from over fifteen years ago and is conducted with South-African teachers, there are no reasons why this shouldn't apply to the Netherlands, especially in the earlier years and lower levels of secondary biology education.

For representing the molecular level of organisation, we need representations that allow students to focus on the energy and breakdown elements of cellular respiration and the similarities and differences between different concrete examples. At the same time, these should allow the students to identify them for what they are: *representations* of molecules, not actual molecules, see also the discussion of cell biology and systems thinking by Verhoeff (2003).

There are numerous graphical illustrations and animations to be found depicting cellular respiration; an internet search for images using cellular respiration as a keyword would probably be the fastest way to illustrate this. Unfortunately this also illustrates that many of these graphical representations either include none or all of the chemical steps involved in the process. Since it is our objective to use a representation that allows for a focus on the elements of breakdown and energy release in cellular respiration without going into too much chemical detail[1], such a search did not yield any appropriate illustrations or animations. Fortunately, a study by Yip (2000) used an illustration method that did seem to be useful. In this study that aimed at promoting students' understanding of lactic acid fermentation he used an illustration of the molecules as basic carbon-chains, leaving other elements out of the graphical representation. As an example, figure 4.1 describes the overall reaction for aerobic respiration and is based on the illustrations in Yip's paper. This, combined with words describing the substances involved can help students see how a larger molecule (with a larger carbon-chain) is broken down into smaller carbon-chains or separate 'carbon-particles'. This method inspired the design of illustrations for describing aerobic and anaerobic respiration at the molecular level of biological organisation.

Connecting levels of biological organisation.

With the molecular level of organisation brought into view, students also need to see how the processes at this level relates to other levels of

[1] The official curriculum for senior general secondary education does not require a concept of glycolysis or the Krebs-cycle (see section 4.3.1).

organisation and how such a detailed understanding can help us explain processes that take place at the cellular and organism levels of biological organisation. Because of students' unfamiliarity with the molecular level of organisation and systems thinking (Verhoeff, 2003), they will need some sort of motive for investigating the molecular process and relating it to other levels of organisation.

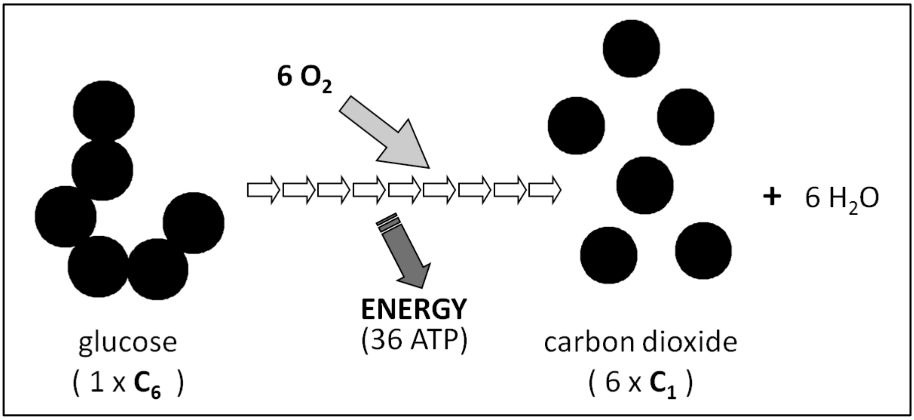


Figure 4.1. Schematic representation of aerobic respiration that focuses on the breakdown of carbon chains

Previous studies from Knippels (2002) and Verhoeff (2003) have shown that it is advisable to start with a problem that can be easily recognised at the organism level of biological organisation. In the case of cellular respiration, such a problem should ideally have an obvious focus on the energy-element of cellular respiration, without needing a cellular perspective. Also, the problem should be one that students can identify with, allowing them to develop a motive for such an exploration. In terms of context-based biology education, this means that the problem should be related to a context that is recognisable for students, and that they can identify themselves with a participant in that context. Starting there, the motive should focus students on the cellular level by a continuous process of focusing on more detailed aspects of the problem and levels of organisation. This process has been described by Knippels (Knippels, 2002) and was termed the Yoyo LT-strategy[2] for genetics education. Judging the outcomes of her study and studies by Verhoeff (2006) and others (Westra, 2008), a yoyo-structure allows students to go down from the organism to the molecular level of

[2] In order to avoid confusion with the LT-strategy developed during this research project, it is referred to as a yoyo-structure in the remainder of this thesis.

biological organisation and relate these different levels from the same general perspective in a step-by-step LT-process. This can be a viable method for allowing students to cope with the chemical nature of the process and the molecular level at which it takes place. In fact, this yoyo process might be viewed as a process of vertical recontextualising (see also: chapter 1), but we shall refer to this as a yoyo-structure for the remainder of this study in order to clearly distinguish it from recontextualising between different (biological) contexts. This brings us to the *conceptual perspective* on cellular respiration that includes various versions of similar processes within and between organisms as well as different interpretations in different contexts.

The concept is inclusive in nature

In addition to the molecular nature of the concept, cellular respiration is also *inclusive* in nature and refers to different processes in different organisms. This is in addition to possible difficulties brought along by different perspectives on a concept in different social practices, which has also been discussed in the previous chapter.

Same concept, different processes

The aerobic and different anaerobic variants of the process are concrete examples of cellular respiration in different types of cells and organisms, which only come into view with a cellular or molecular perspective. For instance: one needs to be familiar with concrete examples of aerobic respiration as well as anaerobic respiration viewed from the perspective of energy-need in a cell, before being able to reason that cellular respiration *needs to* and actually *can* take place in all cells or all living organisms, even those that have no oxygen available (see also statement 2 in section 1.3). Likewise, examples of cellular respiration involving other molecules than glucose are needed before one can reason that cellular respiration is not limited to the exemplary glucose, but that all these are comparatively large, energy-rich, and organic molecules. The more we look at the details in these biochemical processes, the more differences between specific variants of cellular respiration come into view. For instance: many organisms can employ both aerobic and anaerobic respiration for their energy utilisation.

Additionally, anaerobic respiration has many variants, such as: lactic acid fermentation, alcoholic fermentation or methane fermentation. When comparing just one of these aerobic or anaerobic variants between specific organisms, such as lactic acid fermentation in human muscle fibres and lactate producing bacteria such as *Lactobacillus subtilis*, more differences come to mind. Examples of such differences include, but are not limited to: the fate of its end product lactate (which can be a final waste product in some cells or is utilised as a metabolic intermediate in others), or the structure of the enzymes involved in cellular respiration. In addition, the function of cellular respiration-variants can differ between organisms as well. For example and in contrast to popular beliefs; the function of anaerobic cellular respiration in muscle fibres is quite different from its function in yeast. Although the main function in both examples is the release of energy, yeast employs it to assure the release of energy in the absence of environmental oxygen, while its main function in muscle fibres is a fast release of energy (Brooks, 2000; Brooks, 2009; Gladden, 2001; Philp, Macdonald, & Watt, 2005). As will be explained in the following section (4.3), many biology education textbooks emphasise a lack of oxygen as the cause for anaerobic respiration in eukaryotes (i.e.: organisms with cells containing a nucleus and internal membrane, such as plants, animals and fungi). Although this is at least partially true for most well-known eukaryotes – like yeast for example – it is not the main reason for using the process in, for instance human muscular tissue. Because this idea is quite recent, it has not found its way into the biology education textbooks that were part of this study (see section 4.3). Current research points into the direction of lactate as an intermediate metabolite in catabolism, instead of an end product per se, an idea expressed in a 'lactate-shuttle' hypothesis. Additionally, lactate is no longer the main culprit for exhaustion and tissue damage as it was believed to be. For a detailed overview of de development of these ideas, we refer to a collection of commentary and review articles from the last decade (Brooks, 2000; Brooks, 2009; Gladden, 2001; Gladden, 2004; Philp et al., 2005; Svedahl & MacIntosh, 2003).

There appears to be consensus on the existence of extra- and intracellular lactate shuttles enabling cells to increase their rate of glycolysis by converting pyruvate into lactate, shifting the chemical equilibrium of the glycolytic pathway towards pyruvate. Lactate shuttles are responsible for removing lactate from the cytoplasm (either by passive or active transport to other cells or by transport to the mitochondria) and subsequent, further oxidising in aerobic pathways. This indicates that high energy requirements in a cell are at least partially met by an increased glycolytic rate and that lactate fermentation occurs to keep this rate up. Thus, we can identify the *speed* of fermentation as a major functional aspect of the process in muscle cells, instead of decreased oxygen levels.

Same concept, different perspectives

The second distinction in the inclusive nature of the concept is that, when viewed from different perspectives, different functional and procedural aspects of the concept come to light. For example: the practice of wine production. Without going into an in-depth discussion of this practice here, it can be said that the focus in this and similar practices is on the *products* of cellular respiration, and not on its *biological function*. From a vintner's perspective, the production of alcohol is the functional aspect of cellular respiration. From a biological perspective, the production of alcohol is procedural and a consequence of cellular respiration; it is not a function for the organism. Similarly, these social practices also differ in how they use a particular biological object in their key activity, which leads to completely different perspectives on that object. Let us have a look at the example of yeast: in the *life-world*[3] practice of baking homemade bread, the yeast is employed to make the dough rise. It can easily be obtained from any supermarket in standard-sized sachets. Here, yeast is not much more than an ingredient for bread production as part of a standardised recipe, and successful bread production does not require any understanding of it being a living organism, let alone any understanding of cellular respiration. Moving on to the *professional* practice of a baker, a perspective of yeast as a living organism might be helpful to further refine the bread production process, or to properly preserve large quantities of yeast. In neither of these two examples a biological perspective on yeast as a living organism that requires energy and thus, cellular respiration, would be necessary. In contrast, a biological engineering company wanting to gain an edge on the competition on the yeast strain market would benefit from such a perspective. They might try to develop an enhanced strain of yeast, capable of faster or more prolonged alcohol production. This would require a molecular understanding of cellular respiration, the substances and enzymes involved, and their genetic regulation.

Implications for an LT-strategy from education literature

These conceptual differences between social practices are interesting from an education research perspective in that they might bring the

[3] See chapter 1, for a description of *life-world, professional, and scientific social practices.*

recontextualising process into view. From an educational viewpoint: focusing on these differences between practice-specific uses during reflection activities can make the need for (explicit) recontextualising more apparent for students. Using Sfard's theory on object construction (Sfard, 2000), van Oers (van Oers, 2001) described the process as such (p. 292):

"(…) we can describe the process of contextualisation for abstraction as an argumentative process, that constructs an implicate order by way of a series of nested points of view, that finally ends up as collaboratively focusing on those (material or ideal) elements of the concrete situation that can be put together in an object, and that can be subsequently employed as an instrument to understand the situation and to transform the target object according to one's needs."

Or, using his words (p. 300) again:

"Abstractions are gradually created by a focusing of attention on concrete elements of a given situation that can be seen as coherently related."

What does this tell us about the case of cellular respiration? For the sake of argument, have a look at the following abstraction of cellular respiration, which is consistent with the definition given in section 1.3 (box 1.1):

Cellular respiration is the cellular metabolic process responsible for releasing the energy needed for all other metabolic processes by breaking down large, organic molecules ('food') into smaller, molecules. Because all living cells of all organisms need energy at all times, cellular respiration also takes place in all cells of all living organisms, all the time.

This description was constructed in an attempt to include all types of cellular respiration that might be encountered in different types of cells and organisms. It completely obstructs any view on the variations between these types, although it can only have been created with a perspective on at least a number of different incarnations of the concept. By viewing different concrete examples of the process at the cellular level from a certain perspective, one might come to see similarities between all these very different processes. In the case of the above description of cellular respiration, the most important perspective necessary seems to be the idea of energy-need and -conversion in a cell or organism. In academic biology this perspective gradually formed over a long period of time, through a continuous, cooperative process of focusing and refocusing on different aspects of the process in different organisms. It seems safe to say this process was not confined to the scientific practice of biology, but included many participants from different (scientific) practices.

What does this mean for an LT-strategy for cellular respiration? Certainly, we cannot expect students to go through a similar focusing process; it would take far too much time and would be impossible to review all possible interpretations of the concept that have come along in its conceptual history. *But what we can do* is to view the concept in a number of contexts that use different organisms as their biological object of focus. These different contextual perspectives on cellular respiration should allow students to both investigate the different organismal versions of the process and view the concept from different motivational perspectives.

This is where the teacher and LT-strategy come in. It is the teacher's role to help the students in creating such a perspective, by allowing them to develop a motive for viewing organisms and cells from a perspective of energy-need and utilisation (or a "cellular respiration-perspective") and repeatedly focusing their attention on elements of cellular respiration in concrete examples that can help students to recognise different incarnations of the concept in different organisms and contexts and distinguish them from each other and from all other metabolic processes in a cell. A previous part of this section described problems related to the molecular nature of the process. These showed that any LT-strategy aimed at the (initial) development of cellular respiration should help students by starting at the *organism level of biological organisation* out in a *familiar context,* which *focuses on a problem related to the release of energy* as a biological function aspect of cellular respiration. It should also *use a yoyo-structure* to descend to the molecular level of organisation, allowing time for reflection and relating the phenomena with the intermediate levels of biological organisation. The requirements for visualising the molecular level of biological organisation and for connecting the different levels of biological organisation are summarised in the following criteria:

Design criterion 4-1	Connecting the molecular level to more familiar levels of biological organisation
	An LT-strategy for developing cellular respiration should *use a yoyo LT-strategy that starts at the organism level of*

biological organisation. Such a yoyo LT-strategy starts with LT-activities that refer to the familiar organism level of biological organisation, and gradually moves down to the cellular and molecular levels of biological organisation in a step-by-step LT-process. Frequent reflection LT-activities should invite students to explicitly connect these levels of biological organisation.

Design criterion 4-2

Visualising the molecular level of biological organisation

Descriptions and visualisations of cellular respiration at the cellular and molecular level of biological organisation should *focus on its primary, biological function and its conceptual core:* the release (conversion) of energy through the breakdown of relatively large, energy-rich molecules. Detailed molecular descriptions or representations like structural formulas, or descriptions of glycolysis and the Krebs-cycle, can dilute such a focus and invoke additional learning difficulties for students.

In addition to the requirements in these two design criteria, the implications for education described in this section also indicate the need for allowing students to view different variants of cellular respiration processes, and different uses for the concept in several contexts. This research project aims to find a suitable LT-strategy for recontextualising cellular respiration in Dutch biology education. It should therefore, at least take note of the current (general) view on the concept in senior general secondary education in the Netherlands. Before detailing any design criteria related to the different process and context variants of cellular respiration, the following section describes examples from three different biology education textbooks for senior general secondary education.

4.3 Cellular respiration in Dutch secondary biology education

Prior knowledge and official examination requirements

In the Netherlands, general attainment targets for the different levels of secondary biology education are described in an official government document that is first published in the 'Staatscourant' [law gazette]. These documents are available for teachers via several websites (CEVO, 2007a). These general attainment targets are further specified in a syllabus (CEVO, 2007b). This details attainment targets that are tested in national exams.

For attainment targets not tested in the national exams, 'Stichting Leerplanontwikkeling' (SLO) published a guide for teachers and educators (Legierse, 2007). While this guide for school-based examinations has no official status, it is commonly referred to by teachers and designers of educational materials for determining the aspects of cellular respiration students are required to understand by the end of their secondary school career.

This warrants a short overview of the description of cellular respiration in both these documents and educational materials or textbooks. Note that this is not used as a restrictive description of cellular respiration for purposes of the LT-strategy designed in this research project. Rather, it is used to determine the detail of the required understanding of the concept for senior general secondary biology education. Attainment targets are categorised in domains and subdomains. Cellular respiration is part of the domain 'metabolism' and the subdomain 'cellular metabolism' (D2), which is described generally in the official document with attainment targets for senior general secondary biology education (CEVO, 2007a):

*"**Subdomain D2:** Cellular metabolic processes: A student can discriminate between different assimilation- and dissimilation-processes, connect them to different levels of biological organisation, note which factors influence these processes, and discuss their use in biotechnology."*

This is the only mentioning of cellular respiration in the official, general attainment targets. Since this subdomain was not part of the national exams, this thesis refers to the unofficial guide for school-based examinations for a further specification of learning goals related to cellular respiration (Legierse, 2007). After quoting the general attainment target for this subdomain (cellular metabolism) from the official documents, the guide continues with a short description of the expected prior knowledge from the first three years of senior general secondary education (p.24). It mentions that students already should understand how plants and animals get their food, that they should have 'some insight' in the concepts energy and heat, and that they can distinguish between digestion and combustion. After mentioning relations between cellular metabolism and other domains in the curriculum such as ecology or genetic biotechnology, it provides a more detailed description of learning goals related to cellular respiration (p.24, author's translation):

"The student can …
(…)
…note that carbohydrates (and other organic substances) are used in build-up, recovery, cellular respiration and formation of reserves.
(…)
…note that metabolic processes such as anabolism and cellular respiration take place in all cells of all organisms.
…note that there are different kinds of cellular respiration of organic substances that release energy.
…describe the formula for aerobic dissimilation of glucose:

glucose + oxygen → carbon dioxide + water + energy
…note how anaerobic dissimilation is different from aerobic dissimilation, especially in:

- *no use of oxygen;*
- *less release of energy (in the form of ATP);*
- *energy-rich end products: alcohol or lactic acid (with anaerobic respiration).*

…name the types of energy that play a role in organisms, especially:

- *light;*
- *heat;*
- *chemical energy;*
- *kinetic energy.*

…note that in plants, the build-up of organics substances involves the capture of energy.
(…)
…note the functions of carbohydrates, fats, and proteins in plants and humans, especially:

- *build-up*
- *recovery*
- *storage*
- *supply of energy*

…note that biotechnological production takes place through optimisation with:

- *yeasts in the production of bread-, wine- and beer;*
- *bacteria for use in laundry detergents;*
- *bacteria for use in cleaning wastewater;*
- *bacteria for use in food production.*

(…) "

This detailed description reveals that students at the senior general secondary level of education are required to understand cellular respiration as an overall, chemical process and are not required to distinguish separate, underlying processes like glycolysis or oxidative phosphorylation. This is an important issue, since a detailed exploration of these processes would require a number of chemical concepts not available to all students in a typical biology class. The learning goals clearly state the release of energy as an important biological function for cellular respiration, and that the process takes place in all cells of all organisms. However, they do not explicitly mention this release (or conversion) of energy as the connection between cellular respiration and anabolic processes in a cell. The description concludes with pointing out a few biotechnological practices, suggesting contexts for use in an LT-strategy for recontextualising cellular respiration.

An omission in these goals seems to be the necessity of enzymes for carrying out cellular respiration; it is only mentioned as necessary for all metabolic processes in the description of other learning goals. This does not need to be problematic. The importance of enzymes can be the focus for other educational strategies, following one in which students have had the opportunity to understand the cellular respiration as a necessary biochemical process and connect it to other levels of biological organisation. Finally, there is no mentioning of any difference in the speed between aerobic and anaerobic cellular respiration processes. This is not surprising, since this difference has only recently been used for explaining differences between types of muscle fibres (see section 4.2). For a view on how these attainment targets are interpreted in many secondary biology education practices, this section continues with a brief overview of how cellular respiration is addressed in three biology text books for senior general secondary education.

Cellular respiration in Dutch biology textbooks

Before reviewing a number of textbooks, it should be noted here that the official exam requirements as described in the previous section have a strong influence on the content of these textbooks. Although most tend to stay close to these requirements, there are differences in the level of detail, focus on levels of organisation and sequencing of the conceptual construction in these materials. In order to provide an overview of the different strategies employed, we have chosen three different textbooks, based on their frequency of use according to a survey by the Netherlands Institute for Biology (NIBI) (Malmberg, 2007). The first, 'Biologie voor Jou' [biology for you] (Smits, Waas, Bos, & Lagerwaard, 2004a & 2004b) is used most frequently, followed by 'Nectar' [nectar] (Bijsterbosch, Maier, & van Wijck, 2005a & 2005b). The third textbook is internet based and entitled

'10voorBiologie' [10 for biology][4] (van Straaten-Huygen et al., 2010). It is based on a hardcopy textbook previously terminated from publishing, entitled 'Synaps' [synapse]. Although this 'electronic textbook' is not as frequently used as other textbooks for Dutch secondary biology education, it is used with increasing frequency according to the previously mentioned survey by NIBI. It was first intended and available only for pre-university secondary education, but has included senior general secondary material since 2010 and continues to expand on this. Although the results from the survey mentioned here have been published in 2007 and therefore cannot refer to the senior general level version of '10voorBiologie', it can be expected to be used more often in the future. This is due to its flexible nature and the fact that many teachers teaching pre-university biology also teach the subject at the senior general level of secondary education. Besides the increasing use of this method, another motive for including this third method in this review is the only completely internet-based textbook, in contrast to other textbooks that add internet-based assignments to hard-copy text books.

All three textbooks assume a basic, overall knowledge of 'combustion' at the organism level as prior knowledge from the first three years of secondary education. This review starts with a general description of the structure of content matter and main perspective on cellular respiration in each textbook, followed by a more detailed description of how cellular respiration is presented in all three in terms of levels of organisation and the focus on aspects (see section 1.3, box 1.1) of the concept.

Biologie voor jou: content structure and perspective on cellular respiration.

'Biologie voor Jou' consists of two textbooks, accompanied by two separate exercise books. The content is presented in fifteen chapters totally, organised according to themes like metabolism, food and digestion, ecology, gas exchange and excretion. This results in most subject matter being presented once during the final two years of senior general secondary education. In general, each chapter starts with an introductory paragraph giving an overview of the subject and linking it to prior knowledge. Most textbook content is presented in a general way, meaning that biological

[4] The number '10' in this title refers to the 10-point scoring system traditionally used in the Netherlands for grading students' work, where 1 is the lowest and 10 the highest possible score.

concepts are described with generalised definitions, applicable to all or a group of organisms. Cellular respiration is covered in the chapter entitled 'Metabolism' [in Dutch: 'Stofwisseling'] and describes cellular respiration in the following, general terms:

'Biologie voor Jou': "Cellular respiration takes place in all cells at all times, during the day as well as at night. Without cellular respiration a cell dies. The more energy an organism uses (…), the more cellular respiration will take place in that organism. In organisms, energy is usually released through the respiration of glucose. Respiration of glucose can take place with oxygen (aerobically) or without oxygen (anaerobically)." (Smits et al., 2004b, p. 14)

After the general description, aerobic respiration, lactic acid and alcoholic fermentation are described subsequently, followed by a sub-paragraph on the respiration of fats and proteins. Assignments in the exercise book that accompany each textbook chapter require students to reproduce the information presented in the textbook, to recognise the concept in concrete examples (organisms) or to solve a problem using the concept(s).

Nectar: content structure and perspective on cellular respiration.

'Nectar' is a hardcopy (paper) textbook, and combines exercises and information in a single book (with two volumes), instead of having a separate exercise and textbook. The eighteen chapters cover the subject matter in thematically organised chapters that closely follow the biological organisation of content, with themes like food, ecology, and reproduction. Although this organisation of chapters is similar to that of 'Biologie voor Jou', its chapters represent the content with fewer general descriptions and use more concrete examples. The chapter detailing cellular respiration is the final chapter in the series and entitled: "On a razor's edge". It concerns exercise or sports physiology in general and starts with an introduction, meant to give an overview of the entire chapter and to link students' prior knowledge to the chapter's content. After detailing the physiology of muscles and muscular contraction, cellular respiration is introduced and described as part of this system using sports physiological terms, such as 'the phosphate battery' and 'anaerobic system':

'Nectar': "The phosphate battery is the fastest available source of energy for the muscle. After that, anaerobic respiration takes over and finally aerobic respiration. During these processes, ATP is formed. With aerobic respiration,

this occurs in the mitochondria. Aerobic respiration of glucose yields carbon dioxide and water. Anaerobic respiration of glucose in muscles yields lactic acid as rest product. Aerobic respiration releases more energy per molecule of glucose than anaerobic respiration." (Bijsterbosch et al., 2005b, p.218)

Chapter 18 of 'Nectar' continues after its discussion of cellular respiration with gas exchange in blood, structures and functions of tissues and lungs, and finishes with the neural regulation of breathing. There is no generalised description of cellular respiration for all kinds or groups of organisms in this chapter, but in contrast to 'Biologie voor Jou', cellular respiration is covered at different places in the general content structure. The alcoholic variant of fermentation is mentioned and covered in a single exercise in this chapter, but discussed in another chapter entitled "Fast food island", which discusses biotechnological techniques in food production. It should be noted that the discussion of lactic acid fermentation in this chapter only describes cellular respiration at the organism level of biological education, as in the following statement for example: *"lactic acid bacteria transform amylose into lactic acid"* (Bijsterbosch et al., 2005: p. 218) and does not use any of the terms cellular respiration, "anaerobic respiration", or "fermentation".

10 voor biologie: content structure and perspective on cellular respiration.

The final textbook in this overview, '10 voor biologie', is organised in a different matter and separates exercises and theoretical content descriptions. Exercises are structured in themes, some of which are organised around biological content matter, such as "build-up and breakdown" or "health and food". Others are more contextually organised, such as "sports physiology" or "organ transplants". Again other themes are conceptually organised, like the themes: "photosynthesis" or "biodiversity". The theoretical descriptions are organised in chapters with titles such as "metabolism", "behaviour", and "reproduction". There are sixteen of such theoretical chapters, while there are more than thirty different themes.

Due to differences in organisation of theoretical descriptions and exercises and the large amount of exercises and themes, teachers (and students) are encouraged to determine their own, preferred structure of content matter while students are required to refer to several different theoretical chapters when doing the exercises assigned by their teacher or that they have chosen themselves. Cellular respiration is covered in the theoretical chapter “metabolism”, concerning metabolic processes in general and is focused on in different themes: “build-up and breakdown” focuses on metabolism in general, while “the running footman” concerns sports physiology and “the bus runs on liquor” briefly touches on alcoholic and methane fermentation.

The theoretical chapter, like the chapter on metabolism in ‘Biologie voor Jou’, starts with an introduction in metabolism and basic thermodynamics, followed by energy transformations in cells and the central role of glucose. After detailed descriptions of organic and inorganic molecules involved in metabolism, cellular respiration is introduced with the following generalised description:

’10 voor biologie’: “Cellular respiration is a collective noun for all metabolic processes that release energy. The energy is released in the form of units of ATP. It also releases heat. The substance being respired, the respiratory substrate is always an organic substance. (…) There is a large difference between the amount of energy released in respiration the presence of oxygen (aerobic conditions) and respiration without oxygen (anaerobic conditions).”

The chapter then continues with a detailed description of aerobic respiration and separate descriptions of alcoholic and lactic acid fermentation.

Representation of levels of organisation and conceptual elements of cellular respiration.

In general, we can say that all three textbooks focus on the cellular and molecular level of organisation in their descriptions of cellular respiration. With this said, there are differences between the textbooks’ descriptions of cellular respiration and use of terms denoting other levels of organisation. For an exemplary view on how each describes cellular respiration, we give a sample description of aerobic respiration from each textbook followed by a brief description of how levels of organisation and conceptual elements of cellular respiration are addressed.

‘Biologie voor Jou’: In aerobic respiration (combustion), glucose molecules are completely broken down. This forms carbon dioxide and water molecules (the combustion products). All chemical energy that was captured in a glucose molecule during photosynthesis is now released again. This

energy is temporarily stored in ATP molecules. Then, the energy can be used for life-processes. The chemical formula for the aerobic respiration of glucose is: $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + energy$*. The aerobic respiration of glucose largely takes place in the mitochondria. The oxygen needed for aerobic respiration is taken up by the organism from the environment. Whenever there is enough oxygen present in the cells of organisms, the respiration is always aerobic. The carbon dioxide that is produced with aerobic respiration is released into the environment.* (Smits et al., 2004b, p. 15)

The above description of aerobic respiration in 'Biologie voor Jou' clearly focuses on the cellular and molecular levels of organisation, although the final three sentences jump quickly from the cellular to the organism levels without making a clear distinction. From a conceptual element perspective, there is a focus on the aspect of breaking down large molecules and releasing stored energy from these molecules. In contrast, there are now graphical representations of the molecules, which can enhance such a focus for students. The role of mitochondria in aerobic respiration is mentioned, but not really focused on, especially in omitting this detail of location in its description of anaerobic respiration. Differences in speed are not mentioned, neither are any underlying processes. For its description of anaerobic respiration, 'Biologie voor Jou' illustrates the process with a description of both required, well-known variants: alcoholic fermentation in yeast and lactic acid fermentation in bacteria and human muscles.

In terms of level of organisation, 'Nectar' focuses mostly on the cellular and sub-cellular level but its descriptions also contain frequent switches in level of organisation such as in the following description of aerobic respiration:

'Nectar': "Esther runs at three-quarters of her full power on the treadmill. She can keep that up for a long time, much longer than Pieter can sprint on the home trainer. About two minutes after the start her muscles receive sufficient extra oxygen. Now glucose can be broken down in the mitochondria to CO_2 *and* H_2O*. This complete breakdown releases 19 times as much ATP as the lactic acid system. That is enough to keep running for a long time. Additionally, Esther does not suffer from the formation of lactic acid. This 'combusting' of glucose is called aerobic respiration."* (Bijsterbosch et al., 2005b, p.218)

Although the above description indicates how cellular respiration supplies a (muscle) cell with the energy required for exercise, it doesn't mention the cell specifically. There seems to be an immediate jump from an organ level description in the second sentence to a sub-cellular description in the third and fourth, only to jump right back to the organism level in the fifth sentence. With respect to the core idea of molecular breakdown in cellular respiration (see section 4.1), 'Nectar' illustrates aerobic and anaerobic respiration using graphical representations of the molecules involved allowing for a clear view of the relative sizes of these molecules. Although it also mentions aerobic respiration occurring in the mitochondria and anaerobic respiration in the cytoplasm, this aspect is not really focused on and even seems to be neglected in a question requiring students to name the one organelle responsible for breaking down glucose. 'Nectar' is the only one of the three textbooks reviewed here that speaks of the difference in contractile speed between fast-twitch (white) and long-twitch (red) muscle fibres, although attributing these directly to differences in myoglobin and oxygen supply, instead of the speed of both processes with respect to one and other. This description of fermentation in 'Nectar' focuses on lactic acid fermentation. The alcoholic variant is mentioned in one exercise and in a previous chapter, and uses examples of micro-organisms for food production. As in 'Biologie voor Jou', 'Nectar' does not include any more detailed description of cellular respiration using underlying processes like glycolysis or the citric acid cycle.

In contrast to the two previously described textbooks, '10 voor biologie' does mention underlying processes such as glycolysis and the citric acid cycle, but without detailing them, as the following sample description illustrates:

'10 voor biologie': "When cellular respiration takes place in the presence of oxygen, we call it aerobic respiration (aero = air). Aerobic respiration is the same as combustion. The first step is splitting glucose into two equal halves. We call this splitting process glycolysis (glyco = glucose, lysis = to split). It releases some energy in the form of 2 ATP. The two halves are then broken down further. This breakdown occurs in a complicated series of reactions. Each reaction requires specific enzymes. At the end of the large number of subsequent reactions, both half glucose molecules are each split into three molecules of carbon dioxide (CO_2) and three molecules of water (H_2O). Due to this complete breakdown of a glucose molecule, the cell has the opportunity to produce a lot of ATP (36) with it."

Again, the breakdown of a substrate with its simultaneous release of energy is clearly focused on in this description. The location – or involvement of mitochondria – is not mentioned in text, but is indicated in graphical illustrations for both aerobic and anaerobic respiration. Like the other two textbooks, ’10 voor biologie’ does not mention the differences in speed between aerobic and anaerobic respiration.

Implications for an LT-strategy from Dutch biology education textbooks

Summarising this review of cellular respiration in educational materials, we can say that all three textbooks attempt to stay close to the detail described in the unofficial guide for school-based examinations (Legierse, 2007). ‘Nectar’ stands out with its more situated description of the processes than the other two and the omission of a generalised description of cellular respiration. The thematic organisation of exercises of ’10 voor biologie’ allows for more different perspectives on the process, although this is very dependent on the choice of the teacher and/or students in themes or specific exercises. ‘Biologie voor Jou’ stays closest to a general description of the process. With respect to levels of organisation, the three do not differentiate explicitly between the levels of organisation, although all focus on the cellular and molecular levels. This can of course be expected, due to the molecular nature of the processes. None of the three textbooks described the difference in speed between aerobic and anaerobic respiration, while the other conceptual elements are at least mentioned in all three in the required detail.

While all three textbooks differ in their choice of detail, they all show a focus on the breakdown element of the concept, with ‘Nectar’ and ’10 voor biologie’ emphasising it in graphical illustrations. With respect to construction of the concept itself, two major opposing strategies can be identified. The first is to start with a general description or discussion of cellular respiration, followed by reviewing specific examples of the process’ variants: aerobic versus anaerobic respiration and lactic acid fermentation versus the alcoholic type. This is the strategy used in ‘Biologie voor Jou’. ‘Nectar’ on the other hand, makes use of the opposing strategy and starts with an organism level view on lactic acid and alcoholic fermentation in bacteria and yeast, without naming the processes. One of the final chapters in that textbook follows up on this with a description of lactic acid fermentation and aerobic respiration. Although no general description of cellular respiration was found in ‘Nectar’, it can be expected that teacher will introduce such a description while discussing cellular respiration with his or her students. The third textbook, ’10 voor biologie’ seems to fall in between the other two textbooks with respect to its approach to cellular respiration. Its theoretical description follows the ‘from-general-to-specific’ route as in ‘Biologie voor Jou’, but its exercises tend to follow the opposite strategy. More importantly, the strategy employed in a curriculum using this textbook is very dependent on the choice and sequencing of exercises and descriptive texts by a teacher and/or students, probably more so than in the other two textbooks reviewed.

With respect to choosing a specific route or *storyline* for an LT-strategy for recontextualising cellular respiration, the insights gained from education research literature described in section 4.2 indicate that starting with a generalised description of cellular respiration would not make much sense and obstruct any view on its different variants. An LT-strategy for recontextualising should allow students to develop a general description for the process by themselves by comparing the differences and similarities between aerobic respiration and several types of anaerobic respiration. This does not have to mean that a generalised description should not be used by a teacher or textbook before students have developed such descriptions by themselves, but it does mean that these descriptions should not become the focus for understanding the concept. With a strong focus on a ready-made generalised description of cellular respiration, students may be less motivated to define the concept by themselves. This leads to a description of a two-part design criterion for an LT-strategy for recontextualising cellular respiration:

Design criterion 5-1

Compare aerobic and anaerobic respiration

An LT-strategy for cellular respiration should trigger a focus on the differences and similarities between *aerobic and anaerobic cellular respiration*, related to the form and function of different organisms, cells, and environmental circumstances.

Design criterion 5-2

Compare lactic acid and alcoholic fermentation

An LT-strategy for cellular respiration should trigger a focus on the differences and similarities between *lactic acid and alcoholic fermentation* related to the form and function of different organisms, cells, and environmental circumstances. Alcoholic fermentation shares important similarities with its lactic acid counterpart. For instance: both release a low amount of energy and have a relatively high reaction speed. A comparison also reveals important differences between their end products, but when comparing both anaerobic processes with aerobic respiration they reveal another important similarity: both involve a *partial* breakdown of a substrate. This idea of a partial breakdown in anaerobic respiration versus a complete breakdown in aerobic respiration is part of the conceptual core of cellular respiration, and deserves special attention during LT-activities for explicit recontextualising.

In addition to allowing students to study and compare the different processes involved in cellular respiration, students should also be invited to study and compare the concept in different contexts. The examples of cellular respiration in the biology textbooks described in this section all provide examples that can be related to specific organisms or other biological processes, although a specific context is often not clear from these descriptions. 'Nectar' is the exception here: it focuses on exercise and is strongly related to sports physiology contexts, although there is no introduction in the social practice of sports or exercise physiology. Combining these insights with those described in section 4.2, we can formulate criteria for choosing suitable contexts in an LT-strategy for recontextualising cellular respiration:

Design criterion 6-1 Choose contexts that use the conceptual core of the concept

An LT-strategy for developing cellular respiration should start with a context that allows students to develop a motive for learning that is related to the conceptual core of the concept. This can be achieved by starting with a context where the differences in energy-release between aerobic and anaerobic cellular respiration are obvious at the organism level of biological organisation. This context should also be easily recognisable to students, allowing them to recognise and identify with a participant in that context.

Design criterion 6-2	Choose contexts that use different variants of cellular respiration The contexts explored in an LT-strategy for developing cellular respiration should allow students to explore and compare different variants of cellular respiration. A comparison of different anaerobic variants of cellular respiration, such as lactic acid vs. alcoholic fermentation, requires comparing different types of organisms.

Having explored the concept of cellular respiration in education research literature and Dutch educational textbooks, the following section concludes with an overview of the design criteria concerning cellular respiration and their relation to the three criteria for recontextualising biological concepts in general.

4.4 Design criteria for an LT-strategy for recontextualising cellular respiration

Reviewing the results from our exploration of cellular respiration described in this chapter, we can say that the most important problems in learning and teaching cellular respiration in the Netherlands are related to the inexperience of many students with the (sub-) cellular levels of biological organisation (systems thinking), the molecular nature of the process, and the different processes included in the concept.

As others have pointed out, the ways in which we try to teach cellular respiration to our students can be held responsible for a large part of the problems mentioned here. For instance, an underestimation of students' abilities often results in removing the cellular perspective altogether. Consequently, the process is represented to students in an oversimplified manner or with a focus on the substances involved, leaving the energy-utilisation as its main function out of view. Also, previous Dutch biology content analyses from for the subject of genetics (Knippels, 2002; Knippels, Waarlo, & Boersma, 2005) and for cell biology and systems thinking (Verhoeff, 2003) have shown that many educational textbooks do not sequence the material according to the levels of biological organisation.

This has again been made apparent in our investigation of cellular respiration in three educational textbooks (see section 4.3).

This chapter now concludes with a specification of the design criteria for an LT-strategy that aims for students to develop the concept of cellular respiration in senior general secondary biology education. Although these criteria are presented separately from the design criteria for recontextualising (see chapter 3), they cannot be completely disentangled from these. As a result, these descriptions of the design criteria related to cellular respiration include notions related to the design criteria for recontextualising that have been described in the previous chapter.

Design criterion 4-1

Connecting the molecular level to more familiar levels of biological organisation

An LT-strategy for developing cellular respiration should *use a yoyo LT-strategy that starts at the organism level of biological organisation*. Such a yoyo LT-strategy starts with LT-activities that refer to the familiar organism level of biological organisation, and gradually moves down to the cellular and molecular levels of biological organisation in a step-by-step LT-process. Frequent reflection LT-activities should invite students to explicitly connect these levels of biological organisation.

Design criterion 4-2

Visualising the molecular level of biological organisation

Descriptions and visualisations of cellular respiration at the cellular and molecular level of biological organisation should *focus on its primary, biological function and its conceptual core:* the release (conversion) of energy through the breakdown of relatively large, energy-rich molecules. Detailed molecular descriptions or representations like structural formulas, or descriptions of glycolysis and the Krebs-cycle, can dilute such a focus and invoke additional learning difficulties for students. Additionally, the attainment targets for senior general secondary education do not require such a detailed perspective. Therefore, a very detailed molecular perspective can be avoided, while still allowing students to understand that the breakdown of molecules results in the release of energy.

Design criterion 5-1

Compare aerobic and anaerobic respiration

An LT-strategy for cellular respiration should trigger a focus on the differences and similarities between *aerobic and anaerobic cellular respiration*, related to the form and function of different organisms, cells, and environmental circumstances.

Design criterion 5-2

Compare lactic acid and alcoholic fermentation

An LT-strategy for cellular respiration should trigger a focus on the differences and similarities between *lactic acid and alcoholic fermentation* related to the form and function of different organisms, cells, and environmental circumstances. Alcoholic fermentation shares important similarities with its lactic acid counterpart. For instance: both release a low amount of energy and have a relatively high reaction speed. A comparison also reveals important differences between their end products, but when comparing both anaerobic processes with aerobic respiration they reveal another important similarity: both involve a *partial* breakdown of a substrate. This idea of a partial breakdown in anaerobic respiration versus a complete breakdown in aerobic respiration is part of the conceptual core of cellular respiration, and deserves special attention during LT-activities for explicit recontextualising.

Design criterion 6-1

Choose contexts that use the conceptual core of the concept

An LT-strategy for developing cellular respiration should start with a context that allows students to develop a motive for learning that is related to the conceptual core of the concept. This can be achieved by starting with a context where the differences in energy-release between aerobic and anaerobic cellular respiration are obvious at the organism level of biological organisation. This context should also be easily recognisable to students, allowing them to recognise and identify with a participant in that context.

Design criterion 6-2 Choose contexts that use different variants of cellular respiration

The contexts explored in an LT-strategy for developing cellular respiration should allow students to explore and compare different variants of cellular respiration. A comparison of different anaerobic variants of cellular respiration, such as lactic acid vs. alcoholic fermentation, requires comparing different types of organisms.

A more in-depth exploration of these design criteria, and those described in the previous chapter (see section 3.5), needs a more detailed description that is related to possible contexts used in an LT-strategy for recontextualising. The next chapter provides a description of the design process leading to the LT-strategy that was designed in this research project.

Chapter 5

A preliminary LT-strategy for recontextualising cellular respiration

The two preceding chapters described the design criteria related to recontextualising (chapter 3) and cellular respiration (chapter 4). These design criteria were used in the design of an LT-strategy for recontextualising cellular respiration. This LT-strategy was detailed in a scenario: a detailed description the expected student and teacher actions during the LT-activities. In conjunction with the development of the scenario, LT-materials (worksheets, teacher's guide) were developed to guide the students and their teacher through the LT-process. Both the LT-strategy and its related LT-materials were tested in two classes for senior general secondary education, in two subsequent case studies: α1 and α2 (see chapter 2 for a more detailed description of the case studies and the data collection). The results from observations of the lessons and analysis of students' work served to identify strengths and weaknesses in the design, which were used to redesign parts of the LT-strategy or its related LT-materials, where necessary.

This chapter describes the development of the LT-strategy during the first cycle of the design research phase. Section 5.1 starts with a description of the three practices that were used as contexts in the series of lessons that were part of the LT-strategy. Section 5.2 then continues with a global description of the LT-strategy and its related LT-materials. Section 5.3 provides a description of the strengths and weaknesses in the design of the LT-strategy and its related LT-materials, based on the results from case studies α1 and α2. Finally, section 5.4 briefly describes the redesigned LT-strategy for the second design research cycle. The implementation and results of this second design cycle are described in chapter 6.

5.1 Choosing practices for recontextualising cellular respiration

The design criteria for the LT-strategy as a whole (see chapters 3 and 4) were also used for choosing suitable practices for the LT-strategy, in addition to criteria for choosing contexts that have been already described in other studies (Prins, Bulte, & van Driel, 2008; Westra, Boersma, Waarlo, & Savelsbergh, 2007). This section arguments the choice for the three practices that were part of the LT-strategy: sports physiology, biotechnology, and biological research.

Sports physiology and cellular respiration

The choice for a sports physiology context as a starting point for the lesson module in this LT-strategy was strongly influenced by the criterion of focus (criterion 1, see section 3.5). It describes the need for starting with a context that students can recognise and allow them to identify with a participant in that context. After a general introduction in the profession of a sports physiologist, students should be invited to focus their attention on a specific problem related to cellular energy-need. Such a problem focuses on the cellular level of biological organisation, which is not directly observable and recognisable. Because of many students' unfamiliarity with the cellular level of biological organisation (see chapter 4), it is advisable to start an introduction at the organism level of biological organisation. Therefore, it would be advisable to start with a context in which a problem related to *cellular* energy need is obvious at the organism level of biological organisation. With these criteria for a proper introduction and focus on a problem related to the concept of cellular respiration, sports-related contexts soon came to mind. Such contexts are used often in biology education; teachers in the development team for context-based lesson modules had also chosen such contexts in a few of their lesson modules; they are also frequently touched upon in textbooks for biology education. Finally, a sports-related context is mentioned in a study by Yip (2000) on promoting students' understanding of lactic acid fermentation (p.40):

"*Encouraging students to apply their knowledge of aerobic respiration and lactic acid fermentation to design strategies for competing <in> a 100 metre sprint or a marathon race provides excellent opportunity for them to appreciate the abstract and complex nature in a concrete way*." (Yip, 2000; p.40).

Sports-related contexts seem ideal in many ways: the idea of cellular energy-need relates strongly to the biological function of cellular respiration that is part of its conceptual core (design criterion 6, see section 4.4). However, a context of sports or professional sports in and of itself does not provide an obvious motive for comparing the muscular physiology of athletes down to the cellular and molecular levels of biological organisation. This requires a more biological or medical perspective on athletes, which can be found in sports physiology. As biomedical professionals, sports physiologists require a detailed understanding of cellular respiration in human muscle cells down to the molecular level. Their role in (professional) sports can easily be highlighted in an initial introduction of the context, allowing students to identify with such a role and accept the perspective. With a biomedical perspective on athletes, students can then be invited to compare power- and endurance-focused athletes. Table 5.1 describes observable differences between sprint- and marathon runners.

Table 5.1
Form and function of sprint-runners (power-focused) vs. marathon runners (endurance-focused)

Form (physiology)		**Function (performance and energy-need)**	
Both athletes have a well-developed muscular system and athletic build.		Both athletes deliver a substantial performance, requiring a substantial amount of energy, supplied by a substantial amount of food.	
Sprint runner	*Marathon runner*	*Sprint runner*	*Marathon runner*
Body: very muscular, with especially thick and muscular legs, the muscular system dominating the runner's stature. Gait: very tense, powerful.	Body: slim (in comparison to a sprint runner) The muscular system does not dominate the runner's stature. Gait: -seemingly- relaxed.	Explosive performance: fast and powerful, requiring a very fast release of energy.	Long-term performance: slow and less powerful in comparison with sprint runner, requiring a slow and gradual release of energy.

Combined with a sports-physiologist's goal to support professional athletes in improving their performances, the observed differences can provide a motive for understanding how these can be explained. Differences in performance and muscular structure between power- and endurance-focused athletes are reflected at the cellular level of biological organisation with differences between type I (red) and type II (white) muscle cells[1]. Tables 5.1 through 5.5 illustrate this with a summary of the similarities and differences between: athletes (organism level, table 5.1), their muscles (organ and tissue levels, table 5.2), muscle cells (cellular level, table 5.3), and cellular respiration (cellular and molecular level, table 5.5).

Table 5.2

Form and function of power- vs. endurance-trained muscles

Form (physiology)		**Function (performance and energy-need)**	
Human skeletal muscles are always connected to the bones in our limbs. Oppositely connected, paired muscles (antagonist muscles) provide the bending and stretching movement in many joints. The many blood vessels splitting off from the aorta to the vast amount of skeletal muscles provides the fuel and oxygen needed. Human muscles are built up from bundles of muscle fibres, interwoven with vascular and connective tissues (the fibre bundles). A muscle fibre is actually a single, long, and multi-nuclear cell. It develops due to a lengthwise merging of muscle cells, resulting in a fibre-like structure.		The skeletal human muscles provide athletes with the running abilities and power needed for their performance. The energy needed is derived from fuel, like glucose, from our food. These substances are separated from our food in the digestive organs and transported to and by the blood to the muscles.	
Sprint runner's muscles	*Marathon runner's muscles*	*Sprint runner's muscles*	*Marathon runner's muscles*
Very thick and short in structure, especially when compared to the performance-trained muscles of marathon runners. Have a large number of white (type II) muscle fibres.	Long and slim in structure, compared to those of the power-trained sprint runner. Have a large number of red (type I) muscle fibres.	Fast contraction, with great power. Become exhausted quickly. Require a fast method for releasing the large amount of energy available from fuel substances ("glucose").	Slow contraction, with moderate power Can sustain or repeat contractions over a long time-period. Require a method for a slow release of the energy.

[1] To reflect the design of LT-activities and their related LT-materials, the term 'muscle cells' is used instead of 'muscle fibres' when referring to the cellular level of biological organisation.

A comparison of the similarities and differences between power-focused and endurance-focused athletes in tables 5.1 through 5.4 shows how this problem can be illustrative and helpful to students for developing the concept of cellular respiration.

An LT-strategy that uses a similar step-by-step exploration of the problem can allow students to relate the different levels of biological organisation and is consistent with the necessary yoyo LT-structure for developing cellular respiration. This can also be described as narrowing the focus of attention in a step-by-step sequence of LT-activities, until arriving at the concept of cellular respiration.

Table 5.3

Form and function of red (type I) vs. white (type II) muscle cells

Form (physiology)		**Function (performance and energy-need)**	
Human muscle cells (≈ fibres) contain two types of interconnecting micro-filaments: the actin- and myosin filaments. Human muscle cells contain mitochondria, important structures for "cellular respiration" and thus releasing energy from food substances such as glucose.		The microfilaments (see: build) can slide along each other, increasing or decreasing the fibre or cell in length. This sliding action provides contractile movement to the fibres, and eventually to the muscle as a whole. Of course, this sliding action requires a large amount of energy, made available through a process of "cellular respiration".	
White (type II) cells	*Red (type I) cells*	*White (type II) cells*	*Red (type I) cells*
Contain more microfilaments than red (type I) cells. Contain fewer mitochondria than red (type I) cells. The structures (enzymes) needed for anaerobic respiration, are located in the cytoplasm of the cell.	Contain fewer microfilaments than white (type II) cells. Contain more mitochondria than white (type II) cells. The structures (enzymes) needed for aerobic respiration, are located in the mitochondria of the cell.	Fast contraction, with great power. Become exhausted quickly. The energy needed is released through lactic acid fermentation. This is fast, but releases a low amount of energy in relation to the fuel (glucose) consumed. Also, this process results in a large build-up of lactic acid, needing to be removed and further broken down after the performance.	Slow contraction, with moderate power Can sustain or repeat contractions over a long time-period. The energy is released through aerobic respiration, which is a slower than anaerobic variants, but far more efficient in terms of fuel use. An added advantage of this process is in the end products carbon dioxide and water, which are easily released to the blood for transport out of the body.

Table 5.4

Form and function of aerobic vs. anaerobic cellular respiration

Form (process)		**Function (energy-release)**	
Specialised proteins (enzymes) in the cytoplasm and the mitochondria are responsible for the step-by-step reduction of glucose or other large, organic molecules into smaller, (in-) organic molecules in cellular respiration.		The sliding action of the microfilaments is achieved by a step-by-step release and renewal of chemical bonds between the microfilaments. This requires energy in the form of ATP molecules or ‘units of energy’. Cellular respiration releases the needed energy from fuel molecules like glucose in the form of ATP.	
Anaerobic cellular respiration	*Aerobic cellular respiration*	*Anaerobic cellular respiration*	*Aerobic cellular respiration*
Breaks down a C_6-molecule (fuel, glucose) into two C_3-molecules Requires a small number of steps, making it a very fast process.	Breaks down a C_6-molecule (fuel, glucose) into six C_1-molecules (CO_2) and six water molecules (H_2O). Requires a large number of steps, making it a rather slow process.	Partial breakdown of organic fuel (glucose) quickly releases a small amount of energy: 2 ATP.	Complete breakdown of organic fuel (glucose) slowly releases a large amount of energy: 36 ATP.

The comparisons in tables 5.1 through 5.4 illustrate how the initial focus “form and function of sprint runners vs. marathon runners’, is narrowed down to the focus ‘form and function of aerobic vs. anaerobic cellular respiration”. This process seems similar to the process of sequential construction of attended foci, described by Sfard (2000). Finally, sports-physiology is a professional context instead of an academic one. Because senior general secondary education in the Netherlands is intended to prepare students for higher vocational education, a professional context is more consistent with students’ immediate possibilities for future education after graduation from secondary education.

Summarising the above argumentation, we can say that the practice of ‘sports physiology’ allows for a clear distinction between the aerobic and anaerobic variants (criteria 5-1 and 6-2) at all applicable levels of biological organisation (criterion 4-1). It can easily be related to familiar (life-world) sports contexts (criterion 1), and can provide a motive for exploring the differences in energy need and energy expenditure in cells (criterion 6-1, section 4.4).

Biotechnology and cellular respiration

The context of sports physiology provides opportunities for contrasting aerobic and anaerobic cellular respiration. However, this is not the only comparison between variants of cellular respiration that is necessary according to the design criteria in section 4.4. With sports physiology covering lactic acid fermentation as one version of anaerobic cellular respiration, another context should preferably be focused on an organism that can use alcoholic fermentation (criterion 5-2). Therefore, the first step in choosing a second context for exploring cellular respiration revolved around the choice for a suitable organism. While reviewing several possibilities, yeast soon came to mind as a suitable organism. It is a relatively well-known organism, used in both life-world and professional practices. Many students were expected to have at least heard of yeast and its possible uses in food preparation before, making it easier for them to identify a context in which it is used. Also, yeast can employ both aerobic respiration and alcoholic fermentation, allowing for good comparison with aerobic respiration and lactic acid fermentation in humans (criteria 5-1, 5-2, and 6-2). Besides a comparison of lactic acid and alcoholic fermentation, this allows for a comparison of the organisms' functional reasons for employing aerobic or anaerobic respiration as well. For instance: the previous section showed that in humans; the *main functional reason* for a white muscle fibre to employ anaerobic respiration lies in the need for a fast release of energy. In contrast; the *main functional reason* for yeast is the availability of oxygen in its environment. Finally, chapter 3 described how participants' motives for *using the organism* and *understanding the concept* differ greatly between practices as well. These differences between the use of cellular respiration from a participant's perspective (on the concept) and from an organism's perspective (regarding the process), can allow students to see how different elements of cellular respiration come into focus with differing perspectives.

An experiment with yeast

The choice for yeast was finalised by information from a study by Reinking, Reinking, and Miller (1994), which described a classroom experiment that made use of the Pasteur-effect. Without going into a detailed description, this effect can be described as a higher reaction speed for anaerobic compared to aerobic respiration, resulting from differences in the enzymatic regulation of aerobic and anaerobic respiration. Reinking et al. (1994) describe a relatively simple experiment for comparing the carbon dioxide production by yeast under aerobic and anaerobic conditions for 10 to 15 minutes. Due to the Pasteur-effect, the carbon dioxide production under anaerobic conditions will be far greater than the amount of carbon dioxide produced under aerobic conditions. This contrasts with the theoretical description of cellular respiration in any definition, since these clearly show that aerobic respiration should yield thrice as much carbon dioxide than anaerobic respiration (see for example: box 1.1). Thus, if students would first be allowed to develop and describe aerobic and anaerobic respiration at the cellular and molecular levels of biological organisation, and then formulate a hypothesis for their experiment; the results would differ greatly from their hypothesis. These unexpected results were probably the cause for Pasteur's first description of the effect (Pasteur, 1861). It can focus students on the differences in speed between anaerobic and aerobic respiration, which can later be used for an explanation of the functional differences between human red (type I) and white (type II) muscle cells as well.

There are also disadvantages to incorporating a practical experiment in the LT-strategy for recontextualising cellular respiration. First of all: it complicates the design of the LT-strategy because if incorporated, students should be incited to develop a motive for doing the experiment from an orientation on a certain biological practice. Second, it requires extra preparation for all who are involved in the enactment of the lesson module, and planning the experiment in line with a school's timetable may be difficult. Third: incorporating practical work for conceptualising processes at cellular and molecular levels of biological organisation presents specific learning and teaching difficulties (Abrahams & Millar, 2008). Despite these disadvantages, the unexpected results yielded by this experiment provide a pleasant change from many experiments regularly described in textbooks for biology education, and allow for a focus on the element of speed in cellular respiration, which is needed for solving the problem in the sports physiology context (see chapter 4). Also, experimentation skills are clearly mentioned in the attainment targets for biology in senior general secondary education (CEVO, 2007a), and experimentation should be a regular part of biology lessons if students are to develop such skills.

With yeast as the organism of focus for the second context, and even a series of possible LT-activities for practical work sketched out, we are left with a specific practice as a basis for our context. Chapter 4 already described a number of obvious choices mentioned in official curricular documents and biology textbooks: the production of bread, wine and beer. However, a more detail inspection of these practices reveals several issues when trying to incorporate them into an LT-strategy.

Bakeries and cellular respiration

First of all, amateur or professional baking practices have an obvious use for yeast and are easily recognisable for most students. However, any conceptualisation of cellular respiration in such a practice is limited to the production of bread. This means that such perspectives do not focus on yeast as a living organism, but rather as an ingredient in the production of bread that is necessary for making the dough rise. Within these practices, a description of cellular respiration might be limited to yeast using 'sugars or starch from the dough' for producing 'air' (carbon dioxide and gaseous alcohol) that is trapped within the dough, thereby increasing its volume. For a typical baker, there does not seem to be any need for understanding cellular respiration at a more detailed level and as such, cannot provide students with a motive for doing so.

Beer or wine producers and cellular respiration

Might we then be able to derive such a motive from an exploration of the production of beer of wine? Unfortunately, we are again forced to conclude that these practices provide us with a number of difficulties to that respect as well as some other difficulties involving a more detailed exploration of biological concepts that lie beyond the objective focus on cellular respiration for this LT-strategy. First of all, neither the production of wine nor beer requires a very detailed understanding of cellular respiration. Of course, the alcohol produced by yeast is a very important and central element of the production process, but participants do not focus on this in trying to improve the quality of their products. This quality is very dependent on other metabolic and enzymatic processes involved before, during, and after fermentation takes place. Furthermore, other organisms besides yeast also have a profound effect on the quality of these products. For instance: photosynthesis and sugar production in grapes have a great influence on the taste of wine. Similarly, the moulting or malting process in wheat cereal grains are determining steps in beer production. This illustrates that the focus of most practitioners in these practices is on a variety of other biological processes and concepts than cellular respiration. Refuting this argument, one might correctly reason that the choice of a particular strain of yeast is also very influential in the eventual quality of the products, but this does not disqualify the fact that participants in most real-world brewing practices are not concerned with this choice. In most of the examples of practices reviewed during this investigation, the choice for a particular strain of yeast is motivated by one of two common explanations. First, a rather romantic and important cultural-historical motive is found in the fact that some professional breweries still breed their own yeast-strains, some with a history of a couple of hundred years. A second explanation can be found in the yeast strains available from retailers and professional yeast producers. These provide any would-be buyer with thorough descriptions of the uses and capabilities of their strains, without going beyond the organism level of biological organisation. Such descriptions seem the most obvious source of information for professional and amateur brewing practices when choosing a particular strain of yeast. Therefore, brewing practices – like bakery practices – do not provide a proper perspective on cellular respiration to warrant an exploration of the concept at the cellular and molecular level of biological organisation.

Yeast producers and cellular respiration

These unsuitable practices do bring into view another practice that can warrant a more detailed investigation of the concept in yeast. Yeast producers grow and sell yeast strains in large quantities to other practices, such as breweries and bakeries. In order to keep up with their competition, they require a constant innovation of their product. This is where a more detailed biological or biotechnological perspective comes into focus. In order to breed, compare and possibly even genetically modify[2] yeast, one requires a view of the substrates, products, and enzymes involved with cellular respiration in yeast. The experiment of comparing the respiratory capabilities of yeast under aerobic and anaerobic conditions described by Reinking et al. (1994) can also be incorporated into an LT-strategy that uses this biotechnological breeding perspective. A yeast producer might try to develop a yeast-strain with improved fermentation qualities (reflecting a high economic value), but which can still reproduce at an optimal rate under aerobic conditions (reflecting a high production value). This perspective provides a motivation for testing the aerobic and anaerobic respiration capabilities of yeast strains (criteria 5-1 and 5-2). Therefore, the practice of a yeast producer can provide the intended cellular and

[2] Although it may be possible, incorporation of genetically modified yeast strains in the production of foods and beverages is currently not allowed by Dutch law.

molecular perspective on cellular respiration in yeast by focusing on the role of a biotechnological engineer in such a practice (criteria 4-1 and 4-1). Also, the close relation of this practice to easily recognisable professional and life-world practices (i.e.: baking, brewing) provide a connection to students' prior knowledge and experience. This allows them to connect the new information to what they already know about such practices and understand yet another use for cellular respiration in a professional context. Finally, like sports physiology, a career in biotechnological engineering is within the scope of educational choices available for students graduating from senior general secondary biology education.

Biological research and cellular respiration
From a biological perspective, a biological research practice might seem an obvious choice for an investigation of cellular respiration. However, because the LT-strategy was developed for senior general secondary education, it made sense not to use a scientific practice as a central part of such an LT-strategy. However, there was still the problem of establishing a consistent connection between sports-physiology and biotechnology contexts. In other words: students still needed a viable motive for stepping away from their exploration in sports physiology and human muscle cells, and take on a biotechnological perspective to experiment with yeast in aerobic and anaerobic conditions (criterion 3). At first the only obvious connection available was a learning-objective for students: to eventually being able to use cellular respiration in different contexts. Without disqualifying this as possibly useful motive for students, the criterion 3 (see section 3.5) explicates a preference for a more context-related motive. Eventually, a variant of the second lesson module explored during the explorative phase (explorative lesson module 2) provided a possible connection, albeit with the use of a perspective of biological research. Another version of this lesson module for pre-university education (van Moolenbroek, 2012) mentioned the biological practice of using a model-organism: exploring biological phenomena in one organism, to explain similar phenomena in another that cannot be experimented on for ethical and practical reasons.

This notion can be used as part of a line of reasoning that can lead students from investigating muscle cells to investigating yeast cells, mimicking the relation between biological and medical research practices, and professional practices like sports physiology and biotechnology. Thus, in essence it is cellular respiration itself that provides a conceptual connection between all three practices. Using this connection, we were able to envision the development of a motive, based in a whole class discussion of on the origin of the biological knowledge (and perspective) of cellular respiration used by a sports physiologist.

5.2 A preliminary LT-strategy for recontextualising cellular respiration

The previous section described the reasoning behind the choice for two contexts that were based on a sports-physiology and a biotechnology practice. Although the argumentation provides an indication of how these contexts were structured in a series of LT-activities, this section is intended to provide a more detailed description. The sports physiology and biotechnology contexts were connected in an LT-strategy through another context, which was based on biological research practices. The embedded structure of the contexts in the LT-strategy is reflected in figure 5.1.

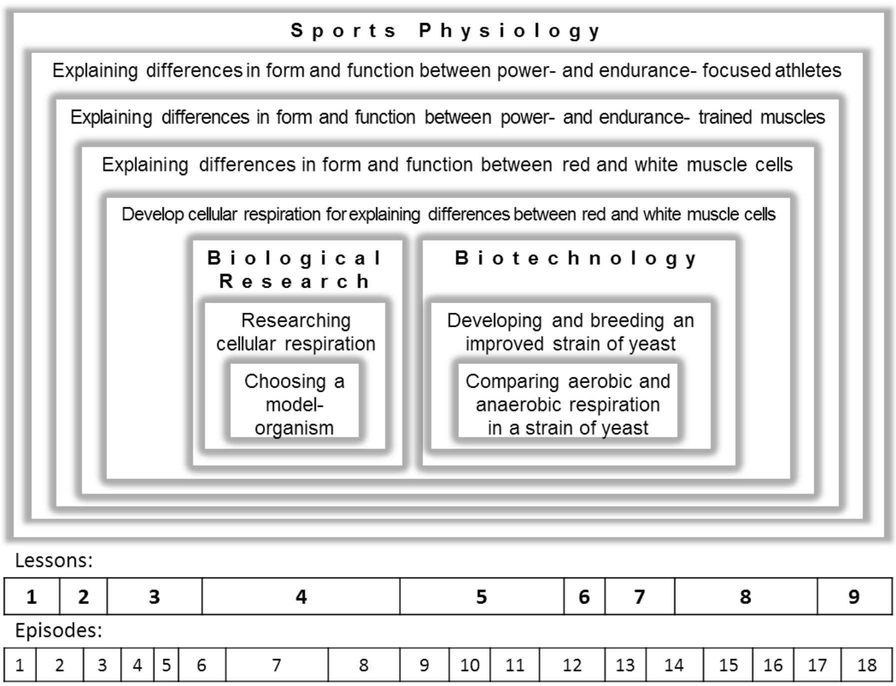


Figure 5.1. A schematic representation of the embedded structure of contexts for the lesson module in the LT-strategy. The two timelines indicate the lessons (upper) and episodes (lower timeline, based on the storyline in the LT-strategy).

Each of the contexts was described in a sequence of orientation and problem-posing LT-activities to focus students on a specific problem in each practice, and allows them to develop a motive for studying cellular respiration in context. The numbered bars in figure 5.1 represents two timelines; the upper timeline depicts the sequence of lessons in the lesson module, not including the lessons used for the pre-, post-, and recontextualising-tests. The lower timeline divides the LT-strategy in a sequence of episodes, each comprising 1 or more LT-activities. The episodes depicted in figure 5.1 are based on the 'storyline' that guides the LT-strategy. This storyline is detailed in the following description and tables 5.5 to 5.8. In addition to a short summary of each episode, the rightmost columns (labelled DC 1-1 to DC 3) in tables 5.5 to 5.8 represent the three design criteria related to recontextualising (see section 3.5).

Description of the storyline in the LT-strategy

Sports physiology: episodes 1-5

The sequence for the sports physiology context (table 5.5) started with an orientation a sports physiology practice and the differences between marathon and sprint runners as examples of power-and endurance-focused athletes (episode 1).

Table 5.5

Description of episodes 1 to 5 in relation to design criteria for recontextualising

Lesson no.	Episodes (no. and description)		Design criteria				
			1-1	1-2	2-1	2-2	3
		Context: sports physiology					
1	1	Introducing sports physiology: differences between power- and endurance-focused athletes.	X				
1–2	2	Study muscle physiology from the organism to the cellular level of biological organisation.	X				
3	3	Reflect on muscle physiology: identify differences in needed energy-supply between type I and II muscle cells as the main problem.	X	X			
3	4	Explicate prior knowledge on cellular energy supply ('combustion'). Redevelop this concept, introducing the term "cellular respiration".		X	X		
3	5	Reflect on the problem using cellular respiration and identify sports physiology as insufficient for developing the concept.	X	X			X

With this specific problem in focus, a yoyo-structure sequenced a series of LT-activities for studying muscular physiology; stepping from the organism to the cellular and molecular level of biological organisation (episode 2, see also tables 5.1 to 5.4 in the previous section). By reflecting on their exploration of muscle physiology, students focus on the differences in form (number of mitochondria) and function (type of performance) between red and white muscle cells (episode 3). This should then lead to the identification of the energy-requirement and the related concept of cellular respiration (combustion) for a possible explanation (episode 4). By inviting students to explicate their prior knowledge on the energy-requirement in a cell and discussing these in a classroom-discussion, episode 4 focuses on the concept of cellular respiration and introduces this label to replace 'combustion'.

Biological research: episodes 6-8

The following episodes (see table 5.6) embedded the biological research and biotechnology contexts within the problem-posing sequence for sports physiology, relating these at the cellular level of biological organisation.

Table 5.6

Description of episodes 6 to 8 in relation to design criteria for recontextualising

Lesson no.	**Episodes** (no. and description)		**Design criteria**				
			1-1	1-2	2-1	2-2	3
3	6	Context: biological research					
3/4	6	Introducing biological research and the idea of using 'model organisms' for studying biological phenomena, like cellular respiration.	X	X			
4	7	Study the cells of several model organisms in biological research and choose one for studying cellular respiration in the classroom: yeast.		X			
4	8	Reflect on the choice for yeast as a model organism.	X	X	X		X

A discussion on the origin of sports-physiological knowledge concerning cellular respiration (episode 5) shifted the focus to a context of biological research and the specific problem of choosing a model-organism for experimentation (table 5.6; episode 6). This should then lead students to study several model-organisms (episode 7) and select yeast for a more detailed exploration (episode 8).

Biotechnology: episodes 9-14

An orientation on a professional, biotechnology practice concerning yeast and cellular respiration (table 5.7; episode 9), should lead to students identifying two possible methods for cellular respiration: aerobic and anaerobic (episode 10).

Table 5.7
Description of episodes 9 to 14 in relation to design criteria for recontextualising

Lesson no.	**Episodes** (no. and description)		**Design criteria**				
			1-1	1-2	2-1	2-2	3
		Context: biotechnology					
	9	Introduce a biotechnologist working to breed yeast strains with optimal cellular respiration capacity in aerobic and anaerobic environments.	X				X
5	10	Explicate two methods for cellular respiration: aerobic vs. anaerobic.	X		X	X	
	11	Identify a problem for the biotechnologist: measuring differences between aerobic and anaerobic cellular respiration in yeast.	X	X		X	
6	12	Design and perform experiment for measuring differences between aerobic and anaerobic cellular respiration in yeast. Unexpected results prompt further investigation.		X			
7	13	Discuss possible methods for verifying the unexpected results. Study the results from similar experiments that measure other variables.		X			
8	14	Explain the unexpected results from the experiment and explicate cellular respiration in yeast cells.		X	X		

Episode 11 was meant to focus students on the biotechnological motive for comparing aerobic and anaerobic respiration in specific yeast strains. With this new focus on a specific problem for the biotechnologist, students were expected to design and perform a practical experiment for comparing cellular respiration in yeast under aerobic and anaerobic conditions (episode 12). The results from this experiment were expected to deviate from the hypothesis students had developed, based on the information provided by the study that described this experiment (Reinking et al., 1994). This was expected to spark a discussion on the experimental results and possibilities for further investigation for verifying these (episode 13). This allowed the teacher to introduce the results from similar experiments that are not easily performed in class due to time limitations (episode 14). These were expected to visualise the differences in speed between aerobic and anaerobic respiration and focus on these as an explanation of the experimental results from episode 12.

Sports physiology: episodes 15-18

Table 5.8 describes the final episodes in the LT-strategy, starting with episode 15.

Table 5.8

Description of episodes 15 to 18 and the final recontextualising-test in relation to design criteria for recontextualising

Lesson no.	**Episodes** (no. and description)		Design criteria				
			1-1	1-2	2-1	2-2	3
8		Context: sports physiology					
8	15	Return to the problem in sports physiology: differences in needed energy-supply between type I and II muscle cells. Explicate the possible use of CR4 in solving it.	X		X		X
8	16	Identify alcoholic fermentation as incompatible with human physiology, making it unfit to solve the problem.		X	X	X	
8/9	17	Introduce and explicate lactic acid fermentation as a variant of anaerobic respiration, solving the problem of fit.		X	X	X	
9	18	Reflect on the original problem and solve it with a step-by-step return to the organism level of biological organisation.	X		X		X
10		Recontextualising – test					
10	19	Explain biological phenomena in other contexts using cellular respiration.	X				X

Having explained the problem of focus in the biotechnology context, episode 15 (see table 5.8) returned to the sports-physiology context by asking students to restate the original questions from that context: the differences in the number of mitochondria between red- and white muscle cells, in relation to the differences in the energy-requirement between these types of cells. The question focuses on the difference in speed of performance between white and red muscle cells, and was expected to allow students to state a possible solution: the newly discovered difference in reaction-speed between aerobic and anaerobic respiration. In addition, the method for anaerobic respiration employed by yeast cells (alcoholic fermentation) was also expected to be easily identified by the students as unfit for human physiology (episode 16). This would allow the teacher to introduce lactic acid fermentation as a counterpart for alcoholic fermentation (episode 17).

With an explanation of the differences between the form (number of mitochondria) and function (speed of performance) of red and white muscle cells, the final sequence of LT-activities used a yoyo-sequence to lead the students back to the organism level of biological organisation and explain the original problem of differences between sprint- and marathon-runners (episode 18).

Following the overall problem-posing sequence that spanned approximately nine 50-minute lessons, the recontextualising-test was administered during the tenth lesson in the lesson module (see table 5.8). This test was designed to invite students to answer questions that related to problems in other contexts, which could be solved by using cellular respiration. The results from this test were used to evaluate and redesign of the items in the test (see also: chapter 2). They were not used for a detailed analysis of students' performance on this test and therefore, these are not described in this chapter. For further clarification of crucial episodes in the LT-strategy, the following section provides a more detailed description of these episodes in relation to the results of the enactment of these episodes, focusing on the strengths and weaknesses in this preliminary design.

5.3 A preliminary LT-strategy in practice: case studies α1 and α2

The following descriptions of episodes are illustrated with examples from the LT-materials and data from the enactment of case study α2, in particular the (translated) written answers from two students in case study α2. These two students (named here as Antsje and Bianca) were selected because they actively participated in most LT-activities in the lesson module. Their written answers can be considered as examples of the answers given by most students.

Episodes 1-3

Orientation on a sports physiology practice

The first three phases of the lesson module was intended for students to focus on cellular respiration in muscle cells. During episode 1, students developed a motive for studying muscular physiology in an orientation on sports physiology and differences between sprint and marathon runners. After a short discussion on professional sports and the role of a sports physiologist in such practices, students were asked to compare photographs and two short video fragments (1-2 minutes in length) of marathon- and sprint-runners in action. They were then asked to write down any differences they had observed between these two types of athletes, and what they thought would be essential knowledge for a sports physiologist.

Table 5.9 shows the written answers from two students in case α2. These illustrate how this LT-activity helped students to develop a focus on muscular structure and function in relation to the type of performance by the athletes. For the second question, students wrote down the results from a whole class discussion that followed this written assignment. Antsje first wrote down the results from a group discussion and marked the results from the whole class discussion by writing those down below a horizontal line (see table 5.9).

These data illustrate how students were able to identify the most important differences in the gait and body of sprint- and marathon-runners. During the following whole class discussion on the required knowledge of a sports physiologist, several aspects came to light. This is illustrated with the answers from Antsje and Bianca in table 5.9.

By focusing on the differences in performance and muscular structure, the teacher steered the discussion in the desired direction. This resulted in a steering question for structuring the following series of LT-activities in episode 2, written down by the teacher on the blackboard and also by Bianca on her worksheet.

Table 5.9
Written descriptions of the differences between sprint- and marathon runners by students Antsje and Bianca (case α2), and their thought on knowledge needed for explain these differences.

Student: Antsje	**Student: Bianca**
Observable differences between sprint-runners and marathon-runners.	
Marathon runners are much thinner than sprinters, who have huge upper legs and muscular arms. They [sprinters] take larger steps, with a lot of power in each step. [the] Sprinter does not have his hands clenched; [the] marathon-runner makes fists. The biggest differences are the muscles. The sprinter is very muscular; the marathon-runner is very thin. [the] Sprinter needs a lot of power for the start, much more speed and is wearing very tiny shoes.	*Sprinter → large steps, broader, more muscular → speed + good start Marathon → smaller steps, less muscular, smaller, lighter.*
Ideas and question that come to mind when thinking about what a sports physiologist should know to explain these differences.	
Which muscles are important for running[?] The kind [of running] you're doing, for example: long- or short disctance. ____________________ How muscles are trained. Allergies. Lung capacity and breathing. Vulnerable muscles and weak points. How is a muscle build-up [structured]?	*Which muscles he [the athlete] uses the most. What is his [the athlete's] diet? → energy How muscles are trained. Vulnerable muscles / injuries. Structure of the muscle → and how it works. How is the structure of a sprinter's muscles different from the structure of those of a marathon-runner?*

From athletes to muscle cells

The orientation on the differences between marathon- and sprint-runners from a sports-physiological perspective was followed by a series of LT-activities for studying muscular physiology (episode 2). During this phase, students studied the structure and workings of skeletal muscles, stepping down from the organism to the cellular level of biological organisation using a yoyo-structure. The LT-materials for this episode were redesigned between case study α1 and α2. In the design for case α1, the information was presented as a collection of texts and images describing the structure and function of human skeletal muscles at each level of biological organisation from organism to cell. Observations of the enactment of this episode in case α1 revealed that students did read the descriptions attentively, but did not seem motivated to rewrite these descriptions in their own words in a concept-map in episode 3. Therefore, the written descriptions of muscular physiology were removed from the LT-materials in case α2. In the design for cases α2 and on, the texts were replaced with a collection of images that illustrated muscular structure at each applicable level of biological organisation. A whole class discussion, followed by a concept-mapping assignment in small groups of 2-4 students served to allow students to make sense of these pictures and develop their own description of muscular physiology. Figures 5.2 and 5.3 show the concept maps produced by Antsje's (3 students) and Bianca's (4 students) group.

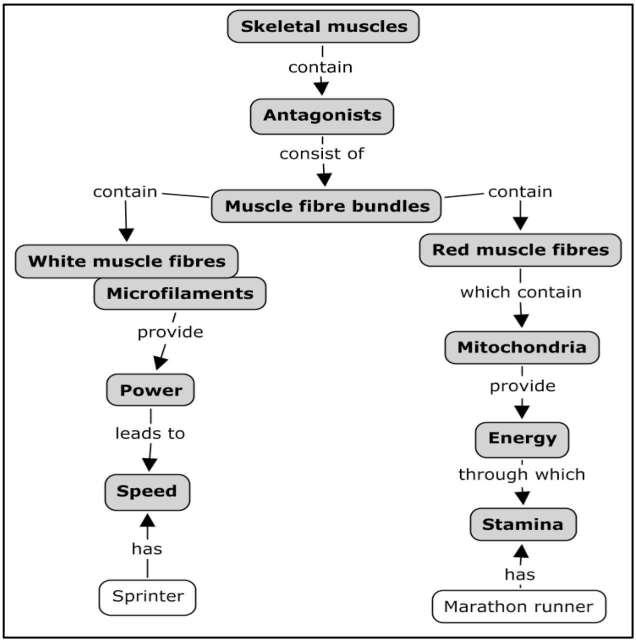


Figure 5.2. A concept map constructed by Antsje's group (of 4 students) during episode 2.

These concept maps (figures 5.2 and 5.3) illustrate how students had difficulty with describing muscular physiology for each level of biological organisation in a single concept map. In retrospect, this can be attributed to the fact that with each level of biological organisation, different biological objects are focused on and compared. Where the organism level focuses on marathon and sprint runners, at the cellular level the focus is on differences between white and red muscle cells. Although the differences at the cellular level reflect those found at the organism level, they are not the same (see tables 5.1 to 5.4 for a detailed description). The concept maps displayed here can be considered as exemplary for most students, leading to a conclusion that concept maps were not the best tool for describing these differences.

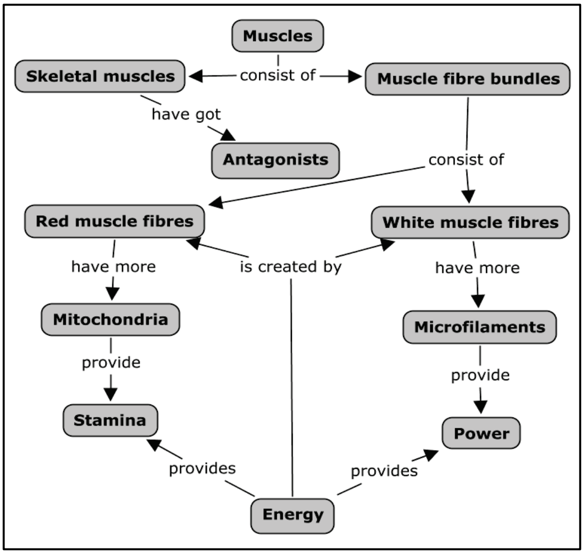


Figure 5.3. A concept map from Bianca's group (of 4 students) during episode 2.

Developing a motive for studying cellular energy supply

To reflect on the new information and allow students to formulate a set of questions that should focus them on cellular respiration (episode 3), students were also asked to describe muscular physiology for each level of biological organisation on a worksheet (see table 5.10). This served as a starting point for another discussion focused on the physiological differences between white and red muscle cells and the knowledge needed to explain these. Table 5.10 shows the descriptions given by Antsje and Bianca, and the questions raised during the whole class discussion.

Table 5.10

Written descriptions by students Antsje and Bianca (case α2) of the differences and similarities in muscular structure, related to the differences in performance between sprint- and marathon runners.

<table>
<tr><th>Student: Antsje</th><th>Student: Bianca</th></tr>
<tr><td colspan="2">Possible answers to the central question, using the information on muscles and muscular structure.</td></tr>
<tr><td>How is the structure of a sprinter’s muscles different from the structure of those of a marathon-runner?
Levels:
Organism: A sprinter has larger muscles than a marathon runner.
Organ: Red muscle fibres contain more mitochondria, provide more stamina, thus [these are] for a marathon runner. White muscle fibres contain micro-filaments, [which] give power, so [these] belong to the sprinter.
Cell: Red muscle fibres contain more mitochondria for stamina, white muscle fibres contain more micro-filaments for power.</td><td>Organism:
Sprinter → more muscles (trained muscles) and power explosive power.
Marathon → more stamina and power for longer distance.
Organ:
Sprinter → more white muscle fibres → more microfilaments.
→ acidify less quickly
Marathon: more red muscle fibres → more mitochondria.
Cell:
Sprinter → more microfilaments.
Marathon → more mitochondria.</td></tr>
<tr><td colspan="2"><Results from the classroom discussion in LT-phase 3></td></tr>
<tr><td>Organism:
The sprinter has more muscles → provides power for each step. The marathon runner has more stamina than the sprinter.
Organ:
Marathon-runner has more red muscle fibres → long-term performance. Cells tend to acidify less quickly. Sprinter has more white muscle fibres → for power and speed, provide power quickly.
Cell:
White muscle fibres are larger due to more micro-flaments, with the sprinter, provide more power. Red muscle fibres contain more mitochondria, long-term contractions, stamina.</td><td>Organ:
Sprinter: → acidify less quickly
→ more power
→ fast energy level
Cell:
Sprinter → are bigger.</td></tr>
<tr><td colspan="2">How do white muscle fibres [cells] get their faster supply of energy than red muscle fibres [cells], while containing fewer mitochondria?
How does the larger number of mitochondria in red muscle fibres lead to their capability of long-term contraction?</td></tr>
</table>

The descriptions in table 5.10 illustrate the difficulty for students in separating the different levels of biological organisation, although the pictures that they based their descriptions on clearly marked for each level of biological organisation. Antsje's description is far more detailed than the one from her fellow student, and there is not much difference between her personal answer and the results from the whole class discussion that she wrote down, which led to two new questions describing a motive for further study of the mechanisms for cellular energy supply. During the whole class discussion, these 'knowledge-gaps' were mentioned by several students; the teacher 'translated' these in the two questions in the bottom row of table 5.10 and wrote them down on the blackboard to enhance students' focus on energy-supply.

Episode 4

Explicating prior knowledge: combustion

With the focus on cellular energy supply created during the first three episodes, the teacher invited students to think about and write down in an individual assignment what they already knew about the energy supply in muscle cells. The individual explanation given by Antsje (table 5.11) seems to refer to the cellular level despite her referral to muscles instead of muscle cells: it mentions combustion of glucose, as well as mitochondria as the suppliers of energy.

Table 5.11

Descriptions of students' (Antsje and Bianca; case study α2) prior knowledge of the energy-supply in muscle cells and their descriptions as a result of a whole class discussion

Student: Antsje	Student: Bianca
Your answer to the question: How does a muscle cell get the energy it needs?	
A muscle gets its energy through combustion of glucose in the mitochondria.	Drink well! And eat a lot of carbohydrates.
<Descriptions of cellular respiration as a results of the classroom discussion>	
glucose + oxygen → CO_2 + H_2O + ATP (energy) $C_6H_{12}O_6$ + O_2 → CO_2 + H_2O + ATP	The combustion of glucose by mitochondria: glucose + oxygen → CO_2 + H_2O + ATP (energy) ↓ $C_6H_{12}O_6$ + 6 O_2 → 6 CO_2 + 6 H_2O + 36 ATP

Bianca's answer does seem to address the cellular level in any way and refers to the organism level, describing food and drink as the source for energy. Most students provided similar answers; either specifically mentioning the combustion of glucose or the need for food as a source for energy. This was in line with the expected prior knowledge for students in senior general biology education who had not studied cellular respiration before (see also: chapter 4).

Introducing: cellular respiration

During the whole class discussion that followed this individual assignment, the teacher invited students to describe combustion as a formula using words, and provided them with a diagram like the one displayed in figure 5.4. This figure is based on illustrations described in a study on improving students' understanding of lactic acid fermentation (Yip, 2000). Like the illustrations from that study, figure 5.4 only displays the carbon atoms that are part of the molecules involved in respiratory reactions, allowing for a focus on the breakdown of the carbon-chain in glucose (design criterion 4-2, see section 4.4). In addition, she provided students with an additional description of the combustion process in molecular formulas, and renamed the process to "cellular respiration".

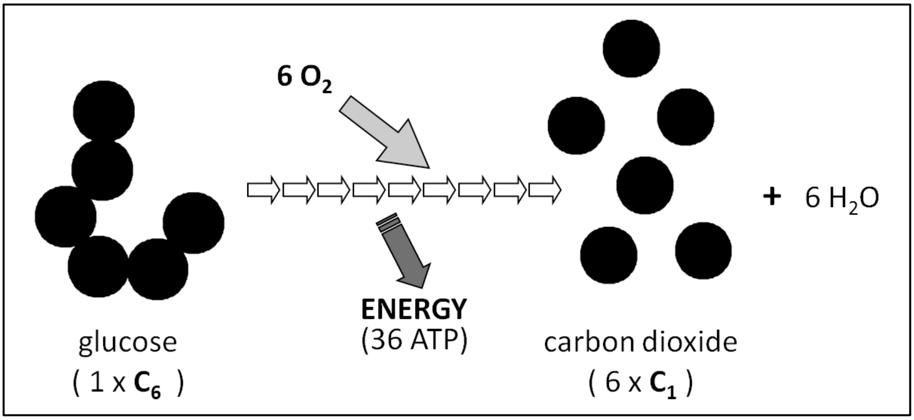


Figure 5.4. Schematic representation of aerobic respiration that focuses on the breakdown of carbon chains

The descriptions of the formula in table 5.11 (bottom row) reflect the manner in which the teacher in case study α2 wrote down the formula on the blackboard. She used molecule descriptions for 'water' and 'carbon dioxide' in the first formula. This did not seem to cause too much confusion for students, who frequently used the terms 'H_2O' and 'CO_2' during whole class and group discussions. Like many other students, Antsje did not mention the number of molecules in the second formula representing at the molecular level of biological organisation. This was in accordance to the instructions given to the teacher not to focus on a correct chemical formula, but rather on the breakdown of the carbon-chain in glucose to six separate carbon dioxide molecules. This episode did not change considerably between cycles α and β.

Episodes 5-8

Developing a motive for recontextualising: model organisms for a practical experiment

The LT-activities in the biotechnology context were meant to be embedded within a problem-posing-sequence in sports physiology, and serve to solve the problem related to sports physiology. Episodes 5 through 9 connect sports physiology with biotechnology though the use of model organisms, a common method in biological and biomedical research practices. The preliminary design for case studies α1 and α2 included a whole class discussion on the origin of sports-physiological knowledge and the idea of using model organisms for a classroom experiment. The discussion in case α2 is described with the transcript in box 5.1.

Box 5.1

Transcript of a short whole class discussion connecting episodes 5 and 6 (case α2)

This transcript follows immediately after an LT-activity in which the teacher introduced descriptions of cellular respiration at the molecular level of biological organisation.

1	Teacher	Well, now we'd want to take a look at: How does a muscle cell, well, combust, in those mitochondria? And we want to research that for ourselves; we will study that for ourselves. So, what do we need for that?
2	Students	<no reply>
3	Teacher	So, let's say. You are going to research how that muscle cell can combust. What do I need for that?
4	Student 1	Oxygen.
5	Teacher	We'll need oxygen, but what kind of the materials [do we need] for researching this?
6	Student 1	A test tube.
7	Teacher	A test tube.

8	Students	*<grinning>*
9	Teacher	Well, wait a minute. I'm going to take you back for a moment to that sports physiologist. The sports physiologist was curious to the answer to the question that we posed today. That sports physiologist, where does he get his knowledge from?
10	Student 2	He learned it [before].
11	Teacher	He learned it, where did he learn it?
12	Student 2	His school, education.
13	Teacher	His education. At that time he probably received a number of books, and those books told him how a muscle is structured. How does the information get into those books?
14	Student 3	Because people write it down.
15	Student 2	Because people do research on it.
16	Teacher	By?
17	Student 3	Researchers.
18	Teacher	By researchers, yes. Who knows how we call those researchers that do research on cells?
19	Student 2	Biologists.
20	Teacher	Biologists, biotechnologists. Yes. […] The biotechnologist works with organisms as well, to see if there is a difference in combustion. What kind of cells does he need to do research on that? Can we use human muscle cells?
21	Student 4	Yes, that's possible.
22	Teacher	It's possible, but…
23	Student 4	You can also use animal cells.
24	Teacher	You can also use animal cells. So actually, we need to go and find a proper model to see how combustion takes place. Because: is it ethically acceptable to look at living, human muscle cells?
25	Student 4	No.
26	Teacher	You need those alive.
27	Student 3	You can take some blood, can't you?
28	Teacher	Will you have muscle cells then?
29	Student 3	No.

30	Teacher	You won't have any muscle cells. Do they still combust then?
31	Students	*<Discuss among students, mostly incomprehensible.>*
32	Student	A monkey!
33	Teacher	A monkey, is that ethically acceptable? To use one here [in class], and divide it up between groups of four [students]?
34	Students	*<Quite lot of commotion, grinning>* *<During the commotion, some students name other organisms, such as frogs and worms.>*
35	Student 3	But is a worm ethically acceptable?
36	Teacher	Well, that is a good question to finish [this lesson]: Is it ethically acceptable? During the following lesson, which is tomorrow, we will look for a proper model organism to see how combustion works.

The first remark (1) in box 5.1 illustrates how the teacher introduced the idea of doing an experiment regarding cellular respiration in class. When the teacher asked them what they would need for doing such an experiment students replied by naming a 'standard' experimental tool: a test-tube, and by naming oxygen as necessary for combustion or aerobic respiration. Realising that her initial question did not provoke the desired response, she invited the students to return to the sports physiology context and asked them if they could think of a possible origin for a sports-physiologist's knowledge on cellular respiration. This line of questioning allowed students to renew their perspective on cellular respiration and identify biological research as a plausible origin for such knowledge. From there, it seemed to be a small step for students to accept the possibility of using another organism for their classroom experiment, and they start naming several animals as possible research obbjects. Although the use of these organisms can be considered ethically acceptable for doing professional research on cellular respiration in muscle cells, the teacher hints at practical (remarks 26 and 30) and ethical (remark 33-36) dilemmas for choosing such a model organism for a classroom experiment. In remark 35, one of the students questioned whether or not the use of a worm would be ethically acceptable in a classroom experiment. This illustrates how the intended motive for recontextualising was developed by introducing biological research and the idea of model organisms, and the fact that sports-physiological practices share knowledge with other practices. This motive also partially relied on the need for doing a classroom experiment.

Criteria for a suitable model organism

Following this introduction of model organisms and classroom experimentation to further study and develop the concept of cellular respiration, students were invited to formulate criteria for using such an organism in a series of group-discussions. They shared their ideas in a whole class discussion and managed to identify several important dilemmas, but had trouble with reformulating these to specific criteria that could be used for evaluating the usefulness of organisms. Therefore, the teacher summarised and reformulated their answers in a set of four criteria regarding the use of a model organism in class:

- Because human muscle cells have mitochondria that (somehow) are involved in cellular respiration, a model organism for studying cellular respiration should resemble human cells as closely as possible, and at least have mitochondria.
- Because we are studying cellular respiration at the cellular level of biological organisation, the cells from a model organism should be relatively easy to use study in a classroom experiment.
- Because of our limited resources, any model organism should be relatively easy and inexpensive to obtain.
- We (students) should find it ethically acceptable to use and sacrifice the organism in a classroom experiment.

Although all of these criteria pertain to the use of a model organism for studying cellular respiration in a classroom experiment, the first of these concerns the concept of cellular respiration in particular: it implies the idea that all organisms respire in one way or another, and focuses on the role of mitochondria in cellular respiration. During the following series of LT-activities, students studied five different texts, each describing a different organism commonly used in biological research.

Choosing a suitable model organism

Using this information, they evaluated the extent to which five different organisms adhered to their criteria, and wrote down their findings in a diagram. Figure 5.5 displays this diagram from the LT-materials and shows the expected findings from students. Each organism’s adherence to each of the criteria is described on a 5-point scale, where ‘– –‘ (double minus) means 'no adherence', and '++', means 'strong adherence'. During both case studies, students did not seem to have much trouble evaluating the organisms; most of their answers resembled the expectations described in figure 5.5.

Criterion → / ↓ Organism	The cells of the organism strongly resemble human cells. They should at least have mitochondria.	Cells from the organism should be (relatively) easy to use and study.	The organism should be (relatively) easy and inexpensive to obtain.	It should be ethically acceptable to use and sacrifice this organism in a classroom experiment.
Rat (*Rattus norvegicus*)	++	-	--	-
Fruitfly (*Drosophila melanogaster*)	++	-	-	+/-
Thale cress (*Arabidospsis thaliana*)	-	+	+	+
Yeast (*Saccharomyces cerevisiae*)	+	+	++	+
Intestinal bacteria (*Escherichia coli*)	-	+	-	+

Figure 5.5. The intended results from students' evaluation of different criteria for choosing a model organism for use in an experiment to study cellular respiration.

This episode (7) served mostly as expected and allowed students to further develop their motive for recontextualising to a motive for studying yeast cells in a classroom experiment. Episode 8 was not an explicit part of the LT-strategy in case studies α1 and α2. Although it was implied in the scenario as well as the teacher's guide, there were no LT-materials that invited students to describe their argumentation. Despite this, most students seemed to have no trouble accepting the use of yeast to further develop their understanding of cellular respiration for explaining differences between human muscle cells.

Episodes 9-11

Developing a biotechnology context and introduction of anaerobic respiration as an alternative for aerobic respiration

In this preliminary design of the LT-strategy in both α-case studies, the introduction of the biotechnologist coincided partially with the introduction of biological research and the idea of model organisms. The transcript in box 5.1 illustrates this, where the teacher reformulated a students' mention of "biologists" to "biotechnologists" (remarks 19 -20 in box 5.1), although this LT-activity should focus on biological research as a practice using *model organisms*. Although there might be biotechnological practices also using model organisms, this biotechnology contexts does research on yeast to further understanding of yeast itself, and not to develop an understanding of another organism, as is the case in many biological and biomedical research practices. While this confusion of two similar contexts apparent did not restrict the development of a motive for recontextualising, it might cause other problems for students later, when coming across other biotechnology or biological research contexts. In addition to the unclear separation of biological research and biotechnology contexts in this preliminary LT-strategy, the biotechnology context in itself was poorly introduced as well. The intention for episode 9 was that the teacher would lead the students in a whole class discussion on the use of yeast in bread- and wine-production, allowing them to identify the anaerobic environment involved in these production methods. Although students easily recognised yeast as an ingredient for bread or wine, this discussion did not allow students to take a biotechnological perspective and identify the environmental circumstances as lacking in oxygen. In addition, instead of allowing students to focus on a specific biotechnology-related problem the LT-activities in this preliminary design only implied the problem with a discussion on how to measure aerobic and anaerobic respiration. As a result, the intended introduction of biotechnology and anaerobic respiration as another mechanism for cellular respiration that could be compared in a classroom experiment remained somewhat artificial and was primarily introduced by the teacher.

Episodes 12-14

Living without oxygen

Despite the artificial introduction of a biotechnological perspective, students were introduced to the idea that yeast can survive in environments without oxygen and as such, needs some form of retrieving energy from its food in another manner. At this time (episode 12), the teacher introduced the concept of anaerobic respiration by focusing students on a schematic representation of cellular respiration at the molecular level of biological organisation. After describing alcoholic fermentation in words and chemical formulas similar to the descriptions of cellular respiration given box 1.1 (chapter 1), students were presented with a schematic representation like the one displayed in figure 5.6, although their version only included a schematic representation of the glucose molecule. Students were asked to complete this schematic by themselves, using the information on alcoholic fermentation they had received from their teacher.

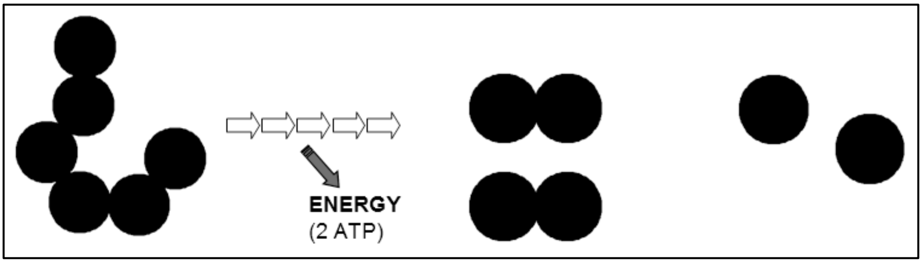


Figure 5.6. Schematic representation of alcoholic fermentation of glucose: a possible route for anaerobic respiration.

During enactment of the LT-activities, students seemed to accept alcoholic fermentation as another route for cellular respiration and can be expected to have connected it to their prior knowledge of yeast as an essential ingredient for brewing wine or beer.

Designing an experiment for comparing aerobic and anaerobic respiration

The next issue on the agenda was to design an experiment suitable for comparing yeast's aerobic and anaerobic capabilities. This primarily focused on possible measurements of cellular respiration in yeast. During this LT-activity, students were asked to think of products from aerobic and anaerobic respiration that would allow for easy measurement and comparison. The teacher kept questioning the students for possible experiments and means for measurement, inviting them to review the dilemmas for each possibility. As such, students eventually were able to identify the differences in carbon dioxide production between aerobic and anaerobic respiration. Also, since carbon dioxide could be expected to be released in gaseous form from a glucose and yeast suspension, it would allow for easy measurement. Having designed the experiment with help from their teacher, students were invited to describe their expectations for the carbon dioxide production, based on the 'theoretical' descriptions of aerobic and anaerobic respiration. After explicating the expected carbon dioxide production to be far greater with aerobic than with anaerobic respiration, students performed the experiment in groups of 2-3 students and measured the carbon dioxide production by yeast during 15 minutes in aerobic and anaerobic suspensions.

Unexpected results from an experiment with yeast

Before asking students to draw any conclusions from their results, the teacher invited them to combine their results and determine the average carbon dioxide production values for the entire class. In contrast to their expected findings, the results from the experiments showed a larger carbon dioxide production under anaerobic conditions. This allowed the teacher to lead the students in a discussion on these results, and discuss follow-up experiments that would be required to find a suitable explanation (episode 13). One such option was to design an experiment that had a larger time-span, but which would be difficult to set-up in class, because a constant aeration of an aerobic suspension would complicate the measurement of carbon dioxide production. Instead of designing and performing such an experiment by themselves, the teacher introduced the (fictional) results for such an experiment in a diagram. This showed how carbon dioxide production under aerobic conditions continued long after any anaerobic production had ceased, eventually producing much more carbon dioxide. This was intended to allow students to identify the difference in speed between both processes as explanation for the unexpected findings from their own experiment. This proved rather difficult for many students in both cases, who displayed difficulties with distinguishing between 'faster' and 'more' carbon dioxide production. The description of cellular respiration by Bianca (see table 5.12) during the following episode illustrates this. As a result, the teachers in both cases finally pointed out the difference in speed and explained how a slower, but more prolonged process could eventually yield more carbon dioxide than a fast process that rapidly depleted its reagent. In an attempt to focus students on this aspect, the LT-materials for the following β-case studies included an additional diagram that showed how the amount of glucose was depleted quickly with anaerobic conditions, but slowly in an aerobic environment.

Explicating aerobic and anaerobic respiration

With the introduction of this new element of cellular respiration for students, they were asked to describe aerobic and anaerobic respiration in yeast (episode 14). Although the criteria for recontextualising concerning 'explication of the concept' (see chapter 3) were already formulated at the time, the design in case α1 only included specific assignments for students to describe the difference in speed, and not the entire concept of cellular respiration in yeast cells. As a result, there was no explication of cellular respiration as a whole during this episode, allowing for a poor comparison of the concept in both organisms during episode 17. This lack of explicit description of the concept by students was partially solved in the design for case α2, which included an LT-activity that invited students to describe and contrast several important aspects of aerobic and anaerobic respiration in yeast. Table 5.12 shows the answers produced by Antsje and Biance in case study α2.

Table 5.12

Comparison of aerobic and anaerobic respiration in yeast by students Antsje and Bianca (case α2)

	Student: Antsje			**Student: Bianca**	
	Aerobic respiration (combustion)	**Anaerobic respiration (alcoholic fermentation)**		**Aerobic respiration (combustion)**	**Anaerobic respiration (alcoholic fermentation)**
Energy yield	*Yields a lot of energy (36 ATP)*	*Yields a little energy (2 ATP)*		*A lot after 60 minutes.*	*a lot in the beginning, it slows down later.*
Speed	*Has a slower reaction [speed].*	*Has a fast reaction [speed].*		*Slow → fast*	*Fast → slow*
Location in a cell	*In the mitochondria*			*In the cell mitochondria*	*In the cell microfilaments*
Products from break-down	*Carbon dioxide and water. ATP*	*Alcohol and water. ATP*		$C_6H_{12}O_6 \rightarrow 6CO_2 + H_2O + E$	$C_6H_{12}O_6 \rightarrow 2CO_2 + 2C_2H_5OH + E$
Reagent (fuel)	*Glucose and oxygen*	*Glucose*		*Glucose*	*Glucose*

This description of cellular respiration in yeast was intended to be compared with a description of the concept in muscle cells during episode 17. It can be viewed as a first attempt to invite students to describe cellular respiration with all its conceptual elements. Bianca's description of energy yield and speed in table 5.12 illustrates the difficulty displayed by many students in distinguishing a fast reaction speed from a large production, or vice versa. She also describes microfilaments as the location for alcoholic fermentation. This is interesting for two reasons. The first is that at this time, no explicit focus on the location of cellular respirations in a cell had been developed. This can be attributed to a lack of focus on this in the design of the teacher's guide and LT-materials. As a result, the teacher had not previously introduced the students with the fact that anaerobic respiration does not require mitochondria, and completely takes place in the cytoplasm. Although this introduction was intended in the design, the storyline also allows for the introduction of this element during this and the following episode (14 and 15), and not considered as very problematic for students.

Although the teacher did mention this during the whole class discussion that followed students' individual assignments for describing the concept, neither Antsje nor Bianca picked up on this. It also shows that although she took part in an experiment involving yeast, Bianca was apparently still thinking of muscle cells when describing cellular respiration at this stage, and never 'left' the sports physiology context.

Episodes 15-18

Returning to the original problem and recontextualising cellular respiration for human muscle cells and sports physiology.

Having developed a detailed perspective on cellular respiration in yeast, the teacher invited the students to return to the original problem and try to explain the differences between white and red muscle cells. This proved quite an easy step for students, since from their apparent point of view they never seemed to have left the sports physiological perspective altogether. When asked to do so by the teacher, students easily managed to formulate the original question that had led them to the experiment with yeast under aerobic and anaerobic conditions. Based on the intended development of cellular respiration by students, there should now be only one problem left to solve: the incompatibility of alcoholic fermentation with human physiology. This was expected to be solved rather easily with the introduction of lactic acid fermentation as another anaerobic variant of cellular respiration. However, students' descriptions of cellular respiration during episode 14 showed that they had not explicated the location of fermentation in a cell as the cytoplasm. Because this idea is crucial in explaining the different amounts of mitochondria between white and red muscle cells, students could be expected to still have trouble seeing anaerobic respiration as a viable solution to this problem. Box 5.2 shows the transcript of a whole class discussion concerning the adaptation of the concept for the sports physiology context. It followed after students' discussion of their descriptions of cellular respiration in episode 14, and started with the teacher restating the original problem.

Box 5.2a

Transcript of a whole class discussion in episodes 15&16, for recontextualising cellular respiration (case α2)

This transcript describes an episode that was part of episodes 15 & 16. This episode started after explication of cellular respiration in yeast cells (episode 14); the transcript starts with the teacher restating the original question regarding energy supply in muscle cells. This discussion concerned the explicit adaptation of the previous description of cellular respiration in yeast to be compatible with muscle cells.

1	Teacher	The differences that I've found here, do these answer that one question that we had not yet been able to answer: How is it possible that a sprinter has less mitochondria, but is still faster <…> He has a faster energy-supply, but has less mitochondria. Did we get an answer to that?
2	Student1	Probably.
3	Student2	Yes, fermentation occurs.
4	Teacher	Fermentation occurs. What kind of fermentation?
5	Student2	Alcoholic fermentation.
6	Teacher	Alcoholic fermentation. So alcohol is released in the body then?
7	Students	<grinning>
8	Teacher	We'd all get drunk. If so, we'd go and do some exercise, and get drunk doing it!
9	Students	<grinning, some incomprehensible remarks>
10	Teacher	But you are close, fermentation does take place. But in a different form. Instead of alcohol, another substance is produced that doesn't have two, but three C-atoms, a

		slightly different formula. And that's lactic acid.
11	Student2	Lactic acid.
12	Student3	Lactic acid.
13	Teacher	So lactic acid fermentation occurs, and that's also faster. So that's faster energy. So with a sprinter, who has a faster combustion, without oxygen, that leads to the production of lactic acid and a faster release of energy.
14	Teacher	Lactic acid, is that good for muscles?
15	Student1	Yes.
16	Student2	No it's acidic.
17	Teacher	It's acidic. It is a by-product, a product of breakdown. When you've produced a lot of lactic acid, it can cause muscle-aches during the next day. So that is the cause for muscle-aches.
	This transcript is continued in box 5.2b.	

Figure 5.7 is a schematic representation of aerobic and anaerobic respiration in muscle cells that was available to students in the LT-materials for these episodes.

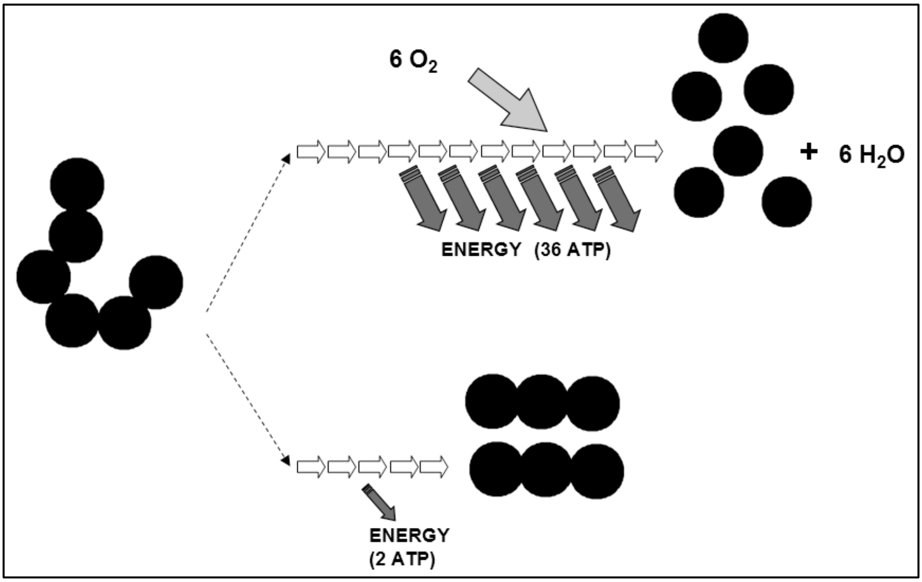


Figure 5.7. Schematic representation of aerobic and anaerobic respiration in muscle cells.

Box 5.2b

Transcript of a whole class discussion*, continued from box 5.2a*.

18	Teacher	That lactic acid, its formula is… I have another ‘dots-model’. <The teacher refers to a schematic representation like the one in figure 5.7.>
19	Teacher	Take a good look at the arrows and the dots; you’ve seen similar schematics before. And I would like one of you to describe what he sees in each reaction, both with and without oxygen. Have a good look at the title for this schematic; this takes place in the muscle cells. The other process from the previous info-sheet occurred in yeast cells, but this occurs in muscle cells. Because here, another substance is produced. Student 4, would you please try to describe it, with the dots and arrows?
20	Student 4	The err...?
21	Teacher	Start with glucose, how many dots does it have? What happens with glucose, on the left [side of the schematic]?
22	Student4	Well, glucose has 6 dots, and then you’ll get oxygen, there at the top [of the schematic]. And then carbon dioxide and water [are produced].
23	Teacher	Hmm, wait a minute. What do those [black] arrows tell you?
24	Student4	That energy is released.
25	Teacher	That energy is released. A lot or a little energy?
26	Student4	Err…
27	Teacher	A lot of arrows, so a lot of energy. What do those white arrows tell us?
28	Student1	Nothing.
29	Teacher	Student 5, can you tell me?
30	Student5	Steps.
31	Teacher	The steps. A lot of steps, so that’s time. Antsje, would you like to continue with the bottom one?
32	Antsje	Well you first have glucose. And then energy is released through fermentation. And it goes very fast, because it has only a few arrows,…
33	Teacher	Hmm, hmm.
34	Antsje	…but only very little lactic acid is released.

35	Teacher	Yes. And lactic acid is three connected dots. Well, you had 6 dots, so how much of that lactic acid is produced?
36	Antsje	Two.
37	Teacher	Two. Two times three gives you six dots again. So with alcohol, three were produced. That was two connected dots. Here, a little less is produced. What is not produced here?
38	Antsje	Water.
39	Teacher	There is no water produced, what is also not produced here?
40	Antsje	Carbon dioxide.
41	Teacher	Carbon dioxide. With alcoholic fermentation, carbon dioxide was produced, but in lactic acid fermentation, no carbon dioxide is produced. And a little energy, but that energy is released very fast.
42	Teacher	OK, does anyone have any questions on this?
43	Student6	So, in that bottom one, it's only lactic acid, nothing else?
44	Teacher	Yes. This occurs in the muscle cell and in a muscle cell, alcoholic fermentation does not occur. So where does lactic acid fermentation occur?
45	Student3	In a muscle cell.
46	Teacher	In a muscle cell. In the cytoplasm.
	End of this transcript and episode.	

Although the transcript in box 5.2 describes a part of episodes 15 and 16, the careful reader already noticed the start of episode 17 with the teacher's introduction of lactic acid fermentation in remark 10 (box 5.2a). Actually in this case, both episodes 15 and 16 together spanned only the first 9 remarks in this episode. It should be noted here that the actual identification of the different episodes as described in table 5.5 to 5.9 took place after the first cycle in the design research phase of this research project. As will explained in the final section of this chapter, a series of design changes to the scenario and the LT-materials were concerned with enhancing the focus on these different steps in the learning and reasoning process.

Aside from the fast occurrence of the episodes 15 and 16, other points are worth noting in the transcript in box 5.2. First of all, notice the teacher's description of the original question, using an organism- and cellular- level at the same time. She speaks of the sprint runner (sprinter) having more mitochondria, and a faster method for releasing energy. However, what she probably meant was that white muscle cells have fewer mitochondria than red ones, although white muscle cells need fast and large supply of energy. This use of different levels of biological organisation in a single description by the teacher was observed frequently during both α-case studies. Similar confusions have also been described in previous studies in biology education, for instance by Knippels (2002) in a study on genetics education, and both explorative case studies. In the teachers' defence, avoiding this while talking and thinking 'on the go' – as is a teacher's role – is a very difficult task, probably impossible to achieve all the time. This was another argument for enhancing the focus on the cellular level of biological organisation during this part of the LT-strategy, through changes in the design of specific LT-activities and the LT-materials. Although confusions like this one were not expected to be completely avoidable, enhancing the focus in the LT-materials should allow students to keep their perspective at the cellular level of biological organisation.

The introduction of lactic acid fermentation during this episode continues in box 5.2b. Now, the teacher invited her students to review a new schematic representation that described aerobic and anaerobic respiration in muscle cells (figure 5.7). She invited two students to describe the processes based on the schematic representation in their own words, allowing for explication of this new form of cellular respiration. Despite some minor inconsistencies in the teacher's description of lactic acid and alcoholic fermentation, the students appeared able to describe the process relatively well. The schematic representations using 'dots' for carbon-atoms were based on schematic representations of fermentation in a study by Yip (2000), and students descriptions based on this illustration were in line with our expectations. However, because students' descriptions of cellular respiration in yeast (during episode 14) were mostly verbal, it can be questioned to what extent these LT-activities invited students to explicitly compare cellular respiration in both organisms. Because in this case each organism represents a different context, there might also be a lack of explicit recontextualising. This is accentuated by the concept maps that were constructed by the students during the continuation of episode 17 in the next lesson. This involved a concept-mapping assignment during which groups of 3-4 students constructed a concept map to describe cellular respiration in muscle cells. The use of concept-maps was expected to allow students to create an overview of the different aspects involved in cellular respiration, and allow them to focus on the aspects that were similar and different between contexts. In retrospect, the previous concept mapping assignment during episodes 2 and 3 did not allow for any explication of cellular respiration in itself, but rather of muscular physiology. In addition, the different levels of biological organisation involved in that description complicated the construction of a correct concept map. The concept mapping assignment in this episode (17) did involve a description of cellular respiration in muscle cells, as can be seen in the concept maps from Antsje's and Bianca's groups in respectively figures 5.8 and 5.9.

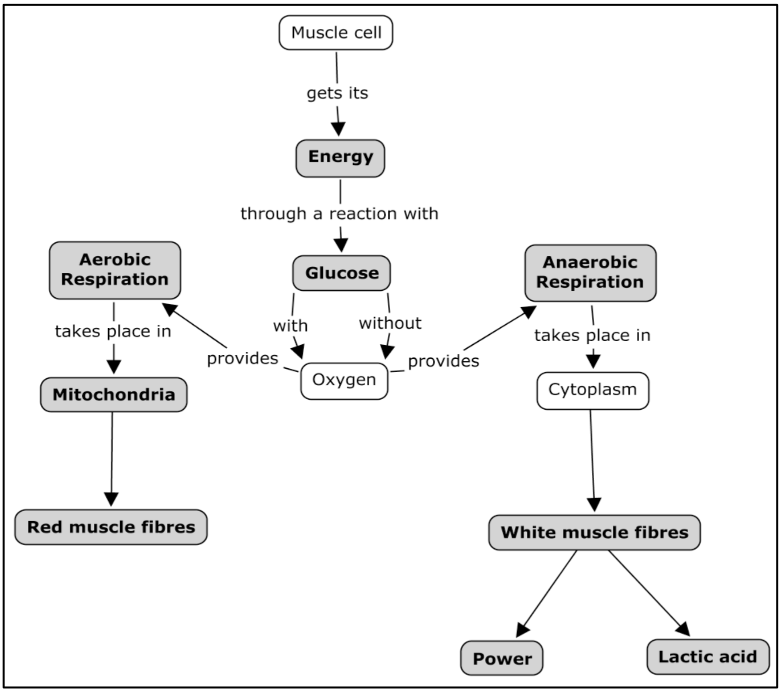


Figure 5.8. Concept map by Antsje's group, constructed during episode 17. The darker concept labels include concepts given as part of the assignment, white concept labels are added by the students themselves.

However, these descriptions were limited with respect to the different aspects or conceptual elements that they highlighted. Again, this was caused by a combination of design choices, such as the selection of concept labels given as part of the assignment.

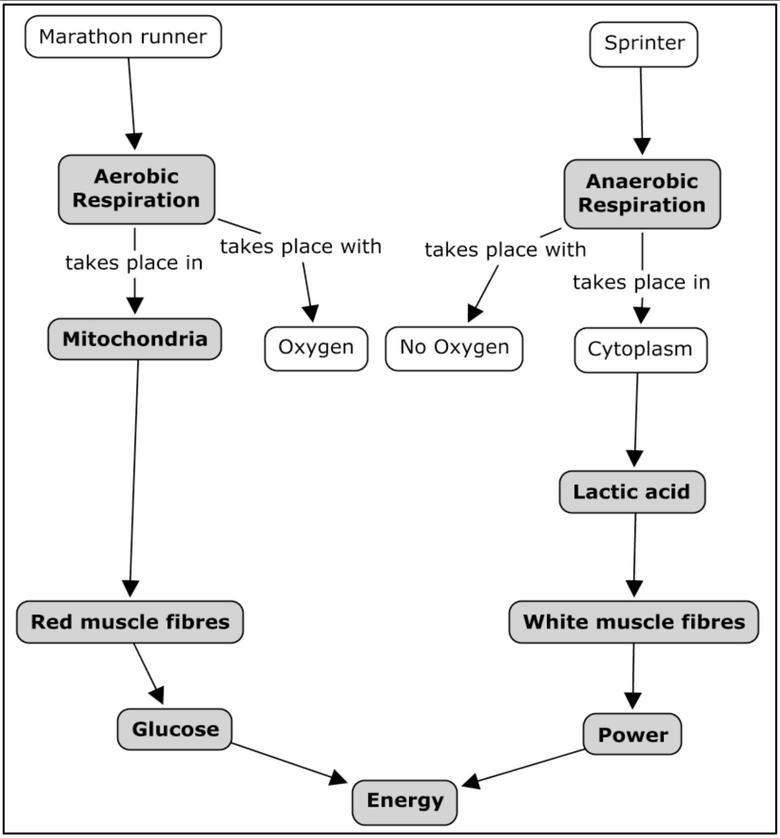


Figure 5.9. Concept map by Bianca's group, constructed during episode 17. The darker concept labels include concepts given as part of the assignment, white concept labels are added by the students themselves.

Finally, due to the different types of descriptions for cellular respiration during previous episodes (for instance: episode 14 and table 5.12), there was no explicit comparison of cellular respiration in the biotechnology and sports physiology contexts.

The results from these first two case studies (α1 and α2) were analysed and used to identify strengths and weaknesses in the design of this first version of the LT-strategy. These issues will be described in the following section, together with a description of their solutions in the redesigned strategy.

5.4 Redesigning the preliminary LT-strategy

The final section in this chapter describes the redesign consideration that resulted from the empirical study of the LT-strategy in practice. The empirical study of this preliminary LT-strategy brought to light a number of issues in its design, which prompted solutions for the redesigned LT-strategy. These issues are discussed briefly in this section, along with their solutions in the redesigned LT-strategy.

Issue 1: Identifying separate steps in the intended conceptual development

Although the scenario provided a detailed description of the intended LT-process for the LT-strategy, the steps in conceptual development were not explicitly described and indicated. As a result, there was no proper explication of the concept during LT-activities that were intended to introduce or change one or more conceptual elements of cellular respiration. To allow for a consistent redesign of LT-activities with a focus on the intended development of the concept, specific steps in students' conceptual development were identified in the storyline (design criterion 1-2). These were eventually described in terms of addition or change of conceptual elements. Table 5.13 describes these different steps in the intended development of the concept. CR_0 (cellular respiration 0) describes students expected prior knowledge of the concept ('combustion'), while CR_5 (cellular respiration 5) represents students expected understanding of the concept after returning to the sports physiology context. For each step, the conceptual elements that were changed or added to the concept are described, the letters refer to the elements as described in chapter 2 (figure 2.7). These different steps also include the introduction of different versions of cellular respiration (aerobic vs. anaerobic: design criterion 5-1; lactic acid vs. alcoholic fermentation: design criterion 5-2).

Table 5.13
Descriptions of the steps in students' intended conceptual development (CR = Cellular Respiration) during the lesson module that was part of the LT-strategy. The letters A – F refer to conceptual elements of cellular respiration described in this thesis.

Step	Elements	Description
CR_0	A 0	Combustion releases energy.
	B 0	Combustion uses glucose.
	C 0	Combustion uses oxygen.
	D 0	Combustion releases water and carbon dioxide.
	E 0	Mitochondria are responsible for a cell's energy supply.
	Object 0	Combustion takes place in the body, because the body needs energy.

Table 5.13 – (Continued)

CR_1	A 1 B 1 C 1 D 1 E 1 Object 1	Cellular respiration releases energy. Cellular respiration needs glucose (carbohydrates). Cellular respiration uses oxygen. Cellular respiration releases water and carbon dioxide. Cellular respiration takes place in / involves the mitochondria. Cellular respiration takes place in all cells of the body, like muscle cells, because all cells need energy.
CR_2	Object 2	Cellular respiration takes place in all cells of all organism, because all living cells need energy.
CR_3	A 3 B 3 C 3 D 3 Object 3 Core (A3+B3+D3)	Aerobic CR releases far more energy (36 ATP) than anaerobic CR (2 ATP). Both types of cellular respiration use glucose molecules. Aerobic respiration uses oxygen, anaerobic respiration does not. Aerobic CR releases 6 water and 6 carbon dioxide molecules. Anaerobic CR releases 2 alcohol and 2 carbon dioxide molecules. Yeast uses aerobic respiration in oxygen-rich environments and anaerobic respiration in oxygen-poor environments. Although both types of respiration break down glucose and release energy from it, the breakdown in anaerobic respiration is only partial, which is why aerobic respiration releases far more energy than anaerobic respiration.
CR_4	F 4	Anaerobic respiration is a much faster process than aerobic respiration.
CR_5	D 5 E 5 Object 5	Anaerobic respiration in muscle cells is similar to anaerobic respiration in yeast cells, but releases 2 lactic acid molecules instead of alcohol. Anaerobic respiration takes place outside mitochondria (in the cytoplasm), while aerobic respiration takes place inside the mitochondria. White muscle cells mainly use anaerobic respiration, and red muscle cells mainly use aerobic respiration.

In addition to the conceptual elements, students' expected understanding of the biological object that uses cellular reparation is described as well

('Object 0 to Object 5' in table 5.13). It may be regarded as an additional conceptual element for the cellular respiration. Finally, a description of the core idea in cellular respiration has been provided with the description of CR_3. Students were not expected to grasp this core at that time immediately, but were expected to gradually develop that insight during following episodes in the LT-strategy. It does however, represent the first possibility for students to connect these three elements and develop a perspective on the conceptual core for cellular respiration. The steps in conceptual development also relate to different episodes in the LT-strategy, and are thus connected to the different motives for recontextualising woven into the storyline. A more consistent sequencing of these steps in conceptual development can result in a more consistent storyline (design criterion 3). For an overview of these steps in relation to the episodes used in this chapter, table 5.14 describes the redesigned LT-strategy and relates the steps in the intended development of the concept to the episodes.

Table 5.14

Description of episodes in the redesigned LT-strategy in relation to the intended steps for conceptual development (CR = Cellular Respiration)

<table>
<tr><th colspan="2">Episodes (no. and description)</th><th>$CR_{no.}$</th></tr>
<tr><td colspan="3">Context: sports physiology</td></tr>
<tr><td>1</td><td>Introducing sports physiology: differences between power- and endurance-focused athletes.</td><td rowspan="4">CR_0</td></tr>
<tr><td>2</td><td>Study muscle physiology from the organism to the cellular level of biological organisation.</td></tr>
<tr><td>3</td><td>Reflect on muscle physiology: identify differences in needed energy-supply between type I and II muscle cells as the main problem.</td></tr>
<tr><td>4</td><td>Explicate prior knowledge on cellular energy supply ('combustion'). Redevelop this concept, introducing the term "cellular respiration".</td></tr>
<tr><td>5</td><td>Reflect on the problem using CR_1 and identify sports physiology as insufficient for developing the concept.</td><td>CR_1</td></tr>
<tr><td colspan="3">Context: biological research</td></tr>
<tr><td>6</td><td>Introducing biological research and the idea of using 'model organisms' for studying biological phenomena, like cellular respiration.</td><td></td></tr>
<tr><td>7</td><td>Study the cells of several model organisms in biological research and choose one for studying cellular respiration in the classroom: yeast.</td><td rowspan="2">CR_2</td></tr>
<tr><td>8</td><td>Reflect on the choice for yeast as a model organism.</td></tr>
</table>

Table 5.14 – (Continued)

Context: biotechnology		
9	Introduce a biotechnologist working to breed yeast strains with optimal cellular respiration capacity in aerobic and anaerobic environments.	**CR_3**
10	Explicate two methods for cellular respiration: aerobic vs. anaerobic.	
11	Identify a problem for the biotechnologist: measuring differences between aerobic and anaerobic cellular respiration in yeast.	
12	Design and perform experiment for measuring differences between aerobic and anaerobic cellular respiration in yeast. Unexpected results prompt further investigation.	
13	Discuss possible methods for verifying the unexpected results. Study the results from similar experiments that measure other variables.	**CR_4**
14	Explain the unexpected results and explicate CR_4.	
Context: sports physiology		
15	Return to the problem in sports physiology: differences in needed energy-supply between type I and II muscle cells. Explicate the possible use of CR_4 in solving it.	
16	Identify alcoholic fermentation as incompatible with human physiology, making CR_4 unfit to solve the problem.	**CR_5**
17	Introduce and explicate lactic acid fermentation as a variant of anaerobic respiration, solving the problem of fit with CR_5.	
18	Reflect on the original problem and solve it with a step-by-step return to the organism level of biological organisation.	
Other contexts		
19	Discuss other possible uses for cellular respiration in other contexts. *(only in case study β2)*	**CR_n**
Recontextualising – test		
20	Explain biological phenomena in other contexts using cellular respiration.	**CR_n**

With this more explicit description of students' intended development of the concept, the LT-activities and -materials could be redesigned to allow students to explicate the concept with each step. This does not mean that students were expected to provide written definitions of the concept with each step, but that the LT-activities did intend for them to more explicitly focus on how they used the concept. These steps were also explicated in the teacher's guide, which provided the teacher with a better view on the development for the concept as well. The most significant changes made for each of the steps in students' intended conceptual development are described here for each step individually.

$CR_0 \rightarrow CR_1$

This step was intended to be an extension of students' explication of their prior knowledge on combustion and took place during episodes 3 and 4 (see also table 5.14). Students were invited to explicate their prior knowledge of cellular respiration (CR_0: combustion). This served as a starting point for a whole class discussion in which the teacher guided the students to rename the process to cellular respiration. This discussion finished with a description of aerobic respiration as a chemical process in words. No major changes were made to this LT-activity in itself, although the worksheet for students now explicitly included an assignment for students to describe cellular respiration at the end of the whole class discussion.

$CR_1 \rightarrow CR_2$

This step should happen at the moment when students and the teacher arrive at the possibility of using a model organism for studying cellular respiration in a classroom experiment (episodes 5-7). In the previous design, the fact that every living organism has to respire was only implied during the discussion, although students did not seem to have any trouble with this idea. To allow students to explicate this fact, the LT-activities were now supported with LT-materials asking them to more clearly describe their reasoning behind the criteria for choosing a model-organism and their final choice for yeast. In addition, this was explicitly mentioned in the teacher's guide as an important step in the discussion.

$CR_2 \rightarrow CR_3$

During episodes 8-10, the teacher led students in a whole class discussion on the use of yeast in the preparation of bread, wine, and beer to introduce a practice of yeast producers. The orientation on a biotechnology practice did not focus on the central activity in that practice. Instead of an orientation on the practice, this discussion was intended for students to develop the idea of anaerobic respiration *and at the same time* think of a possible experiment for comparing it with aerobic respiration. This resulted in an unsatisfactory orientation on a biotechnology practice and inconsistent sequence of LT-activities from a student's perspective. The orientation on the practice of food producer, and focus on a specific problem was improved by introducing an article describing a biotechnological researcher working for a major biotechnological company in the Netherlands (Zeilmaker, 2005).

$CR_3 \rightarrow CR_4$

In the α-design, this step was supported with a worksheet to invite students to describe and contrast aerobic and anaerobic respiration in yeast cells that followed the classroom experiment (episodes 13 and 14). This was intended to allow them to explicate the new element of difference in reaction-speed (see table 5.12). However, the resulting descriptions by students made an explicit comparison between CR_4 and CR_5 difficult, since CR_5 was explicated (too some extent, at least) in a concept map. Therefore, the LT-activity intended for explication of CR_4 was changed to a concept-mapping assignment to invite students to describe aerobic and anaerobic respiration in yeast cells. To help them start, the LT-materials provided the following list of labels that they had to use in their concept map:

- yeast cell
- anaerobic
- aerobic
- oxygen
- glucose
- cellular respiration
- energy (ATP)
- mitochondria
- carbon dioxide
- alcohol

$CR_4 \rightarrow CR_5$

In the α-design, this step (in episodes 15-17) already included a concept-mapping assignment to explicate cellular respiration in muscle cells. In fact, the design for case study α1 included a concept mapping assignment inviting students to describe CR_4 and CR_5 in a single concept map, and note which parts of the concept map applied to sports physiology and which to biotechnology. This combined description for two contexts proved troublesome for students, which is why the concept-mapping assignment was changed to only describe CR_5 in human muscle cells. The result of this change was that in case study α2, students did not construct a concept-map for CR_4 in yeast cells, making a comparison with CR_5 more difficult. With CR_4 now intended for explication in a concept map as well, the concept-mapping character of the LT-activity for CR_5 did not change. However, the new design did not provide any labels for constructing the CR_5 concept map anymore. Instead, it invited students to review their previous (CR_4) concept map and discuss what needed changing for use in the sports physiology context.

Issue 2: A more recognisable sports physiology practice

The original orientation on sports physiology (episodes 1-3) allowed students to focus on the energy supply in cells (design criterion 1-1). The subsequent LT-activities for relating this to their prior knowledge on the subject (episode 4) helped students to focus on the concept of cellular respiration. In addition, the motive developed from this context was recognisable and acceptable for most students (criterion 6-1). During episode 15 for instance, they did not appear to have any trouble returning to the original questions that were posed during the first three episodes. Also, students frequently referred to this context while they were engaged in LT-activities connected to biological research and biotechnology. However, the first lesson included a discussion on the role of a sports physiologist *after* the students had been introduced to the problem involving marathon- and sprint runners. In addition, this addition did provide a real-world example of a sports physiologist. It was expected that by starting the orientation with an example of a sports physiologist in a recognisable sports-related practice, students could more easily identify themselves with a participant in a sports physiology practice. Therefore, the connection of sports physiology with a professional sports practice was strengthened. In the new design, the first lesson started with a video fragment of a Dutch professional football team doing routine training exercises. In this fragment, a sports physiologist employed by that club explained how he assisted the players' training with a combination of strength- and endurance-focused training activities. This provided a starting point for a discussion of the differences between power and endurance in sports, finally focusing on the differences between sprint- and marathon runners.

Issue 3: Breaking up long whole class discussions into separate LT-activities

The desire to invite students to explicate and discuss their conceptual development of cellular respiration resulted in a large number of whole class discussions that required students and teacher to establish and follow a complex or line of reasoning. During both α-case studies it seemed that these discussions took a lot of time, apparently causing students to lose interest and stop participating in the discussions. In addition, the LT-materials that supported these discussions did not invite students sufficiently to provide written descriptions of the concept in context. As a result, explication of the concept by the students was mostly limited to the whole class discussions. Although these discussions did appear to help students with developing the concept, they had no access to a consistent written record of the outcomes of these discussions (design criterion 2-1). The lack of a written record was cause for long discussions at the beginning of many lessons, where students and teacher reflected on the storyline so far. Another result from the lack of a written description of cellular respiration was that a lot of the students became confused with regard to its different types and had trouble keeping track of the similarities and differences between these.

To limit the length and increase the effectiveness of these discussions, and to provide students with a written record of the storyline, many whole class discussions were 'broken up' in separate LT-activities with small groups of 2-5 students. These were then followed by brief whole class discussions for sharing the findings from each group with the entire class. Furthermore, the whole LT-process became more structured by the use of more worksheets, creating more invitations for students to explicate their conceptual development. During case β1, students' were given new worksheets with each lesson, and added these to their workbook. Because some students had trouble keeping an orderly track of these, the complete workbook was given to the students in case β2 during the first lesson.

Issue 4: Including a more explicit comparison of CR_4 with CR_5

The design for case study α1 included a concept mapping assignment that invited students to describe cellular respiration in yeast and muscle cells in a single concept map, and note which parts of the concept map applied to sports physiology and which to biotechnology (design criterion 2-2). This combined description for two contexts proved troublesome for students, which is why the concept-mapping assignment was changed to only describe the concept in human muscle cells. The result of this change was that in case study α2, students did not construct a concept-map for cellular respiration in yeast cells, making a comparison with the context of sports physiology more difficult. The explicit comparison of the concept between the sports physiology and biotechnology contexts was limited to the discussion described in box 5.2 (see section 5.3).

In retrospect, it is remarkable that these LT-activities were sequenced and designed as they were in this preliminary design. This provides an interesting insight in the design process as well. Although the design criteria for recontextualising were already roughly formulated at the start of the design research phase, arguably the most important one (criterion 2: explication and reflection) was left out of view during parts of the design process, while trying to satisfy other design criteria. This illustrates the complexity of such a process and the need for using multiple cycles of design, evaluation, and redesign.

The redesigned LT-activities for explication and development of CR_4 and CR_5 included a more explicit invitation for comparison of these descriptions (see also design criterion 5-2). After students had constructed a concept map for describing cellular respiration in yeast, the students were invited to look at their concept map for yeast cells, and discuss what changes they needed to make to in order to use it in an explanation for the original problem in sports physiology. They could thus be expected to change their descriptions of the concept more explicitly for each context, and compare these context-based descriptions in a series of group and whole class discussions (design criteria 2-2, 5-1, and 5-2). Or in other words: with this comparison, students were expected to more explicitly and consciously recontextualise the concept.

With this description of how the preliminary LT-strategy was redesigned, the description of the second design research cycle has in fact already started. The following chapter continues with a detailed description of the enactment of the β-version of the LT-strategy, and an analysis of the eventual learning outcomes in terms of students' ability to recontextualise cellular respiration.

Chapter 6

An improved LT-strategy for recontextualising cellular respiration

This chapter describes the results from of the enactment of the improved LT-strategy for recontextualising cellular respiration. The second chapter of this thesis described the two questions (RQ III and IV) that were developed to guide the design-research phase of this project. This section compares the results from the enactment of the LT-strategy in case studies β1 and β2 to answer each of these questions separately.

RQ III How can we determine students' ability to recontextualise cellular respiration to other contexts?

- **RQ III-a** Which elements of cellular respiration do students use and develop during the lesson module?
- **RQ III-b** Which elements of cellular respiration do students use when answering questions or solving problems in other contexts?
- **RQ III-c** How can students' use of conceptual elements of cellular respiration in other contexts be explained?

RQ IV To what extent can the LT-strategy be considered adequate for promoting students' understanding of cellular respiration and their ability to recontextualise cellular respiration to other contexts?

As part of an answer to RQ III-a, section 6.1 describes the implemented learning trajectories in cases β1 and β2, but starts with the results from the analysis of students' concept maps that were made during the pre-test to provide an indication of their prior knowledge of cellular respiration. Next, section 6.1 continues with the results from the post-test concept maps in case β2 (there was no such post-test in case β1, see also chapter 2). Although the post-test took place after the recontextualising-test in case β2 (see also: chapter 2), the results from this test are included here in order to allow for an answer to RQ III-a. This answer is provided at the end of section 6.1.

Section 6.2 describes the results from the analysis of students' written answers to the different items in the recontextualising-test, which was designed to assess if and how students recontextualised cellular respiration to other contexts. Again, these results are summarised at the end of the section in answer to RQ III-b.

For finding an answer to RQ III-c, section 6.3 provides another perspective on the learning outcomes with a comparison of students' performance to the different items in the recontextualising-test, and related to the descriptions of the learning trajectories described in the first section of this chapter.

To conclude this chapter, section 6.4 provides an answer to RQ IV and uses this to provide a final description of an LT-strategy for recontextualising cellular respiration, based on the insights gained from the case studies.

6.1 Implementation of the LT-strategy in cases β1 and β2

The redesign issues and solutions for the LT-strategy have been described in the final section of the previous chapter. Included in that description was an overview of the episodes used to describe the intended LT-process, in relation to the intended steps in students' development of cellular respiration (see tables 5.13 and 5.14). These episodes guide the descriptions of the implemented learning trajectories in cases β1 and β2. Before describing the implemented LT- process during case studies β1 and β2, this section starts with a description of the results from the pre-test. This concept mapping assignment was intended to assess students' prior knowledge before the start of the first lesson.

The pre-test: concept maps

In order to assess students prior knowledge on cellular respiration, a pre-test was designed that invited students to construct a concept map with a set of prescribed labels (see chapter 2). The analysis of the concept maps (and descriptions for each of these labels, if provided by students) involved the identification of the conceptual elements (see figure 2.7) that students correctly described or included in their concept maps. For example: concept maps connecting the labels glucose, oxygen and energy as (part of) a 'combustion-formula' were identified as correctly describing the conceptual elements 'cellular respiration releases energy' (A), 'cellular respiration requires glucose' (B), and 'cellular respiration requires oxygen' (C). Many concept maps included minimal descriptions for the connections between the labels, and some of these were ambiguous as to how they could be interpreted. As a result, the identification of correctly used conceptual elements was dependent on the interpretation of the researcher. Therefore, the analysis was verified using the method of inter-subjective agreement (Smaling, 1992) between two researchers. All concept maps and their accompanied label descriptions were analysed separately by two different researchers. This was followed by a comparison of elements identified and a discussion on initial points of disagreement until agreement on the interpretation of each concept map, label description, and coding rule was reached.

Reliability of a coding scheme for concept maps

In order to determine the reliability of the coding scheme that was the result of inter-subjective agreement between both researchers, a substantial portion of the data was later coded again by both researchers (see also: chapter 2). This analysis of the reliability of the coding scheme used to identify which conceptual elements students explicated in their concept maps, is based on 37% of all concept map data in case studies β1 and β2 (25% of all pre- and post-test concept maps, and 50% of the concept maps made by students during episodes 14 and 15; see section 5.4). Tables 6.1 and 6.2 show the observed proportion of agreement and Cohen's (1960) kappa values for each of the coding categories used in the analysis of students' concept maps in case studies β1 and β2. Table 6.1 depicts the Cohen's kappa values and theoretical maximum values for kappa (based on: Umesh, Peterson, & Sauber, 1989) for this analysis. It also includes a subjective category for the reliability of a kappa value from Landis and Koch (1977).

Table 6.1
Values for observed proportion of agreement ($Pr_{(obs)}$), and Cohen's kappa (kappa) for the analysis of students' concept maps. These values pertain to the correct inclusion of an element, independent of whether or not it also differentiated between aerobic and anaerobic respiration.

	Conceptual elements					
	A energy	**B substrate**	**C oxygen**	**D products**	**E mitochondria**	**F speed**
$Pr_{(obs)}$	0.86	0.78	0.92	0.84	0.84	0.92
kappa	0.53	0.21	0.68	0.68	0.59	0.63
kappa max	0.73	0.59	0.84	0.68	0.68	0.84
Category	*moderate*	*fair*	*substantial*	*substantial*	*moderate*	*substantial*

Note. The values for *category* relate to particular categories for kappa values described by Landis and Koch (1977). The values for kappa max represent a theoretical maximum for kappa related to $Pr_{(obs)}$, based on a method from Umesh et al. (1989). These values are based on 37% (=37) of all students' concept maps constructed during case studies β1 and β2 (=101).

The conceptual elements correspond to the conceptual elements also described in chapter 2 (figure 2.7). Cohen's kappa values provide an indication of the reliability of the coding scheme used for coding a given set of data by comparing the coding schemes of two different researchers. In this case, this means that for each written description of a label or concept map, both researchers determined whether or not an element was correctly included in that answer or concept map. In addition to a determination of whether or not a concept map or description correctly included an element, the analysis for concept maps also included whether or not an element was correctly used to differentiate between aerobic and anaerobic respiration. These results are provided in table 6.2, which does not include element 'B', because it does not differentiate between aerobic and anaerobic respiration.

Table 6.2
Values for observed proportion of agreement ($Pr_{(obs)}$), and Cohen's kappa (kappa) for the analysis of students' concept maps. These values pertain to whether or not a concept map correctly differentiated between aerobic and anaerobic respiration for conceptual element.

	Conceptual elements *(aerobic vs. anaerobic respiration)*				
	A energy	**C oxygen**	**D products**	**E mitochondria**	**F speed**
$Pr_{(obs)}$	1.00	0.92	0.86	0.89	0.95
kappa	1.00	0.79	0.72	0.77	0.72
kappa max	1.00	0.84	0.73	0.79	0.90
Category	*almost perfect*	*substantial*	*substantial*	*substantial*	*substantial*

Note. The values for category relate to particular categories for kappa values described by Landis and Koch (1977). The values for kappa max represent a theoretical maximum for kappa related to $Pr_{(obs)}$, based on a method from Umesh et al. (1989). These values are based on 37% (=37) of all students' concept maps constructed during case studies β1 and β2 (=101).

Determining the value of these kappa scores

Although a higher value for a Cohen's kappa generally means a higher reliability for such a scheme, it is difficult to determine whether or not a specific value for kappa represents a low or high reliability (Umesh et al., 1989). However, some indication for the kappa values in tables 6.1 and 6.2 can allow for a better interpretation of these values. Therefore, two possible methods for interpreting the reliability of a coding scheme based on Cohen's kappa values are presented in this analysis. The first method is described by Landis & Koch (1977), who categorised the possible values for kappa in specific categories ranging from no agreement for values below 0, to an almost perfect agreement for values larger than 0.81. These categories are provided in tables 6.1 and 6.2 for each value of kappa found. Using this method, the kappa scores for element C (0.68 and 0.79 in tables 6.1 and 6.2, respectively) in the recontextualising-test indicate *substantial* agreement between both researchers. A second method for interpretation of kappa values is provided by Umesh *et al.* (1989), and is also illustrated in figures 6.1 and 6.2.

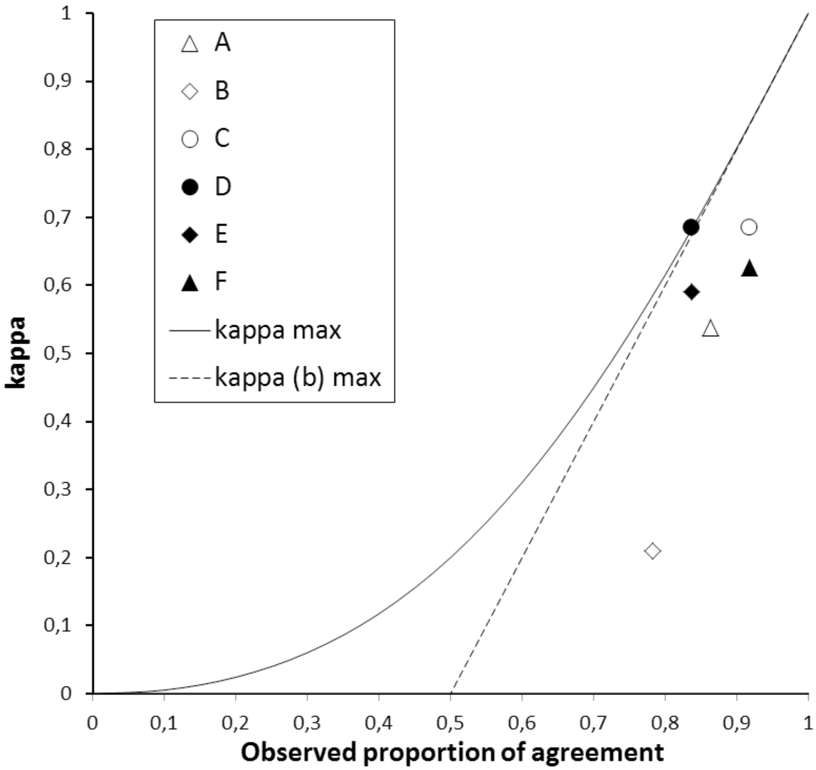


Figure 6.1. Kappa values for the identification of correctly used conceptual elements in students' concept maps in relation to theoretical maximums for kappa (see also table 6.1). Kappa values (vertical axis) related to the observed proportion of agreement (horizontal axis) for correct inclusion of a conceptual element in a concept maps.

These diagrams present the kappa scores for each conceptual element in relation to two theoretical, maximum values for kappa. The calculation of (theoretical) maximum values for kappa is based on the observed proportion of agreement for a specific category (Umesh et al., 1989). The vertical axes in the diagrams in figures 6.1 and 6.2 represent kappa values; the horizontal axes represent the observed proportion of agreement. In both diagrams, two possible maximum values for kappa are represented with a solid and a dotted line, respectively. The maximum value for kappa that is represented by the solid lines ($kappa_{max}$) in both diagrams is based on a minimum value for $Pr_{(chance)}$ for a given observed proportion of agreement (solid line in figures 6.1 and 6.2). This minimum proportion of chance agreement represents a perfectly asymmetrical distribution of the proportion of student's answers that both researchers did not agree on.

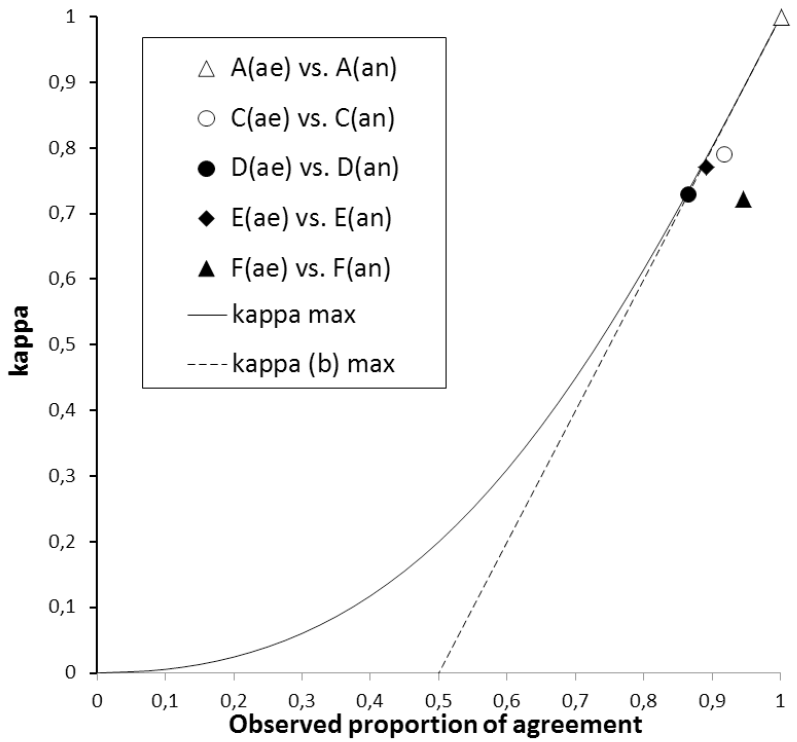


Figure 6.2. Kappa values for the identification of conceptual elements that contrast aerobic (ae) and anaerobic (an) respiration in students' concept maps in relation to theoretical maximums for kappa (see also table 6.2). The diagrams shows the kappa values (vertical axis) related to the observed proportion of agreement (horizontal axis) for determining whether a concept map correctly differentiated between aerobic and anaerobic respiration for a conceptual element.

The other kappa value ($Kappa_{(b)max}$; dotted line in figures 6.1 and 6.2) is based on a maximum value for $Pr_{(chance)}$ that is calculated with a perfectly symmetrical distribution of the codes across the answers. This value is included in figures 6.1 and 6.2 with a dotted line, but not in tables 6.1 and 6.2 because with higher observed proportions of agreement ($Pr_{(obs)}$, horizontal axes in figures 6.1 and 6.2), these two maximum values for kappa are almost the same. More detailed explanations of these methods for determining maximum values for kappa are provided by Umesh et al. (1989, pp. 839-841). These maximum values for kappa provide an indication of the quality of the kappa values, in addition to the categories from Landis & Koch that are given in the same tables.

Using both methods for interpreting the kappa values for the coding scheme used in analysis of students' concept maps, the kappa values for the most conceptual elements can be considered acceptable (moderate to substantial; Landis & Koch, 1977), with the exception of element 'B' (kappa=0.2). This might be caused by the fact that most students used this element in their concept maps, but many of them did not specifically indicate it as a substrate in cellular respiration. Therefore care must be taken with the interpretation of the results from the analysis of students' concept map with regard to element B. Despite the low kappa value for element B, the other values presented here allow for the conclusion that the coding scheme used by both researchers for identification of conceptual elements in students' concept maps was reliable.

Results from the analysis of students' concept-maps in the pre-test

Tables 6.3 and 6.4 indicate the number of students that correctly included the elements A-F (excluding B) in their pre-test concept map (table 6.3) and the number of students that also used an included element to correctly differentiate between aerobic and anaerobic respiration (table 6.4).

Table 6.3

Overview of conceptual elements correctly used in the pre-test concept maps and label descriptions from students in case study β1

Case		Conceptual elements A energy	B substrate	C oxygen	D products	E mitochondria	F speed
β1	No. cmaps (n=19) with element	8	13	13	1	4	0
β2	No. cmaps (n=19) with element	12	16	8	9	5	0

The results from the pre-test in cases β1and β2 show that most students were able to correctly connect glucose to the combustion process (element B), although it must be noted that the agreement value for this element was low and this result should be interpreted with care. The important function of energy release for combustion (element A) was only described in 8 out of 19 concept maps in case 3, while 12 out of 19 concepts maps from case β2 correctly included this connection. 13 out of 19 correctly indicated oxygen as necessary for combustion, while only 8 of them did so in case study β2.

Table 6.4

Overview of conceptual elements correctly used to contrast aerobic and anaerobic respiration in the pre-test concept maps and label descriptions from students in case study β2

Case		Conceptual elements *(aerobic vs. anaerobic respiration)* A energy	C oxygen	D products	E mitochondria	F speed
β1	No. cmaps (n=19) with element	0	4	0	0	0
β2	No. cmaps (n=19) with element	0	3	0	0	0

Note. Element B is not included in this table, because it did not differentiate between aerobic and anaerobic respiration.

In both cases, a few of the students made a distinction between aerobic and anaerobic respiration, connecting oxygen as involved in the aerobic, but not in the anaerobic process. These were all students that had somehow covered the subject of cellular respiration before, either in schools they had recently transferred from or because they had not advanced to the next year and had to repeat this year (10) for senior general secondary education.

The difference between case studies β1 and β2 for element D (‘combustion releases waste products’), can easily be explained by the labels students were given for this assignment: In the pre-test for case study β1, ‘carbon dioxide’ was not included as a label while it was in case study β2. Most students did not use the labels “cellular respiration”, “aerobic respiration”, or “anaerobic respiration” in their concept maps (data not shown). This was expected of course; students had probably never heard – let alone used – these terms before.

The results from the pre-test show that at least half of the students in both case studies could be considered to have some understanding of cellular respiration as ‘ cellular combustion’ or CR_0 (see also: table 5.13). However, this may be an underestimate because many students constructed concept maps that were ambiguous as to how they connected the different labels provided in the test. Most students in both cases had apparently not encountered the term 'cellular respiration' before and did not include this label in their pre-test concept maps. The roles for oxygen and carbon dioxide appeared clear to approximately half of the students; many of them seemed uncertain of how to connect these substances to a combustion process. The role of the mitochondria was not clear for most students, although all students in case β2 identified these as a part of a cell (data not shown). None of the students mention the speed element in the pre-test, as could have been expected from the lack of any labels indicating this element, as well as from the analysis of how cellular respiration is described in biology text books (see chapter 4).

In conclusion, before the start of the lesson module most students had some understanding of combustion as a process responsible for providing energy, but did not conceive this as a cellular process. Furthermore, hardly any of them seemed to have an understanding of aerobic or anaerobic respiration as two separate processes. With this view on students' prior understanding of cellular respiration before the start of the lesson module, the following part of this section moves on to a detailed description of the implemented learning trajectory in case studies β1 and β2.

The implemented learning trajectory for the lesson module in cases β1 and β2

This section describes the learning trajectory for students while they took part in the lesson module that was part of the LT-strategy in case studies β1 and β2. Although both case studies involved two different classes in different schools for senior general secondary education, the learning trajectories for both classes were very similar. Therefore, this section describes the learning trajectories for both classes at the same time, using examples from both these case studies. Unless stated otherwise in the following descriptions of important episodes in the lesson module, these can be considered as adequate examples for most students' work during the LT-activities.

Because students were expected to develop the concept gradually as a tool for solving different context-based problems, and because the entire LT-strategy focuses on solving these problems, students were expected to discuss their different views regarding the concept during most LT-activities in the LT-strategy. However, specific LT-activities for explicitly describing and discussing these views were included with each of the five steps in the development of cellular respiration (see table 5.13). This description focuses on those LT-activities and provides examples from both case studies.

CR_0 (episodes 1 to 4)

Many organisms get their energy by combusting glucose (or other substrates). This process involves oxygen, releasing water, carbon dioxide, and energy (CR_0, paraphrased from table 5.13).

The episode in box 6.1 describes a short whole class discussion in case β1 during which the students described and compared the structure and physiology of sprint and marathon runners. After they had done so for all levels of biological organisation involved (organism, organ, cell), the teacher led them in a short discussion to see if they are able to explain the differences in performance between sprint and marathon runners.

Box 6.1
Transcript of a part of episode 3, in case β1

		(...)
1.	Teacher	Cellular level. What is going on here? Rindert?
2.	Rindert	The marathon runner has a lot more mitochondria in his, err. Because of this, there are more red blood cells. No, no red blood cells, but fibres, muscle fibres.
3.	Teacher	Okay, so red muscle cells. A lot of mitochondria.
4.	Rindert	A lot of ATP that they produce.
5.	Doc	Yeah, there’s a lot of ATP in those, err. That’s being produced by the mitochondria. What does that mean, Anton?
6.	Anton	That he has a lot more energy.
7.	Teacher	That he has a lot more...
8.	Anton	Yes, [he] produces more energy so to say.
9.	Teacher	Okay, so he produces more energy. So he has a lot of energy. Okay, which athlete?
10.	Anton	That’s the marathon runner.
11.	Teacher	The marathon runner. The marathon runner has a lot of ATP, a lot of energy. Well that’s correct so you can write that down. But how, how can that be? Because the sprint runner…
12.	Farid	He needs more energy in a short amount of time.
13.	Teacher	He needs more energy in a short amount of time.
14.	Rindert	They [sprint runners] just need a quick boost.
15.	Teacher	Yes. (…)

		So that sprint runner needs a lot more. But the strange thing is, the strange thing is that the sprinter does not have a lot of mitochondria. At what question do we arrive then?
16.	Farid	Well, how does he [the sprint runner] get his energy? That's what I'm wondering.

After the students had a chance to describe these differences by themselves, the teacher reminded them of the number of mitochondria in red and white muscle cells. Although students did not explicate this difference by themselves during this episode (they did during episode 2), this reminder elicited a quick response from Farid (remark 12 in box 6.1). He identified the discrepancy between his understanding of mitochondria as energy-suppliers and the differences in number between white and red muscle cells. Interestingly, both Farid and the teacher kept referring to the organism level by describing sprint- and marathon runners as having more or less mitochondria and ATP. Despite its obvious discrepancy with design criterion 4-1 (see chapter 4), this did not impair their descriptions at this time. Despite the focus on the cellular level of biological organisation in the LT-materials and the teacher's guide, teachers and students in both case studies kept using organism-level descriptions where cellular level descriptions were better suited. Although there did not seem any problem with such descriptions at this time, such inconsistent use of levels of biological organisation may have caused confusion for students at a later time during the lesson module.

Following the episode partially described in box 6.1 (episode no. 3, see table 5.14 for a summary of all episodes in the LT-strategy), the teacher continued the whole class discussion in an attempt to get students to better formulate this problem. After some other students had managed to identify the discrepancy between their current understanding of cellular energy supply and the number of mitochondria in red and white muscle fibres, the teacher reformulated their descriptions by writing down the central questions for this context on the whiteboard. Next, students were invited to describe their own understanding of this process in an individual assignment during episode 4. This assignment was similar to the one described in chapter 5. Tables 6.5 and 6.6 show descriptions that relate to the cellular level and the role of mitochondria made by two students in case β1 (table 6.5) and two in case β2 (table 6.6). There were 21 students in case study β1; quite a number of them failed to write down an answer for this assignment. A total of 14 of these written descriptions were collected and analysed, and 11 of those mentioned a role for mitochondria in cellular energy supply.

Table 6.5
Two written explanations for the supply of energy in red and white muscle fibres, made by two students (Rindert and Mohammed) during episode 3 (see table 5.13) in case study β1

Student: Rindert	**Student: Mohammed**
Your answer to the question: How does a muscle cell get the energy it needs?	
The red muscle cells [get their energy] through the mitochondria. These produce ATP, I don't know which substance is needed for this, but chances are its glucose again.	*Through the energy that is already present in the muscle (just delivered). Energy goes directly to the mitochondria, from where the energy is gradually used up.*

Table 6.6
Two written explanations for the supply of energy in red and white muscle fibres, made by two students (Dewi and Sandra) during episode 3 (see table 5.13) in case study β2

Student: Dewi	**Student: Sandra**
Your answer to the question: How does a muscle cell get the energy it needs?	
Glucose is combusted in the mitochondria that turn ATP into energy, which is transported through the blood to the muscles.	*He [the athlete] eats, and there are nutrients in there from which the body retrieves substances. [These] arrive in his cells, where they turn themselves into actine and myosine. And the mitochondria transform these substances into energy.*

The descriptions in table 6.5 can be considered as examples for most students' descriptions that mentioned mitochondria in case β1. However, it is clear from a few descriptions like Mohammed's (see table 6.5) that not all students had separated the release of energy in cellular respiration and use of this energy as distinct processes. Similar to the students in case β1, about half of the students in case β2 (9 out 19 collected descriptions) mentioned a role for mitochondria. However, unlike the students in case β1, the students in case β2 had not just finished a series of lessons on cellular anatomy before the start of this lesson module. As a result, they appeared to have more trouble with separate descriptions for the cellular level of biological organisation. This is reflected in the examples in table 6.6: Dewi's description correctly includes mitochondria as producers of ATP, but goes on to mention that this is then transported to the muscles. Although Sandra's description apparently mentions mitochondria when 'the energy arrives' at the cellular level, it confuses processes of energy release and utilisation by describing actine- and myosine as being transformed into energy.

A surprisingly small number of students' written descriptions of their prior knowledge for cellular respiration (6 in CS β1 and 6 in CS β2) included sugar or glucose, although most of the students in both case studies included glucose in their pre-test concept-maps (see section 6.1). When we combine the results from this LT-activity with those from the pre-test concept-maps we can safely conclude that most students had an understanding of glucose as important for energy supply, and that mitochondria are somehow involved. However, only half of them managed to connect the process of cellular respiration (still labelled as 'combustion' at this time) to the cellular level of biological organisation. This is in line with the description of students' expected prior knowledge (CR_0) in episode 4.

$CR_0 \rightarrow CR_1$ (episodes 4 and 5)

Cellular respiration is a cellular process that converts glucose to energy, by combusting it with the use of oxygen, releasing water and carbon dioxide as waste products. Mitochondria are responsible for this process (CR_1, paraphrased from table 5.13).

Students' descriptions of their prior knowledge regarding the supply of energy in muscle cells provided the starting point for a whole class discussion intended for students to discuss their different descriptions. Following this, the teacher intended to reformulate their remarks and explicitly connect the process to the cellular level. The following episode (in box 6.2) is from case β1, and shows a part of the whole class discussion.

Box 6.2
Transcript of a part of episode 4, in case β1

1.	Teacher	The blood [then] goes to the muscles. Okay, [that's] very good. Then what happens?
2.	Rindert	There the energy and oxygen are passed on, as it where, I think.
3.	Farid	Via the cell membrane. And then proteins, or, no.

4.	Teacher	You're coming a long way. You're actually thinking along quite nicely, Farid. You're at a very small level [of biological organization] already, but I want to (…)
5.	Student	Glucose and oxygen become energy. In cells.
6.	Teacher	In cells, but what? So with that we're already at a very small level. So glucose and oxygen, that goes from the blood into the cell.
7.	Farid	But how?
8.	Teacher	So you see: we're going from a higher level [of biological organisation] to a smaller one. Okay, Farid?
9.	Farid	How does it pass the cell membrane? Because it isn't a protein.
10.	Teacher	No, it's not a protein. It's an, err, nutrient. Well, that's actually a bit beyond this series of lessons, but I can tell you because you already know something about it. In that cell membrane are protein gates and glucose is taken up by such a protein.
11.	Farid	But it isn't a protein, right?
12.	Teacher	No, but it can come through that gate into the cell.
13.	Farid	But then why is it called, oh, never mind.
14.	Teacher	Rindert?
15.	Rindert	But there's energy being released in combustion, right? But how is that combusted then?
16.	Teacher	What is happening here with glucose and oxygen in the cell?
17.	Rindert	That is combusted.
18.	Teacher	Right, combustion takes place. So that is still the cellular level [of biological organisation]. But what is combustion? Where does it take place?
19.	Rindert	Well, in the cell I would think.
20.	Farid	In the nucleus.
21.	Rindert	That substance is used up, right?
22.	Teacher	Let's see if there's someone in the back. Wanda, where is combustion taking place? Do you know that?
23.	Wanda	Well, in that cell.
24.	Teacher	In the cell. And what substance do you use with that?
25.	Wanda	Enzymes.
26.	Teacher	Yes, you'll probably use those too, but what I mean is: What substances do you use in combustion?
27.	Wanda	I haven't a clue. Oxygen?
28.	Gerko	Fire, fire! Heat and oxygen.
29.	Teacher	Well that's actually a bit of a tricky question, because what is it you can see over there [on the blackboard]?
30.	Rindert	But those are used *up*, not just used. Right?
31.	Farid	Yeah.
32.	Teacher	Those are used *up*, yes.

33.	Farid	But it should, well. What is?
34.	Teacher	So glucose and oxygen are used *up* in combustion. But where? Where is combustion taking place?
35.	Farid	In the nucleus.
36.	Anita	In the cell.
37.	Teacher	In the nucleus, there's DNA remember? So you'll combust that then? No, that's, err.
38.	Students	<laugh>
39.	Student	Burn!
40.	Teacher	Anita?
41.	Anita	In the muscle cell?
42.	Teacher	In the muscle cell, but where in the muscle cell?
43.	Anita	In the muscle, no.
44.	Farid	Oh yes of course! Sir, what about those mitochondria?
45.	Teacher	Let's see if Anita knows.
46.	Anita	<Laughs> No, I don't know.
47.	Teacher	Gerko?
48.	Gerko	No, I don't know.
49.	Teacher	Who then? Jaap?
50.	Jaap	In the mitochondria.
51.	Teacher	In the mitochondria, right.
52.	Rindert	Oh yes of course, because those produce energy.
53.	Teacher	So?
54.	Farid	I have it as well over here.
55.	Rindert	Then now it becomes even stranger that those don't have that many mitochondria.
56.	Farid	Yeah.
57.	Farid	Yeah, that's what I had as well.
58.	Teacher	So now it actually becomes very strange that the sprint runner doesn't have mitochondria. Yes that's right, it's very strange. But by now you do know that glucose and oxygen in combustion result in?
59.	Farid	Sir, what is cellular respiration?
60.	Student	Energy.
61.	Teacher	Energy.
62.	Farid	Sir, what is cellular respiration?
63.	Teacher	Wait a minute; we'll get to that later, not yet. You're going too fast.
64.	Gerko	Cellular respiration is simply combustion as well.
65.	Farid	Yes, but then you might also know the answer.
66.	Teacher	Err, energy. How was that stored again, in the cell? How is energy stored?
67.	Anita	In the mitochondria, those black dots [in the microscopic photograph].
68.	Teacher	Yes, the mitochondria. But it has to be stored in some form.

69.	Wanda	ATP.
70.	Teacher	Wanda?
71.	Wanda	ATP.
72.	Teacher	ATP's, yes. So the energy is stored in ATP's.
73.	Anita	Oh the, err, thingy.
74.	Rindert	What is an ATP? I don't even know that.
75.	Hanneke	Antagonists.
76.	Teacher	No it's err… I can give you a molecular explanation.
77.	Anita	No.
78.	Teacher	But we should do that right now. What you need to know is that it is some kind of rechargeable battery in the cell.
79.	Farid	Yeah, sure.
80.	Rindert	<laughs>
81.	Teacher	So glucose is a very large molecule that contains a lot of energy, and when that would be released all at once the cell would be destroyed. So what does it do? [It] slowly it breaks down in combustion and stores it in ATP's.

Farid's remarks illustrate that he was pondering the question posed during the previous episode (see box 6.1), illustrating how the orientation on a sports physiology practice and a specific context can stimulate the development of a motive for understanding cellular respiration. In fact, he explicitly used that label in exclamations 59 and 62 (box 6.2). He even stated that this might solve the problem discussed in the previous episode (box 6.2; remark 65). This was a result of an intervention by another student directly following the episode described in box 6.1. This other student (Gerko[1]) had informed Farid of the term 'cellular respiration' [dissimilatie] as 'the answer' to the question they were discussing at the time. However, he did not inform Farid of *how* 'cellular respiration' might solve the problem, leaving Farid to guess at the meaning of the term, but with a strong motive for exploring the idea. Although this provided an opportunity for introducing the label 'cellular respiration' [dissimilatie] as an alternative to 'combustion', the teacher did not do so. In an interview with the teacher that followed this episode, the teacher explained that he had struggled with that idea, but that he had decided not to do so because

[1] Gerko had already participated in the lesson module during the previous year (case α1); due to unsatisfactory test-scores not specifically tied to biology class, he had to retake all the lessons in the entire school year, which is a common practice in the Dutch educational system.

it was not explicitly stated in the teacher's guide. This example shows how our research strategy, including a description of the various steps in conceptual development, prevented the teacher from improvising on the design, based on what was happening in class.

Aside from Farid's interest in the problem and struggle with the new label 'cellular respiration', the episode from episode 4 in box 6.2 shows how the teacher invited the students to try and describe the process of cellular energy supply by themselves. Some still struggled with the idea of combustion as a process that takes place in living cells.

The discussion illustrates the expected direction for this whole class discussion as described in the scenario. The teacher kept posing questions for the students, reminding them of the need for a description of the process. By reformulating their answers, the teacher guided them to a description for combustion, although it was still the teacher who apparently provided them with the final description as a conclusion to the discussion. Finally, the teacher referred to ATP as a kind of 'rechargeable battery' for a cell, reflecting the design of the LT-materials and design criterion 4-2 (see chapter 4).

CR_1 → CR_2 (episodes 6 to 8)

Cellular respiration takes place in all living cells, of all organisms (paraphrased from table 5.13).

The redevelopment of the concept from CR_0 to CR_1 is illustrated by two excerpts from whole class discussions during episodes 6 and 7 (see box 6.3). These episodes involved the context of choosing model organisms in biological and medical research practices that are concerned with exploring cellular respiration in humans. The first part of the transcript (remarks 1-37 in box 6.3) is taken from episode 6, when the students discussed the possibility of exploring cellular respiration in another practice. The second part (remarks 38-45 in box 6.3) is taken from episode 7, and shows exclamations that included explicit (but partial) descriptions for CR_2.

Box 6.3
Transcript of a part of episodes 6 and 7, in case β2

1.	Teacher	So, how does the sports physiologist get more information about that muscle cell and the energy-supply in that muscle cell? Merel, you just said it to your neighbour behind you,

		would you like to explain it to the rest of the class?
2.	Merel	Well, it’s a little silly but, from biologists?
3.	Teacher	A biologist? Would you like to explain that?
4.	Merel	A biologist knows a lot about cells, I think.
5.	Teacher	Okay and how does a biologist get that knowledge?
6.	Michiel	Well, through research of course.
7.	Teacher	By doing research on what?
8.	Michiel, Sandra	Those cells.
9.	Teacher	And how does a biologist do that?
10.	Michiel	Under the microscope.
11.	Teacher	Under the microscope. And what does he put under that microscope?
12.	Student	Cells.
13.	Teacher	Cells. But what cells? Can we use all cells?
14.	Alex	Muscle cells.
15.	Teacher	Okay, very interesting. Muscle cells. […]
16.	Teacher	Someone here said, Alex said: The sports physiologist gains his knowledge from a biologist and where is he able to read that knowledge? Does the biologist tell it to the [sports] physiologist?
17.	Alex	No, of course not.
18.	Teacher	So where does he get the information from?
19.	Sandra	Research reports.
20.	Teacher	Research reports, and where are those reports?
21.	Alex	<slightly irritated> Well, on paper!
22.	Teacher	On paper, in books. […]
23.	Teacher	Let’s move on a bit to where we were just now. If you going to study that muscle cell, you put it under the microscope. The muscle cell, but how do you get that muscle cell, Alex?
24.	Alex	You’ll simply remove it.
25.	Teacher	From a human?
26.	Student	That’s possible, right? Simply cut off, in a glass.
27.	Teacher	Is that possible?
28.	Student	Oh no, that’s not allowed anymore.
29.	Teacher	That’s not allowed! And is that cell still alive when you take it from it?
30.	Alex	Yes.
31.	Student	No.
32.	Teacher	Can it get any oxygen?
33.	Student	It dies.
34.	Teacher	It does. Okay, so that will be difficult.
35.	Student	Then you can get it from animals, right? That is

		allowed.
36.	Teacher	That's what we're going to discuss now, you may read the next section. Turn to the next page.
37.	Teacher	Ferdinand, would you like to name a criterion for us?
	Next, the students and teacher read the descriptions of five different organisms in the LT-materials together. With each description, another student is asked to read it out loud for the entire class. The following discussion takes place directly after this reading session.	
38.	Ferdinand	The cells have to resemble those of a human.
39.	Teacher	The cells have to resemble those of a human. But what part of the cell do they have to resemble?
40.	Frank	The structure.
41.	Student	Mitochondria.
42.	Ferdinand	Mitochondria.
43.	Student	The structure.
44.	Teacher	Yes, because we're going to talk about combustion. As long as combustion is the same as in human cells. Well, where does combustion take place? In the mitochondria. So not only does it have to resemble a human cell, but primarily its mitochondria. So the metabolism has to be the same.

Although the steps in conceptual development had been described as part of the redesign process between the first and second design research cycles, the teachers' guide in case β1 failed to explicitly state this step of CR_1 to CR_2. As a result, the explication of this CR_2 left to be desired in case study β1. In case study β2, the teacher's guide had been adjusted to explicitly mention this step and the teacher incorporated it in a discussion of one of the criteria needed for choosing a model organism. However, she explicated CR_2 instead of the students, and only partially for that matter. Therefore, we must conclude that the explication of CR_2 did not take place as desired, possibly allowing for an inconsistency in the sequence of LT-activities from a student perspective. However, the idea of using a model organism implies CR_2, and the ease with which students apparently accepted that idea may similarly imply that the students had developed CR_2, or at least to some extent.

CR_2 → CR_3 (episodes 9 to 11)

Yeast can convert glucose to energy in oxygen-rich (aerobic) conditions, but in oxygen-poor (anaerobic) conditions as well. This process of anaerobic *respiration yields far less energy than its aerobic counterpart, due to only a partial breakdown of glucose, leaving alcohol and carbon dioxide as waste products (paraphrased from table 5.13).*

By the start of episode 9, the students had chosen yeast as a model organism that they could use in a practical exploration of cellular respiration. With this organism in focus, the teacher introduced a biotechnology practice that similarly used experiments to explore (and if possible improve) these organisms' capacity for cellular respiration. The LT-materials guiding the series of LT-activities in the lesson module included a (partially rewritten) article from a university periodical (TU-Delta) published by Delft University of Technology (Zeilmaker, 2005).

After the students had a chance to read the article for themselves, the teacher started a discussion on the article, focusing on the biotechnologist's goal for breeding improving yeast strains. By focusing them on the processes involved in cellular respiration, this episode was intended to invite students to recognise the need for an explanation of yeasts' survival in oxygen-deprived or anaerobic conditions. The episode in box 6.4 is taken from case study β1 and illustrates this process of focusing and development of a context from an orientation on a biotechnology practice.

Box 6.4

Transcript of a part of episode 9, in case β1

1.	Teacher	Let's take it to the blackboard. The context is that of the…? Liselotte?
2.	Liselotte	The context is that of yeast, right?
3.	Teacher	Almost, in this case the context is about…
4.	Liselotte	Level.
5.	Anton	Yeast breeders.
6.	Teacher	It's usually about people.
7.	Liselotte	Yes, that company.
8.	Teacher	A company, yes. Who work for that company?
9.	Liselotte	The biotechnologists.
10.	Teacher	Biotechnologist. So the context is that of the biotechnologist. What is his activity? What does he do?
11.	Student	He is looking for a superior yeast cell.
12.	Teacher	Yes, he's trying to make superior yeast cells. How does he do that? How does he get, how does he make that? Anita?
13.	Anita	By breeding [it].
14.	Teacher	Yes by breeding it
15.	Student	Breeding super yeast cells.

16.	Teacher	Yes, but that's not the final goal, because you have to…
17.	Liselotte	…make things ferment faster.
18.	Teacher	And then? Then what happens?
19.	Liselotte	Then everything will go faster.
20.	Teacher	Does that have an advantage?
21.	Liselotte	Yes.
22.	Teacher	Why would that person do that? Why would that company want that?
23.	Student	Profit.
24.	Teacher	Profit.
25.	Liselotte	Well, I think a better food production.
26.	Teacher	More food production or a better quality. That's the goal. Now we're going to have a look at… […] What does the biotechnologist have to know about yeast? Karel?
27.	Karel	How you can grow yeast, yeast colonies.
28.	Teacher	How?
29.	Karel	How you can grow yeast colonies.
30.	Teacher	How you can grow yeast colonies. How you can produce more of those. But is it all about yeast colonies? Wanda?
31.	Student	DNA.
32.	Wanda	He wants to produce more gas or something?
33.	Teacher	He wants to produce more gas. What kind of gas?
34.	Farid	Yeast!
35.	Wanda	Carbon dioxide.
36.	Teacher	Carbon dioxide. Okay, so carbon dioxide is being produced, CO2. Why does there need to be a higher carbon dioxide production? Do you know that? Karel?
37.	Karel	It's easier to make the bread rise.
38.	Teacher	It's easier to make the bread rise. So more CO2, more bread. Or not? How does that happen, in bread?
39.	Student	That's combusted. It's combusted, right? And then these empty spaces arise and then…
40.	Teacher	Okay, so empty spaces in bread. Let's look at an example.

Directly following the discussion in box 6.4, the teacher showed the students two loafs of bread: one made from dough which had contained yeast and had risen, and another that was made from dough without yeast and had not risen. During the short discussion that followed, he asked the students to describe how these two loafs of bread differed from each other and what was responsible for this.

After concluding this discussion with an emphasis on the release of gasses by yeast and an expected lack of oxygen in dough, the teacher invited students to compare this with the conditions in the breeding suspension used in the biotechnology practice. This discussion (in box 6.5) illustrates how the teacher, by continuously reformulating and questioning students' remarks, kept inviting students to describe their own views.

Box 6.5
Transcript of a part of episode 10 in case β1

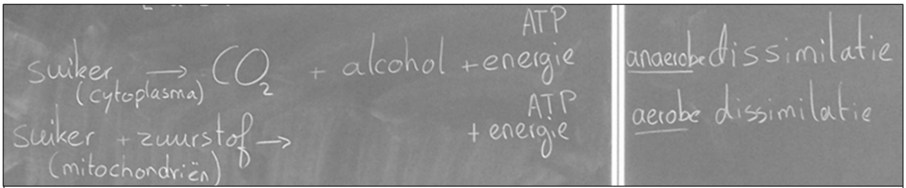
1.	Teacher	How does it work in that propagator that the man uses, that biotechnologist? Is there any oxygen in there? Anita?
2.	Anita	A bit of oxygen, a bit of sugar.
3.	Teacher	A bit of… If you want to grow yeast, it needs oxygen. If you want to use yeast for [making] bread, or wine, or other products it shouldn't have any oxygen. But what is there being produced?
4.	Farid	Alcohol.
5.	Teacher	CO2, and in the case of wine… Willem?
6.	Willem	That's going to ferment as well, right?
7.	Teacher	That's going to ferment as well. Willem, Farid?
8.	Farid	Alcohol!
9.	Teacher	Another question. What does yeast use to make that?
10.	Farid	Oxygen.
11.	Teacher	Mohammed?
12.	Mohammed	Sugar.
13.	Teacher	Sugar. <writes down 'sugar' on the blackboard, see figure 6.1> Does he use oxygen in this process as well?
14.	Student	Yes.
15.	Student	No.
16.	Teacher	In bread or wine? Karel?
17.	Karel	No.
18.	Teacher	No. So there's no oxygen in this process.
19.	Farid	But where does that sugar come from?
20.	Teacher	Where does that sugar come from? You add that to wine, for example. And bread contains sugars as well. So it can get sugars.
21.	Farid	But how did it have sugar before that? Is it in there?
22.	Teacher	Before it's there?
23.	Farid	Yes.
24.	Teacher	Where does it come from, bread?

25.	Farid	Well from, wheat and stuff.
26.	Teacher	Yes, wheat, grain. Where does that come from? Wheat and grain, what are those?
27.	Farid	How would I know? Well, just, from a plant.
28.	Teacher	From a plant. Yes. And a plant uses sunlight to produce sugars.
29.	Farid	Oh, glucose.
30.	Teacher	Yes.
31.	Farid	So, that's a sugar.
32.	Teacher	Glucose is a sugar. How does yeast do this? It has two possibilities: Without oxygen, this happens. <points at the blackboard again, see figure 6.3> What happens with oxygen? Any ideas? What does the text say? Does yeast use sugar then as well?
33.	Farid	Does yeast use sugar?
34.	Teacher	Yes, when it uses oxygen.
35.	Willem	Yes, aerobic and anaerobic.
36.	Liselotte	Yes.
37.	Teacher	Yes? In that propagator, right? Because what does he put in there? Liselotte?
38.	Liselotte	Oxygen and a lot of sugar.
39.	Teacher	Okay, so sugar is in there as well. And if you want to grow yeast, add oxygen as well. Well, later we're going to have a better look at the products that come from that. Where do these processes take place?
40.	Student	In the mitochondria.
41.	Farid	In the bread itself, right?
42.	Anton	Say: 'in the mitochondria'.
43.	Teacher	We're not actually in the bread anymore now, but…
44.	Hans	…in the cell.
45.	Teacher	In the cell, yes. And where does this happen?
46.	Anton	<whispering> Mitochondria.
47.	Hans	In the mitochondria.
48.	Teacher	In the mitochondria.
49.	Student	<unintelligible>
50.	Teacher	Almost, yes. One of the processes takes place in the mitochondria. That's sugar and oxygen. The other process without oxygen takes place in the cytoplasm of the cell.
51.	Farid	Where should we write that down?
52.	Teacher	If there's any space left on the back of your worksheet, you can write it down there.

53.	Willem	What does that cytoplasm stuff mean?
54.	Teacher	What is cytoplasm? People?
55.	Farid	Well, I can't really put it in words, but I do know what it is.
56.	Teacher	<points at the blackboard again, see figure 6.3> Okay, this process: turning sugar and oxygen into carbon dioxide and alcohol, that takes place in the cytoplasm.
57.	Willem	All-righty.
58.	Teacher	Yes?
59.	Student	Why <unintelligible> ?
60.	Teacher	Why? Next question, people. Why does yeast do this?
61.	Student	Why not?
62.	Teacher	Why does this happen?
63.	Farid	They like it.
64.	Student	To stay alive.
65.	Teacher	Maybe you should now make a connection with the marathon runner and the sprint runner.
66.	Student	It provides you with energy.
67.	Teacher	It provides the yeast cell with…
68.	Students	…energy.
69.	Teacher	Energy, right. That's in the form of…
70.	Farid	…of ATP.
71.	Teacher	Of ATP, very good people. So those processes provide energy. They provide ATP's, charged ATP's.

Finally, the teacher summarised this discussion by writing down formulas on the blackboard to describe the aerobic and anaerobic variants for cellular respiration. He also explicitly labelled these as 'aerobic respiration' and 'anaerobic respiration', in line with the intended learning trajectory described in the scenario for the LT-strategy. The teacher's descriptions are displayed in figure 6.3.

The upper half of figure 6.3 is a photograph of a section of the blackboard taken during episode 9 (case β1). The bottom half of figure 6.3 provides an English translation of the teacher's descriptions. Although the descriptions in this figure do not describe the waste products for aerobic respiration, the teacher did finish this description during this episode.



ATP
Sugar → CO_2 + alcohol + energy — anaerobic respiration
(cytoplasm)
ATP
Sugar + oxygen → + energy — aerobic respiration
(mitochondria)

Figure 6.3. The teacher's summary of a classroom orientation on a biotechnology practice and identification of two distinct variants for cellular respiration (case study β1). Above: part of a photograph of the blackboard in episode 10. Below: an English translation of the descriptions in the photograph.

A similar discussion took place during the orientation on a biotechnology practice in case study β2 as well. However, an important difference with the discussion in case β1 was the absence of any explication of element E, which describes mitochondria as responsible for aerobic, but not anaerobic respiration. This was due to a small change in the design, intended to introduce this conceptual element at a later time, when students were expected to describe CR_5 by adjusting their concept map for CR_4 to make it suitable for explaining the original problem in the sports physiology context. This design change was implemented because of the idea that at this stage in the LT-process (CR_2 → CR_3), there was no context-based need for explication of this element. Despite this difference in timing for the introduction of this conceptual element, students in both case studies explicated this element in their concept maps made during the following episodes.

CR_3 → CR_4 (episodes 12 to 14)

Anaerobic respiration is much faster than aerobic respiration (element 'F', paraphrased from table 5.13).

The classroom experiment that was part of episode 12 (see table 5.14) yielded results similar to those from case studies in design research cycle α, although the results from some student couples were unreliable due to mistakes made during the experiment. During the lesson that followed the experiment, the teacher showed students the results from the experiment, using average values for the entire class. However, due to practical considerations, she used the results from the previous year (case α2) as a starting point for a discussion of the results from the experiment. Figure 6.4 is a diagram of these results from case α2, which was included in the teacher's guide for cases β1 and β2. It shows how yeast produced more carbon dioxide under anaerobic, than under aerobic conditions. The solid line displays the average, total carbon dioxide production (in ml.) for yeast in aerobic conditions. The dotted line represents the carbon-dioxide production in an anaerobic environment.

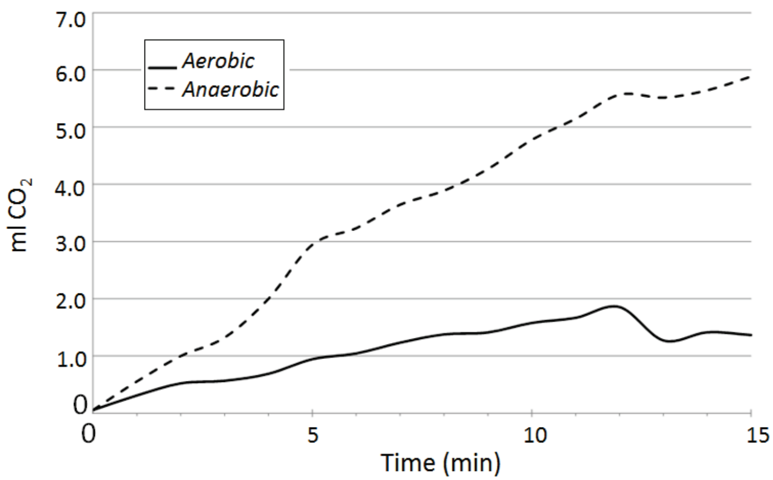


Figure 6.4. Results from the experiment in case α2 (average across all students in that class), which were included in the teacher's guide for case studies β1 and β2.

As in case studies α1 and α2, the unexpected results caused some students to ask for an explanation, although most of them simply concluded that they must have done something wrong. The teacher started the whole class discussion by focusing students' attention on the diagram (see figure 6.4), and explained why she used the results from the previous year. Before they could move on and discuss the meaning of these results, one of the students (Remco) interrupted her with a question on the function of anaerobic and aerobic respiration. The transcript of this episode starts with the question from Remco (see box 6.6; remark 2), followed by the teacher's explanation of aerobic and anaerobic respiration and a few more questions for clarification from Remco. In remark no. 11 (box 6.6) another student brings the diagram into the discussion.

Box 6.6

Transcript of a part of episode 13, in case β2

1.	Teacher	What would like to ask?
2.	Remco	What was the use for that aerobic and anaerobic [respiration] again? And what was the use for the CO2 production?
3.	Teacher	That's a good question. I wrote the aerobic and anaerobic formulas over here on the blackboard. Can everybody see it? Okay. That yeast needs food, [it] needs energy. So what does that yeast do? It can get its energy by using glucose, because a glucose solution was added the yeast to. By combusting it. Well, combustion always needs oxygen and when yeast combusts that, it [yeast] would get a lot of energy. But as a waste product, quite a lot of energy was produced: namely six molecules of this and some water as well. But that yeast is an organism, it can do it without oxygen as well. So for example: in some environments, like when you're making bread, then there's no, or only a little bit of, oxygen. Well then, that yeast is actually happy, because it can get its energy then as well. It does that without oxygen. So here I've got oxygen, here without. The disadvantage is the low amount of energy that's produced. As a by-product, this substance is produced. What was that again?
4.	Remco	Alcohol.
5.	Teacher	Alcohol, indeed, ethanol. And how many carbon dioxide [molecules] are produced?
6.	Remco	Two.
7.	Student 1	Two.
8.	Teacher	Two, so that's?
9.	Student 1	Less.
10.	Teacher	Less, indeed. Less carbon dioxide.
11.	Student 2	You can't see that in the diagram. <refers to the diagram in figure 6.4>
12.	Teacher	Did everyone hear that? Can you say it again just a little louder?
13.	Student 2	You can't see that in the graph.
14.	Teacher	No.
15.	Remco	But how can that be?
16.	Student 3	But that's not right. Because aerobic should have more yeast production, but that line is lower.
17.	Teacher	Yes.
18.	Student 3	So how can that be?

19.		[…]
20.	Teacher	Who can give us an explanation?
21.	Remco	This is short-term. Can I have a go?
22.	Teacher	Yes.
23.	Remco	This is short term. This is, let's say, an experiment of only ten minutes. Just like with those red and white blood cells. A few pages back, with that sprint runner.
24.	Teacher	You're saying blood cells, but you mean: muscle cells.
25.	Remco	Yes, muscle cells. The marathon [runner] had more white. Those, that line is going up. While those red muscle fibres in the sprint runner, those are going up very fast like the aerobic one, but then it goes down again.
26.	Teacher	Hmmm, let's have a look at page 27, because it may surprise you. Because there you can see the same diagram. <refers to the diagram in figure 6.5>
27.	Remco	Yes!
28.	Teacher	But that's from a longer running experiment. Because here's the same experiment, with carbon dioxide, but we're not stopping here, because the other diagram ended after ten minutes. But we [now] stop after sixty minutes, after an hour. Do you get it? Merel, think about it, what do you see now?
29.	Remco	But then the story with those formulas and stuff is wrong, right?
30.	Merel	Aerobic yields more, more carbon dioxide.
31.	Remco	On the long term.
32.	Teacher	Yes. And would you expect that?
33.	Remco	Yes.
34.	Merel	Yes, it seems so.
35.	Teacher	Yes, so look… <points at the formulas for aerobic and anaerobic respiration on the blackboard> That's still right.
36.	Remco	Oh, that needs to be combusted with oxygen. So that process just takes more time.
37.	Teacher	Yes.
38.		[…]
39.	Teacher	When you now have a look at the diagram with glucose concentrations, at the bottom of page 27. <refers to the diagram in figure 6.6> The bar graph. Have a look at that. What do you see there? What kind of difference do you see between aerobic and anaerobic [respiration] and its use of

		glucose? Remo?
40.	Remco:	Well, that's actually very logical, isn't it? Because that anaerobic uses far more glucose because it can get far less energy from it.
41.	Student 3	Again, please?
42.	Teacher	Yes. What do you see?
43.	Remco:	Well that it's depleted much faster with that anaerobic [respiration].
44.	Teacher	Yes.
45.	Student 3	Yes.

In order to focus students on the differences in speed between aerobic and anaerobic respiration, two more diagrams were included in the LT-materials, and the teacher referred to these during the discussion. In remark 26 (box 6.6) she referred to a diagram similar to the one shown in figure 6.5, which illustrates the (fictional) results from a similar experiment with a longer running time. This diagram was intended to show students how carbon dioxide production would continue in aerobic conditions, had the experiment been continued.

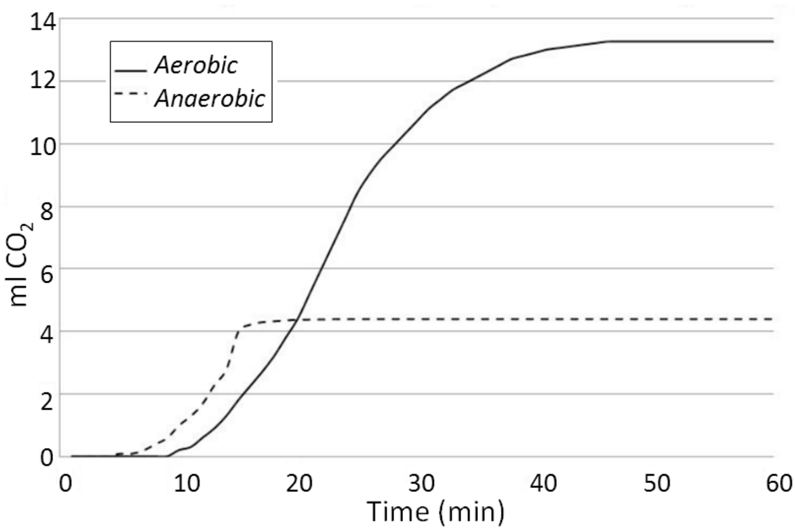


Figure 6.5. Diagram showing results (carbon dioxide production) from a fictional experiment with yeast similar to the experiment that was part of episode 12 in the LT-strategy, but with a longer running time (1 hour instead of 15 minutes).

The other diagram that the teacher in this episode referred to (box 6.6; remark 39) is shown in figure 6.6. That diagram shows the results from a similar (fictional) experiment with an extended running time, but now with glucose concentrations instead of the amount of carbon dioxide that is produced. This time the different measurements were represented using a bar diagram to contrast the speed of depletion of glucose in anaerobic conditions with the slower depletion in aerobic conditions. This bar diagram (figure 6.6) had been included in the LT-materials as part of the redesigned LT-strategy, and was intended to illustrate the difference in speed between both processes from another perspective. At the same time this rapid depletion of glucose in anaerobic, but not aerobic conditions was intended to illustrate differences in the efficiency of both processes.

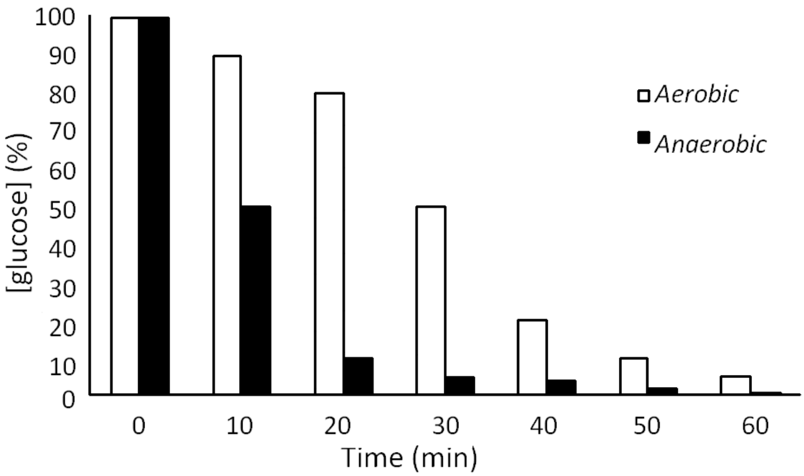


Figure 6.6. Diagram showing results (glucose concentration) from a fictional experiment with yeast similar to the experiment that was part of episode 12 in the LT-strategy, but with a longer running time (1 hour instead of 15 minutes).

This episode from case study β2 illustrates how the unexpected results from episode 12 in the LT-strategy led to the need for an explanation of these results. However, this did not immediately prompt students to question their hypotheses, but rather their own actions during the experiment. This was probably caused by a common practice in secondary biology education: the use of fixed classroom experiments with predictable outcomes (author's personal observation, see also chapter 4). Probably, most of the experiments that the students had performed thus far during their educational career were such fixed experiments. Therefore, in their experience, unexpected results can usually be attributed to mistakes made during the experiment, and are almost never cause for questioning the theory underlying these experiments.

In contrast to this common educational practice, this experiment with yeast was included in the LT-strategy to allow students to further develop their motive for exploring cellular respiration. But because students could not be expected to question the theory by themselves, the LT-materials and the teacher introduced it instead. The discussion in this episode (see box 6.6) illustrates that when the results from another (fictional) experiment are introduced, students can be expected to recognise the difference in speed between the carbon dioxide production in aerobic and anaerobic conditions. Of course, probably not all of the students had probably recognised this speed difference, but the whole class discussion was intended to make this new element available to all students in class. However, there was considerable confusion related to this element (F), as is also illustrated in with the following episode that took place in case β1.

Recontextualising CR_4 before explication in a concept map (case study β1)

Having studied and discussed the results from the classroom experiment during episode 13, the following LT-activities in episode 14 included a written assignment for students to explicitly describe this conclusion, followed by a concept-mapping assignment for describing their current understanding of cellular respiration in yeast. However before doing so, the teacher in case β1 invited students to reflect on the difference in speed and speculate to its use in answering the original question from the sports physiology context. In fact, similar references to the sports physiology context were observed in both case studies during LT-activities based on the other contexts. This illustrates that, although the students and the teacher had been exploring cellular respiration in a biotechnology context, they never fully ‘left’ the sports physiology context, which provided the original motive for exploring cellular respiration. The transcript of this episode is shown in box 6.7.

Box 6.7
Transcript of a part of episode 14, in case β1

1.	Teacher	It might be an explanation for your data of course. Yes, because you’d expect that in the beginning, the anaerobic [respiration] would produce more carbon

		dioxide. Let's see. Would you be able to tell us something about that energy supply in sprint- and marathon runners?
2.	Rindert	So is that anaerobic [respiration] now? Because that one's rising immediately. <refers to the dotted line in figure 6.3>
3.	Teacher	Yes.
4.	Rindert	And after that it stays constant and does go any further. But if you want go further, then the marathon runner actually needs more energy.
5.	Teacher	Yes, so?
6.	Rindert	So if you have that aerobic [respiration], then I would choose that for the marathon runner.
7.	Teacher	Yes, so that one's better you say.
8.	Rindert	Endurance running.
9.	Teacher	And do you remember where aerobic respiration took place?
10.	Student	But don't they know? How can you, as a human, apply aerobic or anaerobic respiration?
11.	Teacher	How is that possible? How can you [apply] aerobic or anaerobic [respiration]?
12.	Student	Because there always is oxygen supply, right? Or does that has something to do with those mitochondria.
13.	Farid	Or maybe with red blood cells or something, how would I know? I think that there's no oxygen in the red blood cells, I think.
14.	Rindert	There actually is.
15.	Farid	Or there actually is, I mean. And in that white there is […]
16.	Maritn	Not.
17.	Teacher	Okay, we need to go back to the muscle, because we're at something crucial here. What kind of muscle cells did the sprint runner have?
18.	Rindert	White.
19.	Farid	White.
20.	Teacher	White muscle cells. Are there mitochondria in those?
21.	Rindert	No.
22.	Farid	Yes, but just a few.
23.	Teacher	A few. The red muscle cell had more, right?
24.	Farid	Yes.
25.	Teacher	And now the marathon runner. What happens in those mitochondria?
26.	Farid	Energy is being produced over there.
27.	Teacher	But with what process? Anaerobic or aerobic [respiration]?
28.	Farid	Well, that's what we don't know.

29.	Rindert	Aerobic [respiration], I think.
30.	Teacher	Jaap?
31.	Jaap	Aerobic [respiration].
32.	Teacher	Aerobic [respiration], yes. That process takes place with oxygen in the mitochondria. There are just a few mitochondria in white muscle cells, but those [white muscle cells] do need a large amount of energy, a very large amount even. So what happens there? Jaap?
33.	Jaap	In the cytoplasm.
34.	Teacher	And what happens is…? Jaap?
35.	Jaap	In the cytoplasm.
36.	Teacher	And that is?
37.	Karel	Anaerobic respiration.
38.	Teacher	Anaerobic respiration.
39.	Farid	In the white [muscle cells]?
40.	Teacher	Yes.
41.	Farid	Huh? But then it's still isn't right.
42.	Rindert	Yes it is.
43.	Farid	Oh yes it is, because you have a short period of time, but need a lot of energy.
44.	Teacher	Yes. So you can do that in a short period of time.

Although this episode (see box 6.7) clearly involved a step from the biotechnology context to sports physiology, it is included in our description of the step from CR_3 to CR_4 because at this time, the crucial difference in anaerobic respiration between the two contexts (i.e.: different waste products) was not yet introduced. The episode described in box 6.7 is included as an example of recontextualising and although it was prompted by the teacher, it illustrates how this process also took place at times when it was not explicitly planned. After the teacher had asked students to provide a possible explanation for the differences in energy-need between sprint- and marathon-runners (box 6.7; remark 1), Rindert quickly replied by mentioning anaerobic respiration in the following remark. However, he did not connect this process to either one of the athletes and formulated it as a question, indicating that he was probably not sure about this. Prompted by the teacher's reply[2], Rindert continued his line of thought

[2] The teacher's replied with "yes" in response to Rindert's remark in exclamation 2. Although Rindert's remark had the form of a question, the teacher's reply appears to have been intended to stimulate Rindert to continue his line of thought, instead of noting his remark as correct or incorrect.

during the discussion that followed, joined by a couple of other students. They managed to properly connect aerobic respiration to the marathon runner and Rindert made some remarks that indicate the difference in speed (box 6.7; remarks 2-8). However, the difference in speed between aerobic and anaerobic respiration was not explicitly stated by the students during this episode. This is similar to what happened in the episode described in transcript 6.6. That transcript illustrates how the students and teacher in case β2 tackled the unexpected results from the yeast experiment and found an answer in the difference in speed. During that episode, Remco made a number of remarks that indicate the difference in speed as well, although he used terms such as “short term” or “long term”. Only in remark 40 (box 6.6), he explicitly stated that glucose is depleted much faster in anaerobic, than in anaerobic conditions.

The examples from both these episodes illustrate what happened during most discussions regarding this specific element: students (and often the teachers as well) discussed the *effects* of this difference in speed instead of the difference in itself. For example: in terms of effect we might say that on the short term, aerobic respiration releases less energy and carbon dioxide than anaerobic respiration, but that in the long term it is the other way around. Descriptions like this one can be expected to cause confusion for students because when speaking in terms of effects, we must include other conceptual elements (such as A and D) in our description. This reduces the focus on the element of speed and may cause confusion as to which one of the two processes produces more energy or carbon dioxide than the other. In other words: these descriptions do not help students to understand the cause for these effects. Without a proper *tool* (conceptual element F) to deduce the differences in the release of energy and carbon dioxide for the short- or long term, students apparently fell back on a rote learning strategy to remember these differences. The result of this was that the actual difference in speed was not focused on as intended during the lessons in both case studies, and students got confused.

Explicating CR_4 in a concept map

Next, the students in case study β1 moved on to describe their current understanding of cellular respiration in a concept map, as did the students in case study β2. To further illustrate students’ understanding of the concept at this point, figures 6.7 and 6.8 are examples of concept maps from students in case β1 and β2, respectively.

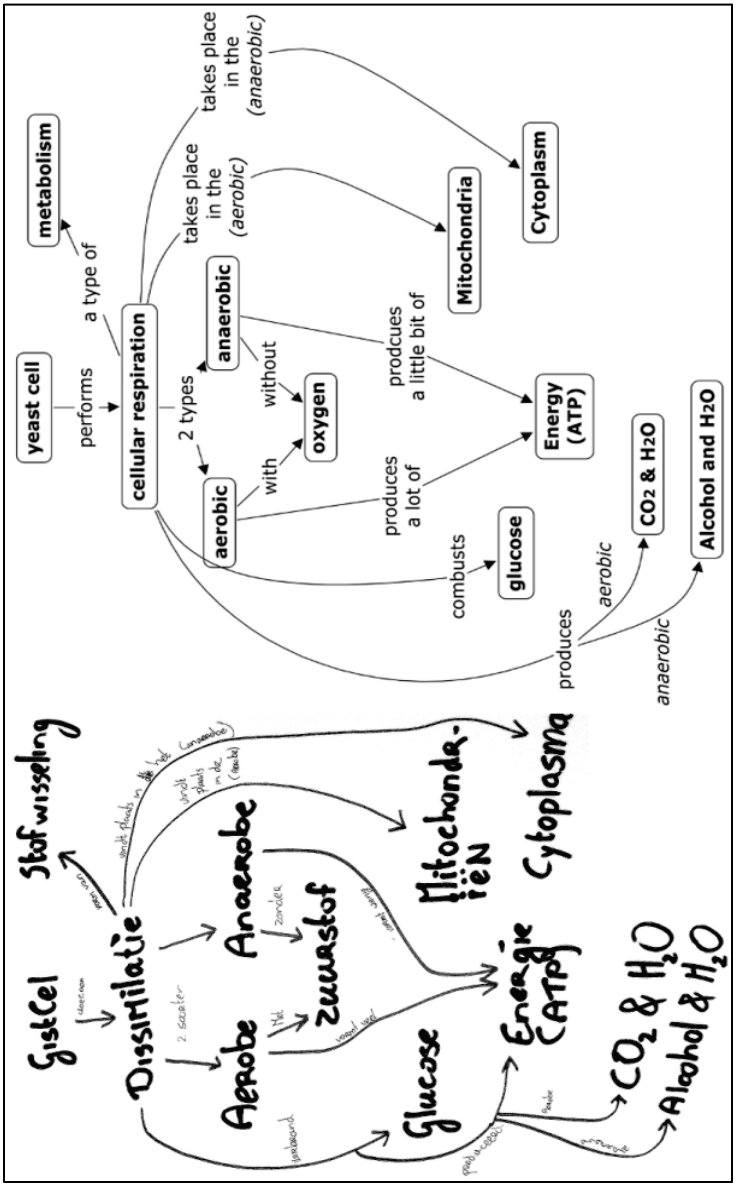


Figure 6.7. A concept map describing cellular respiration in yeast (CR_4), made by 3 students (Karel, Anton, and Simon) in case β1 during episode 14.

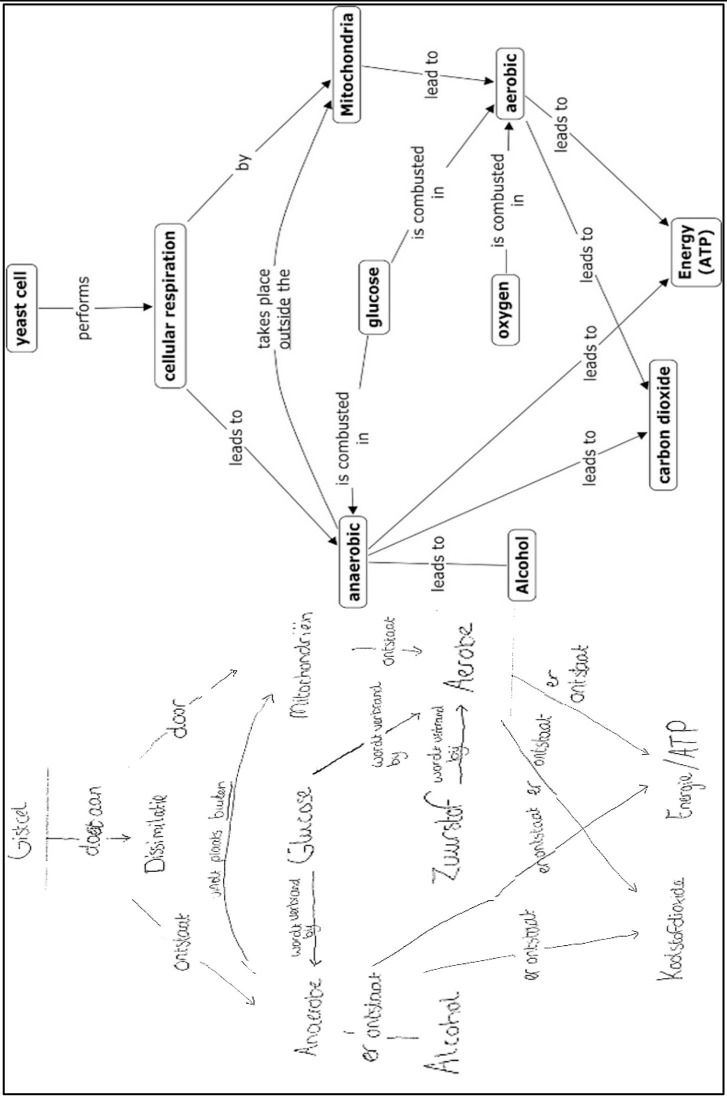


Figure 6.8. A concept map describing cellular respiration in yeast (CR_4), made by 1 student (Miranda) in case β2 during episode 14.

The results for all students' concept maps made during this LT-activity for explication cellular respiration in yeast are described in tables 6.7 and 6.8. These tables describe the results in terms of the conceptual elements that were correctly included (table 6.7) and used to distinguish aerobic from anaerobic respiration (table 6.8) in students' concept maps.

Table 6.7

Total number of biotechnology concept maps (CR_4) that correctly included a conceptual element for cellular respiration (no. cmaps with element). No. students = the number of students that participated in the construction of those concept maps that correctly included a conceptual element.

Case		A energy	B substrate	C oxygen	D products	E mitochondria	F speed
β1	No. cmaps (n=6) with element	6	6	6	3	5	0
	No. students (n=21)	*21*	*21*	*21*	*13*	*17*	*0*
β2	No. cmaps (n=16) with element	11	13	15	14	11	5
	No. students (n=24)	*15*	*16*	*20*	*19*	*15*	*8*

Table 6.8

Total number of biotechnology concept maps (CR4) that correctly differentiated between aerobic and anaerobic respiration for a conceptual element (no. cmaps with element). No. students = the number of students that participated in the construction of those concept maps that correctly included a conceptual element.

Case		A energy	C oxygen	D products	E mitochondria	F speed
β1	No. cmaps (n=6) with element	2	6	3	4	0
	No. students (n=21)	*7*	*21*	*13*	*15*	*0*
β2	No. cmaps (n=16) with element	7	14	14	8	5
	No. students (n=22)	*10*	*19*	*19*	*9*	*8*

Note. Element B is not included in this table, because it did not differentiate between aerobic and anaerobic respiration.

Based on the Cohen's kappa values for interpreting the reliability of this coding scheme for concept maps (see section 6.1), the categories based on these conceptual elements were coded with an acceptable reliability between both researchers, with the exception of element B. Although this element is included in table 6.7, the numbers related to this element should be interpreted with care. Because there is no difference for element B between aerobic and anaerobic respiration, this element is not included in table 6.8.

Table 6.7 shows the number of times each element was correctly included in the concept maps for biotechnology and yeast made by students in case studies β1 and β2. These values (in table 6.7) correspond to the correct inclusion of an element, independent of whether or not this element was used to distinguish aerobic from aerobic respiration. Table 6.8 also shows the correct inclusion of an element in these concept maps for biotechnology, but now only if the element was used to correctly distinguish aerobic from anaerobic respiration.

The numbers in tables 6.7 and 6.8 show that during episode 14 (lesson 7 or 8) most students correctly included element A in their concept maps, indicating that they recognised the release of energy in cellular respiration (table 6.7). However, less than half of the students correctly included the difference in the amount of energy released between aerobic and anaerobic respiration in their concept map (table 6.8). Element C was correctly included and used to distinguish aerobic from anaerobic respiration by almost all of the students. As for the waste-products from cellular respiration (element D), about half of the students in case study β1 mentioned these in their concept maps (table 6.7) and used them to correctly distinguish aerobic from anaerobic respiration (table 6.8). In case study β2 almost all students did so.

The role for mitochondria (element E) in the release or production of energy was recognised by most students in both case studies (table 6.7). However, quite a lot of the students in case study β1 also used this element correctly for distinguishing aerobic from anaerobic respiration, while in case study β2 less than half of them did (table 6.8). This difference might be explained by the episode in case study β1 that occurred just before the start of this concept-mapping activity (see the transcript in box 6.7). During this episode, the teacher and students discussed the possible use for cellular respiration in explaining the differences between sprint- and marathon runners. As part of this discussion, the students had already returned to the original question regarding the number of mitochondria in red and white muscle fibres in relation to their energy-need. In addition, this element was already introduced during episode 10 in case study β1 (see the transcript in box 6.5), but not in case study β2. Therefore, the students in case study β2 could not be expected to correctly include this element in their concept maps at this time.

Finally, the small number of students that correctly included element F (speed) in their concept maps was surprising, especially because this element had just been introduced and provided an explanation for the unexpected results from the classroom experiment. This might be explained by the manner in which students and teachers in both case studies did not explicitly describe the difference in speed between both processes, but rather spoke in terms of its short and long term effects on energy and carbon dioxide release. This is also illustrated in the previously described episode in case study β1 (see the transcript in box 6.7). Additionally, neither the LT-materials nor the teacher explicitly invited students to incorporate this element in their concept maps for this LT-activity. Possibly many students were not sure of their understanding of this element as a result of the confusing descriptions, and avoided it altogether in their concept maps. Therefore, although the element of speed had been introduced during the previous LT-activities and students remembered the short and long term effects of this, they had not fully incorporated this element by the end of episode 14.

CR_4 → CR_5 (episodes 15-18)

Like yeast cells, muscle cells can also use anaerobic respiration. In muscle cells however, this involves lactic acid fermentation instead of alcoholic fermentation. Furthermore, anaerobic respiration does not involve mitochondria, while aerobic respiration does (paraphrased from table 5.13).

After the students in both case studies constructed and (briefly) discussed their concept maps for describing their current understanding of cellular respiration in yeast for the biotechnology context, they were invited to return to the sports physiology context. The first example episode provided here comes from case study β2; its transcript is provided in box 6.8.

Box 6.8
Transcript of a part of episode 15, in case β2

1.	Teacher	We're no returning back to the story we started with. Instead of yeast, we're going back to the muscle. We have just seen that yeast has two ways for getting its energy. And a muscle, a muscle cell has two ways to get its energy as well. But now there's one big problem.

		Who can see that?
2.	Students	<laughter, rumour>
3.	Student 1	Then it doesn't produce any alcohol.
4.	Teacher	What did you say?
5.	Student 1	Then it doesn't produce any alcohol.
6.	Teacher	Yes, that's very good. That would be wonderful of course, because when you'd just go for a bit of a run, you'd get alcohol in your body.
7.	Students	<laughter, rumour>
8.	Teacher	But that's not the case. But then what does it yield? Does anyone know? Who knows what it yields?
9.	Student 2:	Water.
10.	Teacher	Water comes from the aerobic reaction, that always yields water. But in that muscle cell, anaerobic [respiration] also happens. But it doesn't yield any alcohol. There is another product that resembles it. Who knows what that is?
11.	Student 3	Carbohydrates?
12.	Teacher	You combust carbohydrates, actually. What does it yield?
13.	Bart:	Energy.
14.	Alex:	Yes, energy.
15.	Teacher	I think you should know. You've asked about it three times.
16.	Alex:	Lactic acid.
17.	Teacher	Yes, it yields lactic acid.

The discussion in box 6.8 shows how one student quickly recognised that alcoholic fermentation is not suitable for human physiology (box 6.8; remark 3). The teacher then invited the students to think about another possible product for anaerobic respiration, but their unfamiliarity with lactic acid fermentation prompted them to guess at this and name some substances that they knew to be also involved in cellular respiration. They even mentioned energy as a possible solution, disregarding the fact that it is also produced in alcoholic fermentation.

Then, in remark 15 (box 6.8) the teacher reminded Alex of a question he had posed earlier, but which had not been answered yet. This question related to the role for lactic acid in sports physiology, because he already knew about the acidification of muscles as a result of intensive exercise. Reminded of that question Alex recognised lactic acid, although it is not clear from this episode whether or not he immediately understood it in the correct sense. The teacher finished the whole class discussion after repeating Alex's mentioning of lactic acid, and then invited students to review their biotechnology concept maps and think of how they could adapt this one for explaining the energy supply in muscle cells. Students set on to do so and discussed their concept maps in small groups of 2-3 students. During this LT-activity the teacher walked around and helped the different groups with the construction of their concept maps. It was during these small group discussions that she introduced students to the difference in the use of mitochondria for aerobic and anaerobic respiration (as intended in the design).

Explicating CR_5 in a concept map and comparing it with CR_4

The introduction of element E at this time, along with the students struggling with the differences between red and white muscle fibres may have diluted the intended focus on differences in speed as part of the solution to the problem as well. In fact, one of the few times when the difference in speed between aerobic and anaerobic respiration was explicitly mentioned is described in the transcript in box 6.9. This episode took place after the students had reviewed their biotechnology concept map, and were constructing another one for the sports physiology context.

Box 6.9

Transcript of a part of episode 15, in case β2

1.	Teacher	If everyone would like to turn to the blackboard and stop with [constructing] his own concept map. Well, I can now use my concept map [for yeast] to make a concept map for the muscle cell. The muscle cell was of importance for the person with whom we started: the sports physiologist. And what was the sports physiologist curious about?
2.	Student	Cellular respiration.
3.	Ramon	Yes, the speed of combustion of energy in the red muscle cell and the white [muscle cell].
4.	Teacher	Yes, especially the speed. Because when we have a look at this concept map [for yeast], we can see that it's actually faster in the beginning than aerobic [respiration]. And the sports physiologist is actually very curious about that speed. […] We also had a look at the biotechnologist and we incubated that yeast. That is very similar to what? What was the biotechnologist curious about? The speed as well?
5.	Students	No.
6.	Anouk	No, about the combustion.

7.	Teacher	What is the biotechnologist looking for?
8.	Student	For what is best for combustion.
9.	Ramon:	Yes, for the most efficient one.
10.	Teacher	Yes, and what does he look at?
11.	Ramon:	Well, at the amount of ATP that is being released during combustion.
12.	Teacher	The amount of ATP and what more? What amount does he look at as well?
13.	Student	Alcohol?
14.	Ramon:	No, carbon dioxide.
15.	Teacher	Carbon dioxide, yes. So the biotechnologist looks at the products of the reaction and the sports physiologist looks at the speed. So that's actually a completely different focus.That's what you need to learn as well, that different people use the same concepts, but they use them differently.
16.	Student	And the physiologist looks at?
17.	Teacher	He looks more at the speed, right? Because he thinks: how fast does it get its energy? While the biotechnologist is looking at: how much CO2 is there actually being produced? Because yeast needs to produce a lot of carbon dioxide to make the bread rise faster. So, the biotechnologist is looking at other things than the sports physiologist. This [alcohol] is of course very different. What should be in its place?
18.	Student	Lactic acid.
19.	Teacher	Lactic acid, very good. And were there other differences?
20.	Student	Water and carbon dioxide.
21.	Teacher	Water and carbon dioxide, but I already had those. The lactic acid is different.
22.	Student	White muscle fibre.
23.	Teacher	Yes, and where do we put that? The white muscle fibre?
24.	Student	Err, near muscle cell.
25.	Student	On the right [side of the concept map], with anaerobic [respiration].
26.	Teacher	With anaerobic [respiration], white [muscle fibres]. So you might say: [anaerobic respiration] happens most in white [muscle fibres]. Okay, and then?
27.	Nicole:	So this is in white [muscle cells]?
28.	Karin:	Yes, we still have to do that as well.
29.	Student	There's also the marathon runner and the sprint runner.
30.	Teacher	Where did you put the marathon runner?
31.	Student	Above aerobic [respiration].
32.	Teacher	That's right; the marathon runner mainly has aerobic [respiration].
33.	Student	And anaerobic [respiration] is [for the] sprint runner.

34.	Teacher	And so the sprint runner, he mainly has anaerobic [respiration].

The concept maps shown in figures 6.9 and 6.10 are examples of concept maps from students in case study β1 and β2 (respectively) that included most of the conceptual elements.

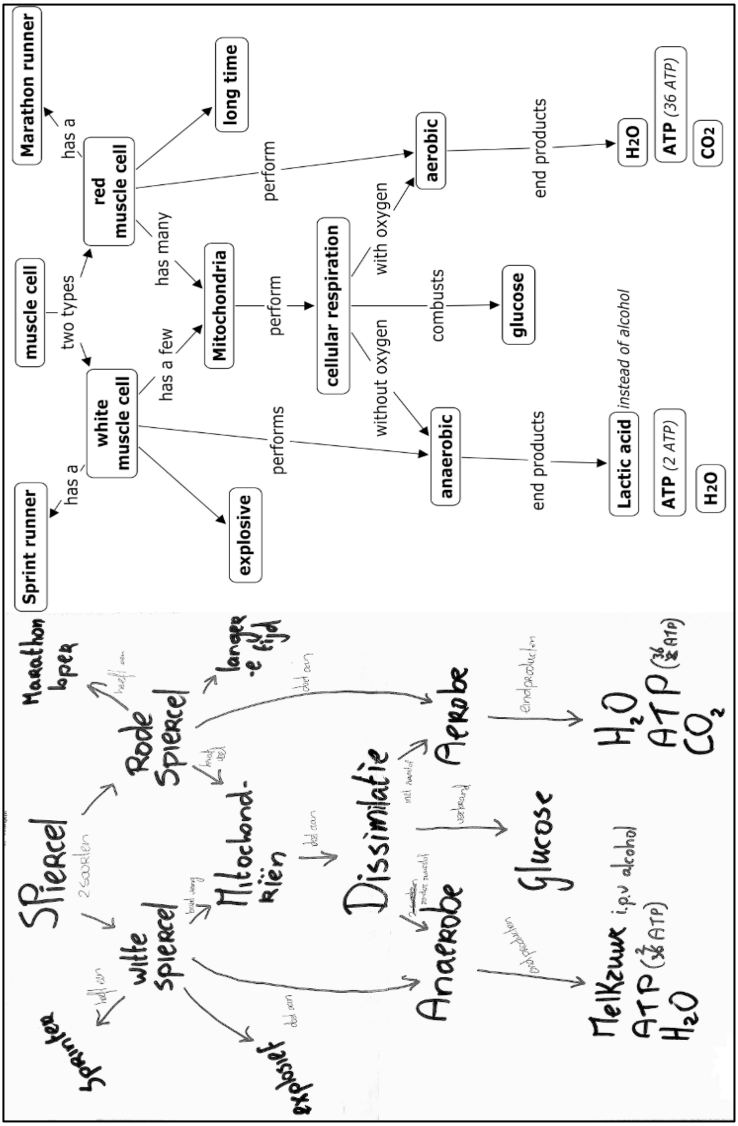


Figure 6.9. A concept map describing cellular respiration in muscle cells (CR_5), made by 3 students (Karel, Anton, and Simon) in case β1 during episode 15.

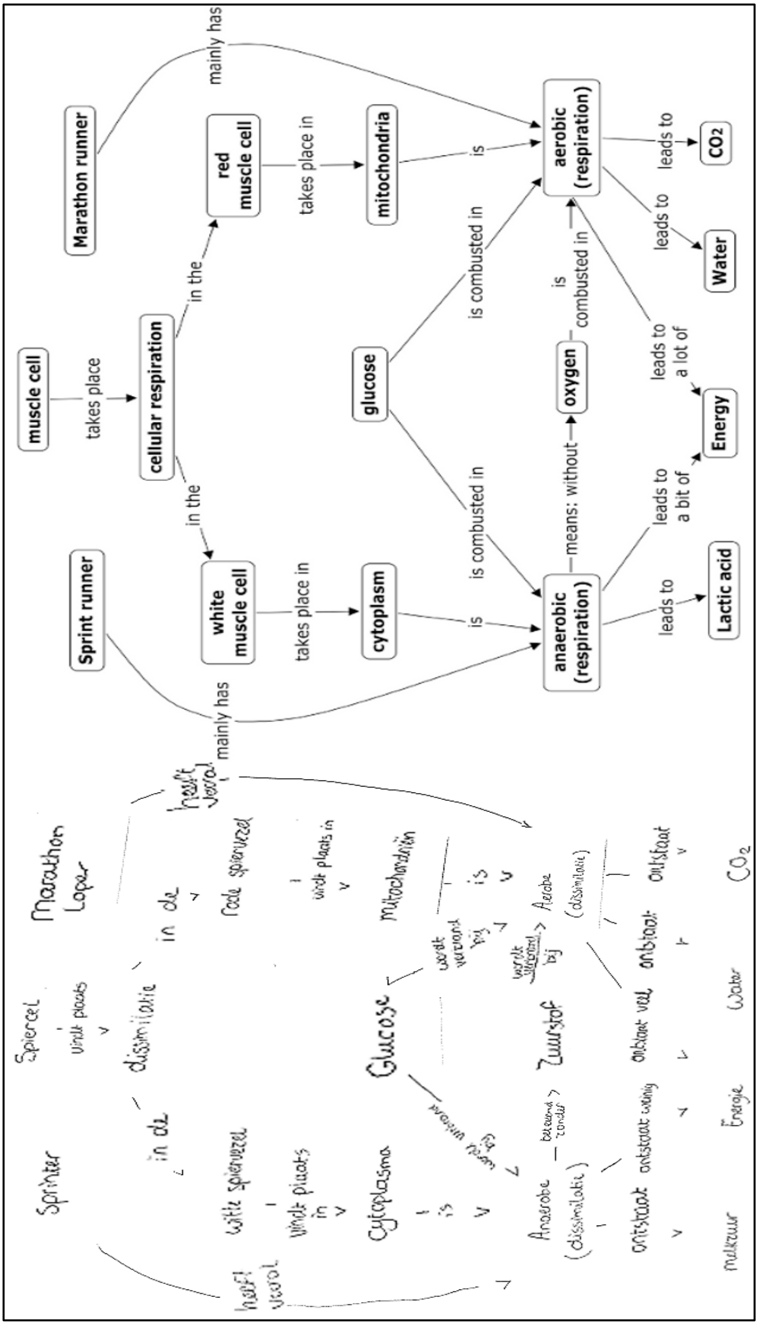


Figure 6.10. A concept map describing cellular respiration in muscle cells (CR_5), made by 1 student (Miranda) in case β2 during episode 15.

The results for all concept maps made by students during these LT-activities in both case studies are shown in tables 6.9 and 6.10. The numbers indicate the number of concept maps (and students involved in the construction of these) that correctly included a conceptual element (table 6.9), and used the element to set aerobic respiration apart from anaerobic respiration (table 6.10).

Table 6.9
Total number of sports physiology concept maps (CR5) that correctly included a conceptual element for cellular respiration (no. cmaps with element). No. students = the number of students that participated in the construction of those concept maps that correctly included a conceptual element.

Case		Conceptual elements A energy	B substrate	C oxygen	D products	E mitochondria	F speed
β1	No. cmaps (n=6) with element	6	6	6	5	6	1
	No. students (n=21)	21	21	21	17	21	3
β2	No. cmaps (n=13) with element	13	13	12	13	8	2
	No. students (n=19)	19	19	17	19	14	4

Table 6.10
Total number of sports physiology concept maps (CR5) that correctly differentiated between aerobic and anaerobic respiration for a conceptual element (no. cmaps with element). No. students = the number of students that participated in the construction of those concept maps that correctly included a conceptual element.

Case		Conceptual elements *(aerobic vs. anaerobic respiration)* A energy	C oxygen	D products	E mitochondria	F speed
β1	No. cmaps (n=6) with element	6	6	5	5	1
	No. students (n=21)	*21*	*21*	*17*	*18*	*3*
β2	No. Cmaps (n=13) with element	12	10	13	7	2
	No. students (n=19)	*17*	*15*	*19*	*11*	*4*

Note. Element B is not included in this table, because it did not differentiate between aerobic and anaerobic respiration.

Judging by the results in tables 6.9 and 6.10, the concept maps in figures 6.9 and 6.10 can be considered exemplary for most of the concept maps from case study β1 and about half for case study β2. Possibly as a result from the combined introduction of elements E and F, most students in case study β2 did not include the second of these two elements in their concept maps to correctly distinguish aerobic from anaerobic respiration. In case study β1 a similar small number of students included element F, although most of them did differentiate between aerobic and anaerobic respiration in their concept maps. Judging from the results from these concept-mapping LT-activities, most of the students in both case studies used elements A-E in their concept map during this 15th episode that neared the end of the lesson module.

During case study β1 a similar discussion to the one described in box 6.9 took place before students started construction of their concept maps for describing cellular respiration in muscle cells. This discussion is not described here, because it took place during a previous LT-activity (see the transcript in box 6.7). Transcript 6.10 provides another example of how students in case study β1 tried to tackle this problem. That transcript describes a short discussion between the researcher and three students. The transcript in box 6.9 provided an example of a whole class discussion that took place during episode 15 in case β2. In both case studies, this explicit comparison of CR_4 and CR_5 took place while students were trying to construct their concept maps for CR_5 in small groups, based on those for CR_4. The example in transcript 6.10 shows how three students in case β1 struggled with this during a discussion between them and the researcher.

Box 6.10
Transcript of a discussion between three students and the researcher during episode 15, in case β1

1.	Researcher	When you have a look at your concept map for the biotechnologist and if you'd want to use the same concepts as the sports physiologist, what…?
2.	Rindert	Change yeast cell into muscle cell.
3.	Researcher	Okay, change yeast cell into muscle cell.
4.	Gerko	For the rest it's the same with regard to energy supply.
5.	Researcher	Okay, for the rest it's all the same, no differences.
6.	Gerko	No.
7.	Farid	No, but this is wrong. <points at the group's biotechnology concept map>
8.	Researcher	What is wrong? Is it the concept map for the biotechnologist?

9.	Farid	This one is wrong. <points at an incorrect connection between the labels 'mitochondria' and 'anaerobic respiration' in the group's biotechnology concept map>
10.	Researcher	Why?
11.	Farid	Well this one [anaerobic respiration] doesn't use mitochondria at all.
12.	Gerko	It uses cytoplasm.
13.	Researcher	Anaerobic respiration takes place in the cytoplasm, not in the mitochondria. Well there's a difference. Were there any more differences between aerobic and anaerobic respiration?
14.	Rindert	So, for the rest, it's the same.
15.	Mohammed	What?
16.	Rindert	With regard to energy, anyway.
17.	Gerko	The question about energy.
18.	Researcher	Okay. Were there any more differences between aerobic and anaerobic respiration? When you have a look at the yeast cell, what other differences were there?
19.	Farid	Aerobic [respiration] has more oxygen, no: produces oxygen, no: gets oxygen. And anaerobic [respiration] doesn't. And that [anaerobic respiration] yields alcohol and that [aerobic respiration] doesn't.
20.	Rindert	The product that comes out of it is different. Alcohol and CO2, and the other one [aerobic respiration]: CO2.
21.	Researcher	When you have a look at the concept map for biotechnologist, what if you put the products over there as well?
22.	Farid	Then you'd come a long way.
23.	Researcher	So do other things need changing?
24.	Farid	I think so, yes.
25.	Researcher	Why?
26.	Farid	Well, I don't think it [the muscle cell] produces alcohol.
27.	Gerko	No, I don't think so either.
28.	Researcher	What doesn't?
29.	Farid	Well, the muscle cell.
30.	Researcher	The muscle cell doesn't produce any alcohol.
31.	Farid	No, that would be something.
32.	Researcher	What would happen then?
33.	Rindert	Then driving a car would become very difficult.
34.	Researcher	Yes, it might.
35.	Rindert	If you produce that much alcohol.
36.	Researcher	Maybe that's something to think about.
37.	Farid	Alcohol is actually poisonous to your body.
38.	Researcher	It actually is, yes.

39.	Farid	So that sure isn't, that's just illogical.
40.	Rindert	Then you're liver would be destroyed.
41.	Researcher	Okay, so?
42.	Gerko	They always say that yeast cells produce alcohol. I don't think muscle cells would do so.
43.	Researcher	So with your knowledge on the yeast cell, can you use that to say something about the muscle cell?
44.	Farid	Yes, you can. Although the products are actually different.
45.	Researcher	The products are different.
46.	Mohammed	Yes.
47.	Researcher	But a muscle cell will probably…
48.	Mohammed	…produce CO2.
49.	Farid	Yes.
50.	Mohammed	You also breathe that out again, so.
51.	Researcher	Yes. And do you breathe that out because the muscle cell is doing aerobic- or anaerobic respiration?
52.	Rindert	Both, I would think.
53.	Researcher	Both?
54.	Rindert	I don't think that you, well… We are not trained for one thing, so then I wonder if you have one or both.
55.	Researcher	But why would a muscle cell use anaerobic respiration?
56.	Farid	Well, because aerobic [respiration] would give you more time, but nothing in the beginning.
57.	Gerko	Well, nothing…
58.	Farid	A little bit. But you do get energy the whole time, for more time. And with aerobic [respiration], in the beginning you'd get…
59.	Rindert	Anaerobic [respiration].
60.	Farid	Okay, it's anaerobic [respiration].
61.	Researcher	Ok, so do you mean it to be the other way around? So when you said anaerobic [respiration], you actually meant aerobic [respiration]?
62.	Farid	Yes. And with anaerobic it's <unintelligible>.
63.	Researcher	Okay, so it would by handy if it could use anaerobic respiration, the muscle cell?
64.	Farid	Yes and the white muscle cells use anaerobic [respiration] and the red ae… Oh, now I'm getting confused.
65.	Rindert	But not with an untrained person, then it would be sort of an equal part for both?
66.	Researcher	It probably is to some extent.
67.	Rindert	Not that the one has so much more than we saw in that picture, right? <refers to a microscopic photograph of red and white

		muscle cells in the LT-materials>
68.	Researcher	Yes, there are red and white muscle fibres in your muscles of course. So with anaerobic respiration you have an explanation for the fast supply of energy that a sprint runner needs.
69.	Farid	And that is?
70.	Researcher	Right?
71.	Farid	No.
72.	Researcher	Okay, so we have cellular respiration: glucose is broken down, which yields alcohol and carbon dioxide.
73.	Rindert	Yes, that is still a problem. The product. We're only sure about CO2, that it's there.
74.	Researcher	CO2, you're sure about that. Why?
75.	Rindert	Everyone breathes out CO2 and uses O2.

The discussion in box 6.10 provides a good example of the intended comparison of CR_4 and CR_5 in the LT-strategy. Similar discussions took place in both case studies in other students groups, both with the researcher and the teacher. The first few remarks indicate that the students did not seem to have any trouble simply copying their biotechnology concept map for cellular respiration in yeast. However, Farid identified a mistake in their biotechnology concept map upon closer inspection: the mitochondria did not differentiate correctly between aerobic and anaerobic respiration (box 6.10; remark 7). They soon corrected this problem and moved on to encounter another one: the production of alcohol. As expected, they quickly drew the conclusion that alcoholic fermentation is not suitable for human physiology. Since they did not know of other kinds of fermentation, Farid and Mohammed concluded that it must be carbon dioxide.

Although the students in this episode did not guess at a number of different possible products like the students in case study β2 (see box 6.9), in both cases they could not be expected to come up with lactic acid fermentation on their own. This problem was not solved during the discussion in box 6.10. Instead, the three students asked the teacher for an explanation directly after this discussion, which he provided. The final part of this discussion shows how the students struggled with the differences in speed between aerobic and anaerobic respiration and the effects of those differences on the amount of energy or carbon dioxide produced. This struggle is similar to the previously described episodes in box 6.7 and box 6.9.

CR_n: Discussing other possible uses for cellular respiration (episode 19)

In case study β1, episode 18 was the last phase before students were allowed to prepare for and do the recontextualising test. This phase consisted primarily of a discussion intended for a complete description of the original problem in sports physiology with the related explanations. Episode 18 took a similar form in case study β2 as in case study β1. These discussions are not presented here, for they can be considered similar to the discussions that have already been discussed and presented in boxes 6.7 through 6.10.

Although this was the final lesson for the students in case study β1 (except for the recontextualising-test and post-test concept mapping assignment), the LT-strategy in case study β2 included one additional episode (no. 19) that took place after they had reflected on and solved the original problem by stepping back along the different levels of biological organisation. Two examples are taken from the whole class discussion here; their transcripts are presented in boxes 6.11 and 6.12. The first example (box 6.11) is a discussion between two students (Sandra and another student). The discussion illustrates how most students struggled with trying to think of other possible practices where cellular respiration could be needed. It appears that they tried to connect the element of energy (A) to other examples where organisms might need energy.

Box 6.11
Transcript of a discussion between two students and the researcher during episode 19, in case β2.

1.	Researcher	Can I interrupt you for a minute?
2.	Sandra	Sure.
3.	Researcher	I see that you already wrote some things down.
4.	Sandra	Yes.
5.	Researcher	So, there I can see something like: bacteria, intestinal bacteria. Goat, fungi and cow. So you've written down all kinds of organisms that had something to do with cellular respiration?
6.	Sandra	Yes.
7.	Researcher	Can you go by them one at a time and tell me how, what you think of with these?
8.	Sandra	Well, with the goat and the cow we thought of…
9.	Student	…milk production.
10.	Sandra	Yes. They eat grass and then milk comes out.
11.	Researcher	They eat grass and then milk comes out. What does that have to do with cellular respiration?

12.	Sandra	Well, there's glucose in the grass. So, it turns that into energy. And with that energy it can produce milk again.
13.	Researcher	Okay, that's clear. So that was the cow, it produces…
14.	Sandra	And fungi, that's the same as in yeast cells. They have to, well; they need energy to proliferate.
15.	Researcher	Yes, just like yeast cell. They need to be able to live and proliferate and that requires energy.
16.	Sandra	Yes, and it's the same with bacteria. They need to proliferate as well.
17.	Researcher	And it's the same with bacteria as well. And what about the goat?
18.	Sandra	That's the same as with the cow. It also eats grass with glucose.
19.	Researcher	And what can you tell me about, for example with a cow or with fungi, who or what kind of people would really need knowledge of cellular respiration?
20.	Sandra	Well, with fungi: a biologist of course. With a cow and a goat: I don't know.
21.	Researcher	You have no idea who would need to know something about cellular respiration in the cells of a cow or a goat?
22.	Sandra	Well, maybe the milkman.
23.	Researcher	Maybe the milkman?
24.	Sandra	Yes, or the biotechnologist or the biologist.
25.	Researcher	And why the biologist or the biotechnologist?
26.	Sandra	Because they do research on it.
27.	Researcher	Okay, they do research on that.

Similar discussions took place among most other student groups during the first part of this LT-activity. This illustrates how many students struggled with trying to think of examples where cellular respiration might be applicable. However, one of the groups came up with an idea to study methane fermentation in cows' manure (in a dung hill). The teacher picked up on this idea and later asked these students to explain their idea to the rest of the class. The transcript in box 6.12 starts after the teacher had asked them to share their idea with the rest of the class, and the short commotion that arose when Remco mentioned that he had thought a dung hill.

Box 6.12
Transcript of a part of episode 19, in case β2

1.	Teacher	Bart, I heard you mention a good example. Would like to share that?

2.	Bart	A dung hill. It had, with bacteria. Bacteria.
3.	Student	Aren't those fungi?
4.	Teacher	Okay, so what's in the dung hill?
5.	Bart	Bacteria. And no oxygen.
6.	Remco	And that's what you put in your bread? <laughs>
7.	Teacher	Okay, so if you have a look at the blackboard. I've summarised it again for you there. There's breakdown of glucose, so what is cellular respiration? The breakdown of glucose. Well, you can do that with oxygen, we know that from humans. The lower two [formulas], [apply] when glucose is broken down in, for example: a dung hill. That dung contains a lot of organic substances. Not only glucose, but other substances as well. So those are broken down. Those are broken down. In that dung hill is very little oxygen, but the dung does become smaller and smaller. It becomes smaller because of the organisms that live in there. What organisms are those? Bart?
8.	Bart	Err, glucose?
9.	Teacher	No, what kind of organisms are those?
10.	Student	Intestines.
11.	Teacher	What organisms do that: breaking down?
12.	Student	<unintelligible>
13.	Teacher	Bacteria, yes. And who has use for the knowledge that bacteria break down glucose? Who has use for that?
14.	Bart	A farmer.
15.	Teacher	A farmer, why?
16.	Bart	So the dung hill doesn't get too big.
17.	Teacher	Well, for example, yes.
18.	Student	A lot of nutrients come in and then <unintelligible> dung hill.
19.	Teacher	A lot of nutrients come in, can you explain that?
20.	Student	Yes. When you… Well, you have this dung hill. Normally it's underneath the stables, right?
21.	Teacher	Yes?
22.	Student	So then <unintelligible> some kind of combustion or something. Then certain substances are released.
23.	Teacher	Yes.
24.	Student	<unintelligible> a certain odour.
25.	Teacher	Yes, then what substances are released?
26.	Michiel	Methane.
27.	Teacher	Where does that come from, the methane?
28.	Michiel	From their anus.
29.	Teacher	No, we're talking about that dung hill. Where does methane gas come from?

30.	Michiel	From the cow, how would I know? From the dung.
31.	Student	From the…
32.	Michiel	It seems that that from cows, that it's very bad for the environment.
33.	Students	<rumour>
34.	Michiel	Because those cows are destroying the ozone layer with their farts.
35.	Remco	Yeah.
36.	Students	<rumour>
37.	Remco	Think about the grass
38.	Teacher	So, just to make sure that everyone gets your reasoning. So we have that dung hill, and there are bacteria in there. Those do not get a lot of oxygen, so what kind of cellular respiration is this?
39.	Remco	Anaerobic [respiration].
40.	Teacher	Anaerobic respiration. Does it yield lactic acid here? Does it yield alcohol?
41.	Remco	Yes.
42.	Teacher	<laughs> So there's alcohol in a dung hill? Sure. But what does it yield here?
43.	Student	Glucose.
44.	Anouk	That gas. Methane gas.
45.	Teacher	A gas, the methane gas. So this is again another kind of cellular respiration. Well, that would be useful for a farmer to know, for example. Michiel?
46.	Michiel	<unintelligible> fungi then?
47.	Teacher	That's right. What does that fungus do with it?
48.	Michiel	It makes it [the dung hill] smaller. It eats the glucose from the manure.
49.	Teacher	Yes that's right. So that works together. Would that produce gasses as well?
50.	Michiel	What?
51.	Teacher	The fungus.
52.	Michiel	Yes.
53.	Teacher	And yeast is a fungus as well, right?
54.	Michiel	Yes.
55.	Teacher	So, it too can use aerobic and anaerobic respiration. And that's cellular respiration as well, right? A fungus uses cellular respiration as well. Michiel, you also had an example, would you like to share it with us?
56.	Michiel	Yes, when a cow farts. But that's about the same, right?
57.	Teacher	Yes, but would you like to repeat it? What organisms do that and where are those organisms?
58.	Michiel	Well, a cow farts sometimes. Those are gasses. Methane gas. Those come from the large intestine

		because bacteria are busy combusting.
59.	Teacher	So, there are bacteria in the large intestine. Then what are they breaking down, those bacteria?
60.	Michiel	Well, the food and stuff. That remains.
61.	Teacher	Yes the remains of the food in the large intestine. And do they do it with or without oxygen?
62.	Michiel	Without oxygen.
63.	Teacher	Without oxygen. So what is that called?
64.	Michiel	Anaerobic [respiration].
65.	Teacher	Anaerobic respiration. So I could write another one down here [on the blackboard]. Apparently, glucose can also be broken down so that it yields methane gas.

This example indicates that, although many students did find it very hard to think of other uses for the concept of cellular respiration, some of them were able to do so. These students (who also had a very active role during a large part of the LT-activities in during the previous lessons) illustrate that they had enough understanding of cellular respiration to be able to recognise it in another context and recontextualise the concept. However, the example in box 6.11 illustrates that most students did not, providing a reason to doubt the usefulness of such an LT-activity at this time. In retrospect, it probably would have been better to first introduce students to other examples for cellular respiration in other contexts first. This could have been done by using the recontextualising-test as a means for formative assessment as well, instead of it mainly summative function during case studies β1 and β2. The contexts in this test provide students with example problems where they practice their understanding of cellular respiration. By discussing the results (students answers) after this test, the students would have been given extra possibilities for recontextualising the concept, as well comparing its use in these different contexts. This might have been easier for students, because it would not require students to think of examples from other contexts by themselves. Episode 19 could then follow the reflection on and discussion of the recontextualising-test.

Finally, both examples also illustrate that students were not prompted to think of other social *practices or contexts* when trying to find other contexts for cellular respiration. They appeared instead to think of other organisms or biological objects in which they might recognise one of conceptual elements that they were now more or less familiar with. Although these examples are too few to allow for any definitive conclusions, this idea of the biological object that is focused on in a context might be an important step in recontextualising cellular respiration.

The following part of this section describes the results from the post-test. Although this test took place after the recontextualising-test, it is used to provide an answer to RQ III-a at the end of this section. Therefore, the results from the post-test concept mapping assignments are discussed here.

The post-test: concept-maps

The final results from the second design research cycle come from the post-test. This test was not included in case study β1, for reasons of incompatibility with the school's timetable (see also chapter 2). However, the results from the concept maps made by those students during episodes 14 and 15 also provide an indication, as do students' written answers to test items 2 and 3 in the recontextualising-test. These will be further discussed in the following section (6.5) that compares the results from the pre- / post-test and the recontextualising-test with the implementation of the LT-activities in the lesson module.

The results from the pre-test have already been described in section 6.1, and included an indication for the reliability of the coding scheme used for all concept maps. With the exception of element 'B', the codes A-F were identified as used correctly in students' concept maps with an acceptable reliability. Moving on to the results for the post-test in case study β2, tables 6.11 and 6.12 indicate the number of students that correctly included a conceptual element in their concept maps (table 6.11), and whether or not they also used these correctly to differentiate between aerobic and anaerobic respiration (table 6.12).

Table 6.11
Conceptual elements correctly used in the post-test concept maps made by students in case study β2.

Case		Conceptual elements correctly included A energy	B substrate	C oxygen	D products	E mitochondria	F speed
β2	# Cmaps (n=23) with element	21	18	23	1	19	3

A comparison of these results with the pre-test (see section 6.1, tables 6.3 and 6.4) reveals an important as well as expected difference between the two: the greater number of students that correctly used conceptual elements to make distinctions between aerobic and anaerobic respiration. In addition, all of the students correctly connected the labels for aerobic and anaerobic respiration in their concept maps. This is off course to be expected of a series of lessons focusing on the conceptual development of aerobic and anaerobic respiration.

Table 6.12

Conceptual elements correctly used to differentiate between aerobic and anaerobic respiration in the post-test concept maps made by students in case study β2.

		Conceptual elements *(aerobic vs. anaerobic respiration)*				
Case		**A energy**	**C oxygen**	**D products**	**E mitochondria**	**F speed**
β2	# Cmaps (n=23) with element	17	23	1	13	3

Note. Element B is not included in this table, because it did not differentiate between aerobic and anaerobic respiration.

A closer look at the results reveals that most students had no trouble distinguishing the amount of energy released in the two processes from each other (A) or their need for oxygen (C). In contrast to the pre-test in this case, the post-test concept mapping assignment did not include the label 'carbon dioxide'. The lack of this label resulted in only 1 student out of 23 describing any products for cellular respiration. However, the results from biotechnology and sports physiology concept maps (episodes 14 and 15) indicate that most students were able to distinguish the products in aerobic from the products in anaerobic respiration in their concept maps. This indicates that the students did not include this element in their concept maps, simply because the label was not prescribed and not because they would not have been able to do so.

Overall, the analysis of concept maps and label descriptions provides the indication that students managed to describe and distinguish aerobic from anaerobic respiration after participating in the lesson module and finishing the recontextualising-test. However, they did tend to include only those elements in their concept maps that are prescribed in the assignment and not to include too many on their own. In a sense, the results show us the high level of context (setting)-dependence of students' use of conceptual elements in a concept-map. By themselves, the results from this post-test concept-mapping cannot give a clear indication of students' conceptions of cellular respiration or their ability to recontextualise these. Therefore, the following section compares the results from the pre- and post-tests with those from the recontextualising-test and the implemented learning trajectories in case studies β1 and β2.

Students' conceptual development during the lesson module

For an answer to RQ III-a, the implemented learning trajectories and students' performance in the pre- and post-test can be combined, as well as the results from test-items 2 and 3 in the recontextualising-test (see section 6.2), which did not require any recontextualising. The description of implemented learning trajectories in both case studies indicates that students were inclined to find an answer for the questions posed during the initial orientation on a sports physiology context. By focusing on the energy-need in a cell and the idea (from prior knowledge) that cellular respiration is responsible for providing this energy, they were inclined to find out more. Students in both cases also did not have much trouble with stepping over to a biological research context and selecting a suitable model organism for a classroom experiment.

Students' explication of CR_2, which had been intended in the LT-activities leading to their final selection for yeast as a suitable model-organism, was limited to short, whole class discussions and not clearly described by students in their workbooks. Despite this, they seemed to have no trouble with the idea of using other organisms and even bring up the idea themselves during discussions on where the knowledge from sports physiologists might come from. After having selected yeast, they easily moved on to yet again another context and developed CR_3 to include anaerobic respiration in their understanding of the concept. As far as students' development of cellular respiration is concerned, there did not seem to be much trouble for them up until this point. The results from students' concept maps from the LT-activities in episodes 14 and 15 indicate that almost all of them were able to use elements A-D in their concept maps, and most of them used these to distinguish aerobic from anaerobic respiration. The results from the pre- and post-test provide similar indications, with the added observation that when not prompted to include an element with a prescribed label, most students did not include it in their concept maps.

The subsequent introduction of the element speed (F) during the classroom experiment and the following discussions did not lead to the intended use in their concept maps. However, the whole class discussions show that students did use it to answer the questions from sports physiology that guided their learning trajectories. They did have quite some trouble with separating a difference in speed between the two chemical processes from differences of speed at the organism level of biological organisation (i.e. performance-speed in athletes). This is apparent from whole class discussions on this topic, but also from many of the answers students' provided in response to test-item 3 in the recontextualising-test (see section 6.3, context 2). However, a minority of the students correctly used element F in their answer to this item (4 students in case β1; 11 in case β2), although quite a lot of others did try to do so but failed. In conclusion, we can say that most students had developed some idea of the differences in speed between the two processes, but found it hard to relate these differences directly to cellular respiration. A new version of the LT-strategy for cellular respiration developed in this project should therefore include additional LT-activities during episodes 14 and 15 to discuss how the problems in both contexts are solved differently, but both include the difference in speed.

The difference between aerobic and anaerobic respiration in element (E) was finally introduced during episode 15, although this had already taken place earlier in case β1. The concept maps that the students had produced during the post-test in case β2 indicate that students did not appear to have too much trouble with this element E. The results from recontextualising test-item 3 show that roughly half of the students correctly included the element in an answer, allowing for a conclusion that at least half of the students had correctly understood the differences in the need for mitochondria between aerobic and anaerobic respiration.

An answer to RQ III-a

In conclusion, most students can be considered to have developed a conception for cellular respiration that correctly included elements A-D. co Roughly half of the students in both case studies did correctly understand the need for mitochondria in aerobic respiration. As for the difference in speed; most the students did remember its significance, but did not connect it directly to the process at the cellular level of biological organisation. Finally, only three students in case study β2 managed to include correct indications of a conceptual core in their answers to item 3 in the recontextualising-test (which is explained in the following section).

6.2 The recontextualising-test: using cellular respiration in other contexts

A few days after finishing the final lesson (storyline-phase 18 in case β1; phase 19 in case β2), the students in both cases took part in a recontextualising-test. A total of 20 students took the test in case study β1; in case β2 this number was 24. The recontextualising test was designed to test students' ability to recontextualise their understanding of cellular respiration for solving problems in other contexts. It consisted of 9 (case β1) or 11 (case β2) items, distributed along 5 (β1) or 6 (β2) contexts.

The contexts and items in this test have been described in chapter 2 and are summarised in table 2.5. A detailed description of all items in this test is provided in appendix I. Also included in table 2.5 are the conceptual elements needed for a complete and correct answer to each of the items.

Validation of test items

Chapter 2 of this thesis describes how the test-items were designed during the first design-research cycle and redesigned based on students' written answers during those case studies. Items 10 and 11 are an exception to this; these two items (context 6) were designed during case β1 and added to the test in case β2. During case β1, the context was described to three students in a final interview after the recontextualising-test and they were asked to explain chronic fatigue symptoms in patients with dysfunctioning mitochondria. Their answers were taken into account in the design of items 10 and 11 in context 6. Moreover, all items in the recontextualising-test were discussed with experts in biology education and – if necessary – redesigned according to the outcomes of these discussions.

For further validation of the test items, other experienced teachers and research experts in (biology) education were asked to provide their thoughts on and rate the difficulty of the test-items. This was done via a web-based questionnaire which presented a short summary of the information on cellular respiration and the contexts that were introduced during the lesson module, in the form of a concept map for the concept and a short description of the contexts involved. The experts were asked to rate the difficulty for each of the items on a 5-point Likert-scale (1 = very easy; 5 = very difficult). In addition, they were asked to rate the difficulty for the entire test on the same scale.

Fourteen experienced researchers and teacher educators were repeatedly asked to rate the questions in this test and to redistribute the request within their network of experienced biology teachers. During the five months that the questionnaire was online, five teachers and teacher educators managed to respond. Despite this small number of respondents, these experts' ratings are valuable as an extra validation of the difficulty of the test items. Table 6.13 shows the ratings given by each of the five respondents to all items, including an indication of the total difficulty for the test. These difficulty ratings for the complete test were provided by the respondents, they are not an average of respondents' scores across all items in the test. In addition to rating the items and tests, the experts were given the opportunity to provide written comments to the test and its items. These comments illustrate the difficulty in developing such items. For example: where one expert noted an increased difficulty of the test items due to an insufficient description of contexts, another noted long context descriptions as a cause for increased difficulty. Although the experts' rating of the difficulty of the items differed greatly for some items, the ratings indicate that no items were too difficult or too easy for this level of education.

Items 7 and 10 were rated as the most difficult by three of the five experts, although the ratings from the experts still differed strongly for these items. These two items related to contexts where students had to explain a lack of aerobic respiration in lactic acid bacteria (context 4) and in the cells of patients suffering from dysfunctioning mitochondria and chronic fatigue (context 6). This was in line with the expected difficulty for the test-items; only a few students in the case studies (α1 and α2) of the first design-research cycle had been able to answer the two questions in this context correctly.

Context 6 (items 10 and 11) was added to find out if there would be any difference in students' performance when confronted with similar questions, but related to a different context and a different, but more familiar biological object (human cells). In conclusion, it is safe to say that the items in the recontextualising-test had an acceptable level of difficulty for a test at this level of secondary biology education.

Table 6.13

Difficulty rating of the items in the recontextualising-test, according to five biology education experts. The experts rated the items according to difficulty on a scale from 1 (very easy) to 5 (very difficult). The first rows show each respondent's current type of employment, followed by the number of years of teaching experience in general and at the level of pre-higher vocational education (HAVO).

		Resp. 1	**Resp. 2**	**Resp. 3**	**Resp. 4**	**Resp. 5**
		Education researcher & teacher	Education researcher & teacher educator	Education researcher & teacher educator	Biology teacher	Biology teacher
Teaching experience						
No. of years teaching experience.		6	12	29	5	7
No. of years teaching experience with general secondary education (HAVO).		5	0	23	1	5
Difficulty ratings for the recontextualising-test items						
Complete test		**3**	**3**	**3**	**3**	**5**
Context no.	**Item no.**					
1	**1**	2	3	2	4	2
2	**2**	2	3	2	3	3
	3	2	3	3	3	5
3	**4**	3	2	3	2	2
	5	3	2	2	2	3
4	**6**	4	2	2	3	4
	7	2	4	3	4	1
5	**8**	3	3	3	3	4
	9	3	4	2	3	3
6	**10**	4	3	4	2	1
	11	3	4	3	2	2

Judging answers as proof of recontextualising

Students' written answers to the recontextualising-test were analysed according to a coding scheme for identifying the conceptual elements that were correctly used in an answer. The results from this analysis and the analysis of the reliability of this coding scheme are provided in the following subsections. Before moving on to those, some issues with judging the correctness of these answers are briefly discussed here.

For judging the correctness of an answer and whether or not it indicated proof of successful recontextualising, not all conceptual elements that were indicated for an ideal answer (see table 2.5) needed to be included for an answer to be judged as proof of recontextualising. Previous versions of the test in the first design cycle (cases α1 and α2) had already indicated that the written answers from most students were not as elaborate as was hoped, despite the fact that the items explicitly invited students to describe their reasoning as thoroughly as possible. Moreover, for items 1 and 11, some students' answers did not even provide an explanation for the choice that was made between an aerobic and anaerobic environment. Therefore, it was needed to determine which conceptual elements were needed to provide proof of successful recontextualising by a student. Therefore, the elements that were needed to indicate recontextualising differ from those in table 2.5, and are included in the description of the results further on in this section. Finally, the written answers that were judged as correct and also included an explanation using the needed element correctly were interpreted as proof of successful recontextualising by a student for a given item.

Element B was not included in the coding scheme because it did not differentiate between aerobic and anaerobic respiration and was not needed to provide a minimal answer to any of the test-items. However, table 2.5 (see chapter 2) does indicate the need for this element in an ideal answer for items 1, 8, and 9, but in all these cases it is required in a correct description for the conceptual core of the concept. Instead, whether or not a conceptual core was correctly indicated in an answer was included in the coding scheme ('core' in table 5.13). For example, test-item 1 (context 1) asked students to choose between an aerobic and an anaerobic environment for the production (replication) of yeast. It also mentioned the fact that yeast requires a large amount of energy to replicate. Ideally, an answer would have included all three elements A+B and D and combined these into a conceptual core for the concept: the amount of energy released in relation to a complete and a partial breakdown of the substrate (in this case: glucose). However, most students' answers did not explicitly describe this conceptual core, and only mentioned differences in the amount of energy released or the products that are involved in aerobic and anaerobic respiration. Moreover, not even the mentioning of all three elements (A, B, and D) was enough for an answer to be judged as describing the conceptual core. For example, the following two descriptions of aerobic respiration were made by two students in cases β1 and β2. Both descriptions are taken from their answers to the same item in the recontextualising-test (no. 1, see the description of recontextualising-test items further on in this section) and only contain that part of each answer that describes cellular respiration:

Rindert (case study β1): *"[…] this [oxygen-rich environment] results in aerobic cellular respiration, which results in a lot of ATP per particle. In aerobic cellular respiration, for example, C6 is combusted to 6 x C. With anaerobic cellular respiration, a C6 particle [is broken down] to 3 x C2, so [it releases] less ATP as well. […]"*

Merel (case study β2): *"[…] this reaction [aerobic respiration] requires glucose and oxygen as combustion-products, from which water, carbon dioxide, and a lot of energy are formed. […]"*

Both descriptions are correct descriptions of aerobic cellular respiration and include elements A, B, and D. However the first one (Rindert's) clearly shows that he uses the idea of the molecular breakdown of glucose to describe why the aerobic process releases more energy than the anaerobic process. Merel's answer also correctly describes the substances involved in aerobic cellular respiration, but her answer does not provide any clue as to why this large amount of energy is released. Thus, while both descriptions apparently make use of the elements A, B, and D, only Rindert's description links them together to the core idea of molecular breakdown. In the end, only a few students' answers provided indications of the use of this conceptual core. However, far more answers did include the larger amount of energy released in aerobic respiration (element A) with a correct choice for an aerobic environment for the production of yeast. Because of the observation that many students only provided minimal answers, this type of answers (i.e.: choose aerobic environment and include element A) was also judged to be proof of recontextualising by a student for this item.

Another problem came to light during the analysis: element C (oxygen requirement) was not explicitly mentioned in most of the written answers from students, but implied in many. While ideal answers for many test-questions did include this element, it was explicated in only a few answers. For instance, the first test item requires students to choose between an ‘oxygen-rich’ and ‘oxygen-poor’ environment for breeding yeast. An ideal answer should include the idea that yeast can only perform aerobic cellular respiration in an oxygen-rich environment. While many students’ answers did include the terms ‘aerobic’ and ‘anaerobic’, they did not emphasise the oxygen requirement, which is needed to explain the greater occurrence of aerobic cellular respiration in an aerobic or ‘oxygen-rich’ environment. This is no surprise since the terms ‘aerobic’ and ‘anaerobic’ have two different meanings or uses in biological practices: they are used in describing environmental oxygen-levels, but also in labelling or categorising cellular respiration processes according to their oxygen requirement. Therefore, answers that did not include this element, but did correctly include the other element(s) needed in a correct answer to a question, were accepted as proof of successful recontextualising.

Finally, there was no need for determining a correct answer with respect to items 2 and 3 in the test (context 2). These involved the context of sports physiology, now expected to be very familiar to the students. These two items were included in the test to see which of the conceptual elements students would use in their description of the information from the lesson module. These results can be used to indicate which of these elements students had included in their understanding of cellular respiration for this context. Because these were not meant for recontextualising their understanding of cellular respiration in these two items, no indication of whether or not an answer was correct and proof of successful recontextualising was needed.

Reliability of a coding scheme for the recontextualising-test

The coding scheme that was developed for the analysis of students’ written answers to the test-items was based on the identification of conceptual elements used in these answers (see chapter 2). This coding scheme was developed during extensive discussions between two researchers who had separately analysed students’ written answers based on a preliminary coding scheme. These discussions served to reach an inter-subjective agreement on the coding scheme and the conceptual elements identified in all written answers. Similar to the re-analysis of the concept maps for judging the reliability of that coding scheme (see chapter 2 and section 6.1), 25% of all students’ written answers to the different test-items were coded again approximately a year after the initial discussions for inter-subjective agreement had taken place. Table 6.14 shows the results of this re-analysis of the data for judging the reliability of the coding scheme for all test-items. It includes the observed proportion of agreement and the related kappa scores (Cohen, 1960) between the two researchers for each element. Because the value of kappa scores is a matter of on-going discussion and any category system for judging kappa scores has a strong subjective component, an indication of the value of the kappa scores is also included in table 6.14.

Table 6.14
Values for observed proportion of agreement ($Pr_{(obs)}$), and Cohen's kappa (kappa) for the analysis of students' answers to recontextualising test items. These values pertain to the correct use of an element in these answers.

	Conceptual elements					
	A energy	**C oxygen**	**D products**	**E mitochondria**	**F speed**	**Core**
$Pr_{(obs)}$	0.91	0.88	0.91	0.98	0.92	0.95
kappa	0.77	0.63	0.78	0.90	0.62	0.68
kappa max	0.82	0.77	0.82	0.96	0.84	0.91
category	*substantial*	*substantial*	*substantial*	*almost perfect*	*substantial*	*substantial*

Note. Element B is not included here, because it did not differentiate between aerobic and anaerobic respiration and was not suitable for indicating successful recontextualising. The values for *category* relate to particular categories for kappa values described by Landis and Koch (1977). The values for *kappa max* represent a theoretical maximum for kappa related to $Pr_{(obs)}$, based on a method from Umesh et al. (1989). These values are based on 25% (N = 111) of all students' answers in the recontextualising-test, across all recontextualising-test items in case studies β1 and β2 (n = 444).

Table entries for *category* are subjective categories for the kappa values based on a category system described by Landis and Koch (1977), and kappa max indicates theoretical maximum values for kappa for the given observed proportions of agreement ($Pr_{(obs)}$), based on a method described by Umesh *et al*. (1989). This second method for judging kappa values is also provided in figure 6.11 (solid line). The dotted line in figure 6.11 is based on another method for determining a theoretical maximum for kappa, also described by Umesh *et al.* (1989) and in section 6.1.

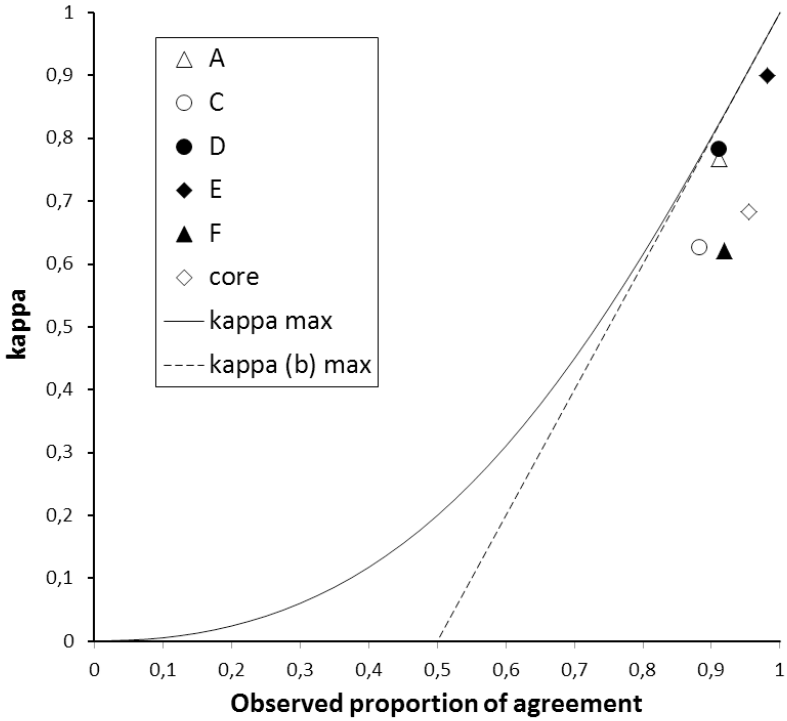


Figure 6.11. Kappa values for the analysis of students' answers to recontextualising-test items in relation to theoretical maximums for kappa. The diagram shows the kappa values (vertical axis) related to the observed proportion of agreement (horizontal axis) for correct inclusion of a conceptual element and the conceptual core (core) in students' answers to the recontextualising-test. These values are based on 25% of all students' answers.

These results (in table 6.14 and figure 6.11) indicate that the coding scheme for identifying the conceptual elements that were correctly used in the recontextualising-test can be judged as reliable when judged across all test-items. The coding schemes used in the analysis differed to some extent between contexts. These differences reflected the expected differences in students' answers based on contextual differences. However, these coding schemes were all based on the identification of the same conceptual elements, and the type of data (written answers to test questions) coded with these was also similar. Therefore, the reliability ratings for these coding schemes could be determined across all contexts and test-items. For an additional indication of the reliability of the analysis of each context-based coding scheme, the kappa values for the elements needed to provide a correct answer to the items in a context are included in the description of students' performance with each context.

Results from the analysis of the recontextualising-test

The results from the identification of conceptual elements in students' written answers to the items in the recontextualising-test are provided in tables 6.15 (case β1) and table 6.16 (case β2).

Table 6.15

Conceptual elements used in students' answers to the items in the recontextualising-test in case β1 (n=20). The numbers in brackets indicate the number of answers that was judged as a correct, and proof of recontextualising. n/a = not applicable; alt. = alternative, correct explanation; Successful recontextualising = the number of students' answers that indicated that a student had successfully recontextualised cellular respiration.

Context	Item no.	Needed elements	Conceptual elements correctly included						Success-ful recontextualising
			A energy	C oxygen	D products	E mito-chondria	F speed	Core	
1	1	(C) + Core *or* (C) + A	10 (9)	9 (6)	2	1	9	2 (2)	*9*
2	2	*All*	4	0	0	2	4	0	*n/a*
	3		16	10	8	9	4	3	
3	4	(C) + D	1	2 (2)	13 (12)	0	2	0	*12*
	5		0	0	15 (10)	0	0	0	*10*
4	6	E	0	1	6	2 (1)	0	0	*1*
	7	A	2 (2)	1	0	0	0	0	*2*
5	8	(C) + Core *or* (C) + D *or* (C)+A *(alt)*	2 (1)	4 (1)	5 (3)	0	3	2 (2)	*5*
	9		0	1	4 (3)	0	5	3 (3)	*5*

Note: Element B is not included in this table, because it did not differentiate between different types of cellular respiration and could not be used to indicate successful recontextualising.

See chapter 2 for a detailed description of the contexts and items in this test; the appendix includes an English translation of these items as they were used in the recontextualising-test.

Table 6.16

Conceptual elements used in students' answers to the items in the recontextualising-test in case β2 (n=24). The numbers in brackets indicate the number of answers that was judged as a correct, and proof of recontextualising. n/a = not applicable; alt. = alternative, correct explanation; Successful recontextualising = the number of students' answers that indicated that a student had successfully recontextualised cellular respiration.

Context	Item no.	Needed elements	Conceptual elements correctly used						*Successful recontextualising*
			A energy	**C oxygen**	**D products**	**E mitochondria**	**F speed**	**Core**	
1	**1**	(C) + Core *or* (C) + A	14 (14)	3 (3)	5	0	5	1 (1)	*14*
2	**2**	*All*	0	1	0	2	2	0	*n/a*
	3		8	8	6	6	10	0	
3	**4**	(C) + D	1	12 (10)	19 (19)	0	8	0	*19*
	5		3	0	13 (13)	1	0	1	*13*
4	**6**	E	0	7	10	8 (7)	0	1	*7*
	7	A	3 (3)	1	0	0	0	0	*3*
5	**8**	(C) + Core *or* (C) + D *or* (C)+A *(alt)*	8 (4)	6 (2)	8 (7)	0	3	0	*10*
	9		6 (2)	1 (1)	9 (6)	0	8	3 (3)	*8*
6	**10**	E	0	1	10	10 (8)	0	1	*8*
	11	A	16 (16)	1	4	3	3	0	*16*

Note: Element B is not included in this table, because it did not differentiate between different types of cellular respiration and could not be used to indicate successful recontextualising.

The numbers under 'conceptual elements' in tables 6.15 and 6.16 indicate the number of students that correctly included a conceptual element in their answer. Tables 6.15 and 6.16 also indicate the conceptual elements that were needed for a correct answer to be judged as proof of recontextualising (column: 'needed elements'). For those elements, the number in brackets indicates the number of answers that was judged as correct. It is possible that students provided a correct answer to a question posed in one of the test-items, without correctly using one of the conceptual elements needed. Finally, the right-hand column in these tables indicates the number of answers that were interpreted as proof of successful recontextualising.

The rest of this section briefly discusses the results for each item individually before finishing with a summary of students' use of conceptual elements in the contexts that were part of the recontextualising-test as an answer to RQ III-b.

Recontextualising-test, context 1: Producing yeast.

The first item briefly described the context of a major Yeast producer, and invited students to choose the best environment (aerobic or anaerobic) for efficiently and effectively producing (replicating) yeast cells, after stating that yeast do require quite a lot of energy to replicate. Two of the students in case β1 provided an answer that gave a clear indication of their understanding of the conceptual core for cellular respiration. Some of students' answers included a correct description of the speed difference between aerobic and anaerobic respiration in their answers. Most students that mentioned this element and also correctly choose an aerobic environment, dismissed speed as an important factor in this context, while the others (2 students in both cases) based their decision on this difference in speed and opted for the faster, anaerobic variant. All answers that correctly stated the difference in energy release (A) or the efficiency of breakdown (core), combined with a correct choice for an anaerobic environment were interpreted as proof of successful recontextualising of cellular respiration. Finally, we can say that 23 out of 44 students in both cases managed to identify the differences in energy release between aerobic and anaerobic respiration as the key element and use it correctly in this context.

Recontextualising-test, context 2: Cellular respiration processes in athletes' muscle cells.

These two items were included as part of the recontextualising-test but were meant to invite students to explain the different cellular respiration processes in athletes' skeletal muscles. In contrast to the other test items, these two items did not require students to recontextualise their understanding of cellular respiration. The results indicate that students used and recognised different combinations of conceptual elements in their explanations, although most of them did not explicate all of the elements, while a complete and precise description should have. These results may indicate that a lot of students had not included a large number of the conceptual elements in their understanding of cellular respiration for this context. However, when looking at the results from the concept-maps made during storyline-phase 15 (see tables 6.9 and 6.10), that may be an incorrect assumption. Those results indicate that most students managed to include elements A-E in their concept maps for sports physiology, although it must be noted that those concept maps were made by students in collaboration, while the recontextualising-test was an individual activity. The results from students' answers to items 2 and 3 in the recontextualising-test are not conclusive as to the elements that students had correctly picked up during the lesson module in the LT-strategy.

Despite this, these results can be used to indicate a minimum number of students that could be expected to explicate an element in any of the other items in the recontextualising test. It should be noted that this will probably be an underestimation of the number of students that had an understanding of these elements.

Recontextualising-test, context 3: Producing Wine.

Item 4

Test item 4 asked students to explain the necessity for producing wine in an anaerobic environment, after providing students with a brief and general description of wine production. As with item 1, the context for this item (and item 5) was related to yeast, an organism already introduced to the students in the lesson module. A majority of the students (31 out of 44) managed to identify the correct element D (alcohol from anaerobic respiration) as the key to their explanation.

Item 5

This item only required students to name the gas, and did not differentiate between aerobic or anaerobic respiration. Therefore, its results cannot provide a clear view of students' understanding or use of element D. But when viewed in conjunction with the answers to the previous item (4) in the same context, we get a better view of students' use of this element. Therefore, any answer correctly stating carbon dioxide (D) as a waste product of the brewing process, was only marked as an indication of correct recontextualising if the same student also showed proper recontextualising in item 4.

Thus, 10 out of 15 correct answers were interpreted as proof of successful recontextualising of cellular respiration to a context of wine production. Summarising the description of items 4 and 5 on wine production, we can say that the majority of students in both cases managed to identify alcoholic fermentation as an explanation of the need for an anaerobic environment in wine production. However, quite a number of those students did have trouble to identify carbon dioxide as a gaseous waste product also released during anaerobic respiration.

Recontextualising-test, context 4: Designing bacteria.
Item 6

Items 6 and 7 posed a greater challenge to students, and involved an explanation of the process of tooth decay with a focus on the idea that it is lactic acid from anaerobic bacteria that feed on glucose and not glucose itself that causes tooth decay. In both cases, students' answers indicated that they still had trouble letting go the everyday idea that glucose or sugar causes tooth decay. This item invited students to provide an explanation for the mouth-dwelling bacteria's inability to break down glucose completely to carbon dioxide and water, instead of a partial breakdown to lactic acid. Given the design of the LT-strategy, it was expected that most students would correctly identify the lack of mitochondria as the key element of cellular respiration needed here. In fact, the teacher in case β1 noted that he would deem this question as to easy, since the key element is stated in the line directly above the question. However, only 1 out of 20 students managed to identify the lack of mitochondria correctly, while in case study β2, 7 out of 24 students managed to do so.

As for the students that did not manage to provide a correct answer to this question, their answers varied greatly and included many different explanations. For example: quite a number of them referred to either a lack of oxygen in the environment for the bacteria (the human mouth), or bacteria's death from a lack of any possibility to cause tooth decay (apparently interpreting this as the main function for these organisms). These results indicate that students had a lot of trouble recognising these bacteria do not have any mitochondria or similar organelles for aerobic respiration.

Item 7

Item 7 was incorporated to get a view of students' understanding of bacteria as autonomous organisms that require energy (and thus cellular respiration) of their own. Only a few students correctly predicted that if these organisms had no way for breaking down glucose, they would die. The variety in students' answers to this test item again indicates they had trouble with developing a correct perspective of these bacteria as self-sufficient, living organisms. Some of these indicate bacteria's main function to promote our health by removing sugar from your mouth and prevent tooth decay (despite the initial explanation of tooth decay in this item), while others indicated that these organisms exist solely for the purpose to destroy our health and needed to find other ways of infecting our bodies.

In summary of this description, we can state that these two items 6 and 7 provided a significant challenge to most students. The combination of a complex contextual description (involving a large amount of new information) and an unknown (from a students' perspective) organism seems likely to invoke elements from everyday understanding or life-world contexts. In absence of such an understanding of bacteria as autonomous organisms, it is impossible to connect the release of energy by cellular respiration to a need for energy in these organisms.

Recontextualising-test, context 5: Waste water cleaning.

Item 8

The final two test items for students in case β1 also concerned bacteria, but were concerned with different bacteria in a different context. Item 8 asked students to explain the benefits of using an aerobic cleaning phase. Together with the other item (9) in this context, it could be answered correctly with a correct explication of cellular respiration in three ways (see chapter 2). Despite this, only 5 students in case β1 and 10 in case β2 managed to recontextualise cellular respiration successfully for this item.

Item 9

Item 9 was very similar to item 8, but now asked students to *choose* between an aerobic and anaerobic cleaning phase in the design of such a facility, instead of merely explaining the use for an aerobic phase already included in an existing facility. Most students used an argumentation similar to the one in their previous answer for item 8, or simply referred to that answer. Most students did not manage to successfully recontextualise cellular respiration for this item. A number of them (5 in case β1; 8 in case β2) used the difference in speed to choose for either an aerobic or an anaerobic cleaning phase. In summary, the results from these two test items in context 5 are similar to the results from items 6 and 7 (which also concerned bacteria): a minority of the students in both cases provided a correct answer and chose the correct key elements for solving the problems in these items.

Recontextualising-test, context 6: Caring for chronically-fatigued patients.

Item 10

In case β2 this context was included for a comparison with context 4. Case β1 had already shown how students had a lot of trouble with recognising the absence of mitochondria in bacteria as an explanation for their inability to break down glucose completely with aerobic respiration. In order to determine if this was a result of any unfamiliarity with element E, or with the bacteria described in context 4, items 10 and 11 were designed to mirror items 6 and 7. Item 10 then asked students to explain the reduced ability for a complete breakdown of glucose in these patients' cells. Eight of them managed to provide a correct explanation and stated that this was due to the dysfunctioning mitochondria. This is only a quarter of the students in case β1, and this number is similar to the number of students that managed to provide a correct answer to item 6 in the same case study.

Item 11

Item 11 was designed to mirror item 7, and asked students to explain the patients' fatigue. Although this question is different from the question posed in item 7 (which asked students to describe the consequences for bacteria when robbed of any ability to break down glucose), the line of reasoning expected from students was similar. A lack of cellular respiration would lead to a lack of energy, causing bacteria to die, and patients to become fatigued. Therefore, students' answers can be compared. In conclusion of this description of the results from the recontextualising-test, the remainder of this section summarises these results in an answer to RQ III-b.

Conceptual elements used by students in the recontextualising test

Summarising the results of students' use of conceptual elements recontextualising-test, table 6.17 shows the combined results for cases β1 and β2. The numbers represent the number of students that correctly used an element in their answer to the different test-items.

Table 6.17

Conceptual elements used in the recontextualising-test combined for in cases β1 (n=20) and β2 (n=24); related to the maximum number of students that correctly used an element in items 2 and 3. The numbers in brackets indicate the number of answers that was judged as a correct, and proof of recontextualising. The shaded cells indicate the key elements that are needed for a correct answer to a particular test-item.

Cases β1 and β2; n=44			**A energy**	**C oxygen**	**D products**	**E mito-chondria**	**F speed**
Humans [muscle cells]	*explain differences between athletes*	*Item 2+3*	*24*	*19*	*14*	*17*	*14*
Yeast [yeast]	select aerobic CR	Item 1	24 (23)	12 (9)	7	1	9
Yeast [wine]	explain need for anaerobic CR	Item 4	2	14 (12)	32 (31)	0	10
	name gas from anaerobic CR	Item 5	3	0	28 (23)	1	0
Bacteria [bacteria]	explain lack of aerobic CR	Item 6	0	7	16	10 (9)	1
	predict consequences of no CR	Item 7	5 (5)	2	0	0	0
Bacteria [waste water]	explain need for aerobic CR	Item 8	10 (5)	10 (3)	13 (10)	0	6
	select aerobic CR	Item 9	6 (2)	2 (1)	13 (9)	0	12

Cases β2; n=24			**A energy**	**C oxygen**	**D products**	**E mito-chondria**	**F speed**
Humans [muscle cells]	*explain differences between athletes*	*Item 2+3*	*8*	*9*	*6*	*8*	*10*
Humans [patients' cells]	explain lack of aerobic CR	Item 10	0	1	10	10 (8)	0
	explain lack of aerobic CR	Item 11	16 (16)	1	4	3	3

Any comparison between the results for the different items and contexts should take into account students' development of the concept as a result of the lessons in the lesson module. Therefore, the first row (*italic*) in table 6.17 represents the number of students that correctly used an answer to test-items 2 and 3. These two items invited students to describe differences between sprint- and marathon runners and students' answers represent their use of conceptual elements in that – familiar – context. Students' answers to both these items have been combined to provide the numbers in table 6.17.

Students' answers to test-items 2+3 provide an indication of the number of students that had included a conceptual element in their understanding of cellular respiration after taking part in the lesson module. A comparison with the results from the concept maps from the post-test and storyline-phases 14 (CR4, biotechnology) and 15 (CR5, sports physiology), reveals that the numbers based on items 2 and 3 are probably an underestimation. This is additionally illustrated by the number of students that use element D for items 2-3 (14 students) and for items 4 and 5 (31 and 23 students, respectively). Although the results from items 2-3 provide an underestimation of the number of students that correctly included an element in their concept for cellular respiration, they do provide an indication of the minimum number of students that could be expected to use an element in the other test-item. Finally, indications of the use of a conceptual core by students are not included in table 6.17, because of the impossibility of deducing this core from students' concept maps. A maximum number of 6 students showed any indication of understanding this core by combining elements A, B, and D in a correct description.

An answer to RQ III-b

In conclusion, most students in cases β1 and β2 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 to 10 lessons that preceded the recontextualising-test. They 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. For possible explanations of these differences, this discussion now moves on to a comparison between these in the following section.

6.3 Comparing the results from the recontextualising-test

Chapters 1 and 3 in this thesis both mention the disappointing results of many studies regarding the transfer of knowledge (or preferably: the recontextualising of knowledge) to different contexts. A major part of that problem is the difficulty with identifying exactly *what was being transferred*. The examples provided by the recontextualising-test show that it is possible to identify separate elements that make up a concept, and which of these are needed in a specific context. As such, the identification of conceptual elements for a concept may provide at least a partial explanation for that problem. The results displayed in table 6.17 can be compared among each other to provide possible explanations for students' performance on the test and apparent ability to recontextualise cellular respiration. In order to allow for a better comparison between the different test-items these results are displayed again in four separate tables (6.18 – 6.21) and discussed here.

Yeast-related contexts

The first of these four compares the two contexts in the recontextualising-test where yeast was the biological object of focus. The results for items 1, 4 and 5 are displayed for comparison in table 6.18.

The number of students that answered items 1 and 5 correctly is almost as high as the number of students that correctly used element A in either of their answers to items 2 and 3 (table 6.18). Even more students correctly answered item 4. Not unexpectedly, the number of students that correctly recontextualised cellular respiration to these two contexts was the highest in comparison to the other results from the recontextualising-test. 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 yeast-related and familiar context was not very problematic for approximately half- to two-thirds of the students.

Comparing the results between the two contexts, we can see that although they do not differ a lot, students do perform better in item 4, (focused on the production of wine), than to item 1 (focused on the production of yeast).

Table 6.18

Comparison of results from contexts 1 (item 1) and 3 (items 4 and 5) in the recontextualising-test combined for cases β1 and β2; contexts where yeast is the biological object of focus. The numbers in brackets indicate the number of answers that was judged as a correct, and proof of recontextualising. The shaded cells indicate the key elements that are needed for a correct answer to a particular test-item.

			Conceptual elements correctly used				
Cases β1 and β2; n=44			A energy	C oxygen	D products	E mito-chondria	F speed
Humans [muscle cells]	*explain differences between athletes*	*Item 2+3*	*24*	*19*	*14*	*17*	*14*
Yeast [yeast]	choose aerobic CR	Item 1	24 (23)	12 (9)	7	1	9
Yeast [wine]	explain need for anaerobic CR	Item 4	2	14 (12)	32 (31)	0	10
	name gas from anaerobic CR	Item 5	3	0	28 (23)	1	0

A possible explanation for the differences between the results from items 1 and 4 could lie whether or not a biological object is part of the objective or just a tool in a given a context. When examining the examples from contexts 1 and 3 (which both involve yeast), one can see that for context 3, yeast's role is that of a *tool*, in service of the objective for the context, which is to produce wine. In context 3, yeast is part of the objective which is to produce more yeast. In terms of activity, yeast is not the object that is being manipulated in context 3, but it is for context 1[1]. Yeasts' role as a *tool* in the production of wine only requires a superficial view on the concept: the notion that yeast produces alcohol in anaerobic conditions. In fact, yeast does not have to be viewed as a self-sufficient and reproducing organism at all; a notion 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, context 1 involves in the explicit manipulation of yeast itself, and as such

[1] It should be noted here that the use of the term 'biological *object*' is rather confusing, because it does not refer to the same *object* as referred to in activity theory.

requires a more complex notion of cellular respiration and yeast: it involves the notion that yeast needs to obtain energy from food to sustain its needs. It also requires the idea that, although allowing the organism to survive thanks to anaerobic respiration, anaerobic conditions are far from ideal with regard to its reproduction, which requires far more energy than merely sustaining its basic functions. This view of yeast as a living organism and its need for performing cellular respiration involves more conceptual elements for that concept than the view on yeast as an ingredient for wine production.

Bacteria-related contexts

A comparison between the bacteria-related contexts and students' use in items 2 and 3 is provided in table 6.19.

Table 6.19

Comparison of results from contexts 4 (items 6 and 7) and 5 (items 8 and 9) in the recontextualising-test combined for cases β1 and β2; contexts where bacteria are the biological object of focus. The numbers in brackets indicate the number of answers that was judged as a correct, and proof of recontextualising. The shaded cells indicate the key elements that are needed for a correct answer to a particular test-item.

			Conceptual elements correctly used				
Cases β1 and β2; n=44			A energy	C oxygen	D products	E mito-chondria	F speed
Humans [muscle cells]	*explain differences between athletes*	*Item 2+3*	*24*	*19*	*14*	*17*	*14*
Bacteria [bacteria]	explain lack of aerobic CR	Item 6	0	7	16	10 (9)	1
	predict consequences of no CR	Item 7	5 (5)	2	0	0	0
Bacteria [waste water]	explain need for aerobic CR	Item 8	10 (5)	10 (3)	13 (10)	0	6
	choose aerobic CR	Item 9	6 (2)	2 (1)	13 (9)	0	12

The results in table 6.19 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 sports 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. These bacteria-related contexts were not very familiar to the students. This could be due to any difficulty with understanding bacteria as self-sufficient organisms, although the contexts in themselves were also quite different. In addition, context 4 pertained to bacteria living in a symbiotic relationship with humans.

A comparison between these contexts shows that students perform slightly better in context 4 than in context 5. Context 4 requires a detailed view on the bacteria as self-sufficient organisms, 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. Again, the simpler view on bacteria[2] in the waste water context seems to be related to the role that these organisms are given: they are *tools* for cleaning waste water. Despite the differences between both contexts, these results indicate that most students had problems with recontextualising cellular respiration in bacteria-related contexts. However, a comparison between items similar to these but related to more familiar contexts and organisms may shed more light on this possibility.

Bacteria- vs. yeast-related contexts

To compare students' performance in yeast-related contexts with that in bacteria-related contexts, table 6.20 shows the results from items 1 and 9 which both required a choice between an aerobic and anaerobic environment. Test-items 4 and 9 are also compared, which required an explanation for the need for an anaerobic and an aerobic environment, respectively.

[2] Of course, the bacteria in the context of cleaning wastewater are not the same as those in the context of manipulating the anaerobic respiratory capabilities of mouth-dwelling bacteria. In fact, context 5 involves a wide range of different types of bacteria, where context 4 focuses on a specific type. However, it is expected that for most students, bacteria are bacteria, meaning that they, at this point, have not had a chance study these organisms in detail and might not even consider them to be organisms at all.

A comparison of the second set of items in table 6.20 reveals that students had more trouble with a bacteria-related context than with the yeast-related context.

Table 6.20
Results from items 1 vs. 9, and 4 vs. 8 in the recontextualising-test combined for cases β1 and β2; yeast-related vs. bacteria-related contexts. The numbers in brackets indicate the number of answers that was judged as a correct, and proof of recontextualising. The shaded cells indicate the key elements that are needed for a correct answer to a particular test-item.

			Conceptual elements correctly used				
Cases β1 and β2; n=44			**A energy**	**C oxygen**	**D products**	**E mito-chondria**	**F speed**
Humans [muscle cells]	*explain differences between athletes*	*Item 2+3*	*24*	*19*	*14*	*17*	*14*
Yeast [yeast]	choose aerobic CR	Item 1	24 (23)	12 (9)	7	1	9
Bacteria [waste water]	choose aerobic CR	Item 9	6 (2)	2 (1)	13 (9)	0	12
Yeast [wine]	explain need for anaerobic CR	Item 4	2	14 (12)	32 (31)	0	10
Bacteria [waste water]	explain need for aerobic CR	Item 8	10 (5)	10 (3)	13 (10)	0	6

Items 4 and 8 represented a similar choice between aerobic and anaerobic respiration, although item 4 required a choice for anaerobic respiration and item 8 required a choice for the anaerobic version. Another difference between the two is that item 8 would have ideally included a correct description of the conceptual core for cellular respiration, while item 4 only required students to recognise the production of alcohol in anaerobic respiration to come up with a correct explanation. Therefore, although students' lesser performance in the bacteria-related context can indicate that bacteria are the problem, although it could also be explained by other differences between the two items.

Items 1 and 9 represent a similar choice between aerobic and anaerobic respiration, but now the choice should be aerobic respiration for both items and an ideal explanation should have included the use of a conceptual core for both items as well. Section 6.3 explained that students' answers were also interpreted as indication of successful recontextualising if they only included the correct use of element A in item 1. Item 9 had a larger range of possible explanations: students could have used element D to reason that aerobic respiration would allow for more desirable waste products, but also that more energy would allow for more reproduction, more bacteria and therefore cleaner water. Even with a wider range of possible explanations for item 9, students performed much better in the yeast-related context than when the context related to bacteria. This indicates that students' unfamiliarity with bacteria did indeed present a difficulty for students when trying to recontextualise cellular respiration.

Bacteria- vs. human-related contexts

The final comparison presented here is one between a context related to humans (context 6) and a bacteria-related context (no.4). Because context 6 was only included in case β2, table 6.21 displays the results from that case study, and not those from case study β1. Because of this, the results from the post-test in case β2 are also included to provide (combined with their answers to items 2 and 3) a better indication of how many students had included an element in their understanding of the concept.

Test-items 10 and 11 were added to mirror items 6 and 7. Items 6 and 10 both 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 when compared with each other, but also when compared with the results from items 2 and 3. These indicate 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' apparent difficulties with recontextualising in item 7 might also be explained by other differences between both items. When students were asked to describe a patients' fatigue as a consequence of a lack from aerobic respiration (item

11), the majority easily identified element A. When asked to predict any consequences for bacteria that are robbed of any ability for cellular respiration (item 7), they perform much worse. Although both items require students to recognise the release of energy as the biological function for cellular respiration, item 11 provides a clear connection with element A with the statement that these patients suffer from chronic fatigue. In item 7, a similar connection is not provided. 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 test-items.

Table 6.21

Results from items 6 vs. 10, and 7 vs. 11 in the recontextualising-test combined for cases β1 and β2; human-related vs. bacteria-related contexts. The numbers in brackets indicate the number of answers that was judged as a correct, and proof of recontextualising. The shaded cells indicate the key elements that are needed for a correct answer to a particular test-item.

			Conceptual elements correctly used				
Case β2; n=24			**A energy**	**C oxygen**	**D products**	**E mito-chondria**	**F speed**
Post-test concept maps (no context specified)			*17*	*23*	*1*	*13*	*3*
Humans [muscle cells]	*explain differences between athletes*	*Item 3*	*8*	*9*	*6*	*8*	*10*
Bacteria [bacteria]	explain lack of aerobic CR	Item 6	0	7	10	8 (7)	1
	predict consequences of no CR	Item 7	3 (3)	1	0	0	0
Humans [patients' cells]	explain lack of aerobic CR	Item 10	0	1	10	10 (8)	0
	explain fatigue from lack of CR	Item 11	16 (16)	1	4	3	3

Explaining students' use of conceptual elements in other contexts

An answer to RQ III-c

In conclusion and in answer to RQ III-c, there are a couple of possible explanations to students' different performance for the different items and contexts in the recontextualising-test.

- The *biological object of focus* in the different contexts in the recontextualising-test, combined with *students' expected familiarity* with these provides a partial explanation of the differences between students' performance in these different contexts.
- Next to differences in the type of biological object, the *actions that are performed on a biological object in a context* may also allow for explanations.
- Students' performance for items 2 and 3 indicates that their *understanding of an element in the original context* (i.e. the context used to develop an element in an LT-strategy's storyline) should also be taken into account when explaining differences in students' performance.
- Differences between the *types of explanation required* for the test items provide a final possible explanation for students' difficulties with recontextualising cellular respiration that is discussed here.

Although the results from the recontextualising-test in cases are not conclusive, they do provide interesting insights in why students have more trouble with recontextualising cellular respiration to one context than to another. Furthermore, these results indicate that none of these can provide a complete explanation of students' apparent difficulties with recontextualising cellular respiration on their own and that all these – and possibly others – should be taken into account in possible explanations. More research, for instance with more carefully design test-items across a larger population of students is required for more definitive conclusions.

6.4 Conclusions from the second design research cycle

The final sub-question that needs answering is RQ IV. As for the lesson module in the LT-strategy, it may be concluded that these allowed students to develop cellular respiration in a stepwise learning trajectory. Many students did not have any apparent difficulty with stepping from one context to another in their search for an answer to the initial questions that arose from a comparison between sprint- and marathon-runners from a physiological perspective. During this process, they developed an understanding of the differences between aerobic and anaerobic respiration in these athletes, but also in yeast cells. This understanding was not complete with respect to all conceptual elements of cellular respiration; element E (mitochondria) was expected to have been used by more students in their final explanations for the questions related to the sports physiology context. A similar conclusion can be draw with respect to element F (speed); although quite a large number of students tried to use this element in their final explanations, they had difficulty with relating differences at the cellular level to other levels of biological organisation. Despite students' difficulty with these last two elements, students were apparently motivated to compare and discuss the differences between cellular respiration in the different contexts during the lesson module. They also seemed to accept the need for changing perspectives to develop their understanding further. With respect to the elements A-D that they did apparently develop during the lesson module, it may be concluded that they had developed a moderately flexible understanding of cellular respiration.

An answer to RQ IV

Judging the results from the recontextualising-test, the LT-strategy was expected to be more successful than it appears to have been in cases β1 and β2. However, there are a number of possible explanations for students' performance in this test. In chapter 2, it was explained that the recontextualising-test was viewed initially as an integral part of the entire LT-strategy. However, the results from the enactment of the LT-strategy during the second design-research cycle showed that it was primarily an instrument for summative assessment. This can be attributed to a mistake in the design, which had not included any LT-activities for discussing the results of the test. Although the recontextualising-test itself did provide students with opportunities for additional practice with recontextualising cellular respiration, the design did not include any reflection activities with regard to students' answers and comparisons between the different contexts.

Having answered the sub-questions RQ I to RQ IV, the structure of the LT-strategy for recontextualising cellular respiration can be reviewed and redesigned a final time. This final version for the LT-strategy developed during this research project is described in the following, final section in this chapter.

A final LT-strategy for recontextualising cellular respiration

A new version for the LT-strategy should probably include an additional focus on the elements E and F during the final storyline-phases, and allow students for more comparison and discussion of the results from the experiment with their final explanation for differences between marathon- and sprint-runners. Although the β-version of the LT-strategy did include a comparison between cellular respiration in yeast and in muscle cells, a more explicit comparison between the explanations themselves could have been fruitful. As an additional benefit of this comparison, students might more easily identify the conceptual core of the concept. A more explicit attempt to do so should be a part of any new version of this LT-strategy for recontextualising cellular respiration. Finally, the redesigned LT-strategy should include a chance for students to reflect on the results of the test, which provides many more examples of recontextualising that the exploration during the previous lessons did. Also, if such a reflection activity is included, it is probably best to reserve any discussion on other possible uses for the concept until after they have seen more examples of the concept in other contexts.

With these conclusions, we can describe a third version for the LT-strategy that is expected to allow students to develop a concept for cellular respiration through a process of continues, progressive recontextualising. A structure for this redesigned version of the LT-strategy is provided in table 6.22. That table describes the storyline-phases in the LT-strategy in relation to the intended steps for students' conceptual development for the concept. In that respect it is very similar to table 5.14. Table 6.22 introduces a few additional phases at the end of the LT-strategy. These new storyline-phases (no's 19, 21, and 22) are highlighted in table 6.22. A final difference is in the timing of a discussion for other possible uses for cellular respiration, which is included after the recontextualising-test and the reflection activities related to it.

Table 6.22

Description of storyline-phases in the LT-strategy, in relation to the steps in conceptual development for cellular respiration (CR).

Storyline-phases (no. and description)		$\mathbf{CR_{\#}}$
Context: sports physiology		
1	Introducing sports physiology: differences between power- and endurance-focused athletes.	

Table 6.22 – (Continued)

2	Study muscle physiology from the organism to the cellular level of biological organisation.	CR_0
3	Reflect on muscle physiology: identify differences in needed energy-supply between type I and II muscle cells as the main problem.	
4	Explicate prior knowledge on cellular energy supply (‘combustion’). Redevelop this concept, introducing the term “cellular respiration”.	
5	Reflect on the problem using CR_1 and identify sports physiology as insufficient for developing the concept.	CR_1
Context: biological research		
6	Introducing biological research and the idea of using ‘model organisms’ for studying biological phenomena, like cellular respiration.	
7	Study the cells of several model organisms in biological research and choose one for studying cellular respiration in the classroom: yeast.	CR_2
8	Reflect on the choice for yeast as a model organism.	
Context: biotechnology		
9	Introduce a biotechnologist working to breed yeast strains with optimal cellular respiration capacity in aerobic and anaerobic environments.	CR_3
10	Explicate two methods for cellular respiration: aerobic vs. anaerobic.	
11	Identify a problem for the biotechnologist: measuring differences between aerobic and anaerobic cellular respiration in yeast.	
12	Design and perform experiment for measuring differences between aerobic and anaerobic cellular respiration in yeast. Unexpected results prompt further investigation.	
13	Discuss possible methods for verifying the unexpected results. Study the results from similar experiments that measure other variables.	CR_4
14	Explain the unexpected results and explicate CR_4.	
Context: sports physiology		
15	Return to the problem in sports physiology: differences in needed energy-supply between type I and II muscle cells. Explicate the possible use of CR_4 in solving it.	
16	Identify alcoholic fermentation as incompatible with human physiology, making CR_4 unfit to solve the problem.	CR_5
17	Introduce and explicate lactic acid fermentation as a variant of anaerobic respiration, solving the problem of fit with CR_5.	
18	Reflect on the original problem and solve it with a step-by-step return to the organism level of biological organisation.	

Table 6.22 – (Continued)

All contexts: Generalising cellular respiration		
19	***Discuss possible generalised descriptions for cellular respiration across these contexts and try to identify the conceptual core.***	***CR_C***
Recontextualising – test		
20	Explain biological phenomena in other contexts using cellular respiration.	CR_n
21	***Reflect on the results from the recontextualising-test by discussing and comparing students' solutions to the problems presented in the different test-items.***	
22	***Return – if needed – to the process of identifying a conceptual core or discuss any suggested changes to that core in d.***	
Other contexts		
23	***Use the conceptual core to find and discuss other possible uses for cellular respiration in other contexts.***	***CR_n***

The final chapter of this thesis discusses a possible generalisation of this LT-strategy for other biological concepts, as well as other insights that have arisen during this research project, possible implications for education and suggestions for further research.

Chapter 7

Generalisation for the LT-strategy and reflections on the research project

Chapters 3 and 4 provided design criteria for structuring LT-activities and contexts in an LT-strategy for recontextualising cellular respiration, thus answering RQ II and RQ III. With these design criteria, an LT-strategy was designed and tested in two iterative design-research cycles. The design process and the outcomes from enactment of the LT-strategy have been described in chapters 5 and 6, finally providing an answer to RQ III and RQ IV. This final chapter returns to the overall research question:

Research Question (RQ)	How can a learning-and-teaching (LT-) strategy, aimed at the flexible use of biological concepts through recontextualising, be structured?

Sections 7.1 and 7.2 provide a two-part answer to this question, and relate findings from this research projects to other sources in an attempt to provide additional, theoretical insights in the process of recontextualising. Section 7.1 describes the first part of this answer with a generalised structure for designing LT-strategies for recontextualising biological concepts. The second part of the answer to the main research question is provided by section 7.2 with a description of possible generalisations of identifying conceptual elements for a concept, and how these can describe context-specific uses for a concept. Section 7.3 discusses possible implications for biology education with regard to the design of LT-strategies and assessing students' ability to recontextualise biological concepts. Finally, section 7.4 reviews limitations of the study described in this thesis and provides suggestions for future research projects that might bring us closer to an understanding of the recontextualising processes.

7.1 An LT-strategy for recontextualising biological concepts

The LT-phases described for the LT-strategy for recontextualising cellular respiration (see chapters 5 and 6), were identified from the 'storyline' in the LT-strategy. This storyline describes student's intended conceptual development for cellular respiration, in relation to the contexts in which it is explored. Because this storyline is specific for this LT-strategy, these specific episodes are not suitable for any LT-strategy for recontextualising other biological concepts. However, by reflecting on the final design of the concept-specific LT-strategy in relation to the design criteria for recontextualising, four different phases are identified that are considered specific for recontextualising. These phases are expected to help students to develop a flexible conception on biological concepts that they can review and adapt for use in different contexts. The four phases in this structure for recontextualising represent essential steps for allowing students to recontextualise a concept properly.

- ***Preparing for recontextualising***
  Students prepare for changing their current understanding and perspective on a concept in LT-activities that invite them to explicating their current understanding of that concept.
- ***Recontextualising***
  Students participate in LT-activities that invite them to use the concept in a new context, requiring a different perspective on the concept. This can involve a change or addition of conceptual elements, depending on the new context as well as students' current understanding of that concept in relation to the conceptual learning goals for the particular LT-strategy.
- ***Reflecting on recontextualising***
  Students reflect on two or more context-based descriptions of a concept. The LT-activities in this phase should invite them to explicate and discuss the similarities and differences between context-based descriptions, in relation to the particular goals and biological object of focus in each context. Additionally (and if possible), students' are invited to identify a conceptual core for the concept by trying to describe those elements that seem constant between all context-based descriptions.
- ***Testing for recontextualising***
  A test for recontextualising essentially consists of a series of recontextualising phases. During a test like this, students are

introduced to one or more contexts and invited to try and solve context-based problems that have been designed to test students' ability to recontextualise the concept to different contexts.

Table 7.1

The structure for the LT-strategy for recontextualising cellular respiration, in relation to the four phases for recontextualising that have been identified as a generalisation of this concept-specific LT-strategy

Episodes (no. and description)		**$CR_{\#}$**	**Structure for recontextualising**
Context: sports physiology			
1	Introducing sports physiology: differences between power- and endurance-focused athletes.		
2	Study muscle physiology from the organism to the cellular level of biological organisation.		
3	Reflect on muscle physiology: identify differences in needed energy-supply between type I and II muscle cells as the main problem.	CR_0	Preparation (1)
4	Explicate prior knowledge on cellular energy supply ('combustion'). Redevelop this concept, introducing the term "cellular respiration".		Recontextualising (1)
5	Reflect on the problem using CR_1 and identify sports physiology as insufficient for developing the concept.	CR_1	Preparation (2)
Context: biological research			
6	Introducing biological research and the idea of using 'model organisms' for studying biological phenomena, like cellular respiration.		Recontextualising (2)
7	Study the cells of several model organisms in biological research and choose one for studying cellular respiration in the classroom: yeast.	CR_2	
8	Reflect on the choice for yeast as a model organism.		Preparation (3)
Context: biotechnology			
9	Introduce a biotechnologist working to breed yeast strains with optimal cellular respiration capacity in aerobic and anaerobic environments.	CR_3	Recontextualising (3)
10	Explicate two methods for cellular respiration: aerobic vs. anaerobic.		Preparation (4)
11	Identify a problem for the biotechnologist: measuring differences between aerobic and anaerobic cellular respiration in yeast.		Recontextualising (4)

Table 7.1 – (Continued)

12	Design and perform experiment for measuring differences between aerobic and anaerobic cellular respiration in yeast. Unexpected results prompt further investigation.		Recontextualising (4)
13	Discuss possible methods for verifying the unexpected results. Study the results from similar experiments that measure other variables.	CR_4	
14	Explain the unexpected results and explicate CR_4.		Preparation (5)
Context: sports physiology			
15	Return to the problem in sports physiology: differences in needed energy-supply between type I and II muscle cells. Explicate the possible use of CR_4 in solving it.		Recontextualising (5)
16	Identify alcoholic fermentation as incompatible with human physiology, making CR_4 unfit to solve the problem.	CR_5	
17	Introduce and explicate lactic acid fermentation as a variant of anaerobic respiration, solving the problem of fit with CR_5.		
18	Reflect on the original problem and solve it with a step-by-step return to the organism level of biological organisation.		
All contexts: Generalising cellular respiration			
19	Discuss possible generalised descriptions for cellular respiration across these contexts and try to identify the conceptual core.	CR_6	Reflection (5)
Recontextualising – test			
20	Explain biological phenomena in other contexts using cellular respiration.	CR_n	Test (n)
21	Reflect on the results from the recontextualising-test by discussing and comparing students' solutions to the problems presented in the different test-items.		Recontextualising (n)
22	Return – if needed – to the process of identifying a conceptual core or discuss any suggested changes to that core in d.		Reflection (n)
Other contexts			
23	Use the conceptual core to find and discuss other possible uses for cellular respiration in other contexts.	CR_n	Recontextualising

The preparation- and recontextualising- phases alternate during the storyline of this LT-strategy: students repeatedly describe their conceptions of cellular respiration in preparation phases, before using the concept in a new context. Reflection-phases are introduced after students have had the chance to develop at least two, similarly detailed, descriptions for cellular respiration (CR_4 and CR_5). When the concept is expected to be developed in the detail that is required in this LT-strategy, a test-phase is introduced. This is essentially a sequence of short recontextualising-phases. Following the test-phase, another reflection-phase is probably needed for student to improve the flexibility of the conception of cellular respiration.

These four phases are not expected to be specific for cellular respiration. Many other biological complex concepts such as ‘photosynthesis’ or ‘proteins’ are used in a large variety of social practices and as such, are expected to have varying meanings and descriptions as well. For example: photosynthesis can be used to study cellular metabolism in plants, but also to describe process on an ecological scale for whole ecosystems or even the biosphere. With its uses in different practices, a concept can be expected to have varying meanings and descriptions as well (see also: chapters 1 and 3 of this thesis). Therefore, students need to be stimulated to discuss these different meanings and be allowed to view the similarities and differences between the different uses for a concept. The structure for recontextualising presented here explicitly includes two phases that are intended for students to engage actively in the activity of defining such concepts and to allow them to develop these in a step-by-step process.

Preparing for recontextualising

First of all, students are introduced to a specific social practice and focus on a specific context where a concept is used, followed by activities for using the concept in that context and recontextualise their prior knowledge related to the concept. However before doing so, students should first determine their current understanding of the concept by engaging in LT-activities that invite them to explicitly describe the concept in relation to the problem of focus. This explicit description *prepares* students for a change of perspective on the concept that redefines its use and meaning. Without such an explicit, contextualised description of a concept students may have trouble recognising the changes that are needed for recontextualising, or see the similarities between contexts. Without a proper view of the differences *and* similarities between contexts, students cannot be expected to include these different perspectives in their understanding of the concept.

For example: In the LT-strategy specific for cellular respiration, students first described and then recontextualised their prior knowledge of ‘combustion’ (CR_0) to a more detailed perspective that was tied to the cellular level of biological organisation with a new label: ‘cellular respiration’[1]. In addition to assigning a new label, they rewrote their description of the ‘overall formula’ in words, using molecular descriptions of the process (CR_1). As such, storyline-based LT-phase 4 incorporated a *preparation* phase for explicating students’ current understanding of the concept, followed by a *recontextualising* phase for changing that understanding.

Recontextualising

Although the name of the recontextualising phase might imply otherwise, it should not be interpreted as the only time when recontextualising is expected to occur. Rather, it means that students are introduced to new context-specific information that creates the need for a new perspective on the concept. This can incite students to review their current perspective and redevelop it to fit the new information that is introduced. However, this change of perspective is still implicit and needs to be clearly described before any introduction of more context-specific information and yet another perspective. In the LT-strategy specific for cellular respiration, the preparation and recontextualising phases alternate with each step in the development of the concept (see table 7.1).

Reflecting on recontextualising

Explicit comparison of context-based descriptions of concepts makes sense after students had developed such descriptions. In the LT-strategy specific for cellular respiration, these were two concept maps that described cellular respiration in yeast cells and human muscle cells. Because of this the reflection phase is not incorporated until after episode 18 in this concept-specific LT-strategy. In this LT-strategy, the timing of this phase depends on the differences between two contextual descriptions and

[1] Of course, in the Dutch series of LT-activities, the label ‘dissimilatie’ is used, instead of ‘cellular respiration’. However, the LT-strategy introduced this Dutch term as a more specific and accurate description of the ‘combustion’ process at the cellular level of biological organisation.

whether or not these enable students to relate them to a conceptual core for the concept, and if these allowed a perspective on important differences between the concept in a sports physiology and biotechnology context. Therefore, the timing of this phase depends strongly on the specific *storyline* for an LT-strategy and can best be determined in direct relation with such a storyline. Thus, the identification of these phases provides an insight in the phases needed in a LT-process to allow students to develop a flexible conception of a concept. But with regard to the inclusion of these phases in particular episodes, the storyline is primary. The storyline should provide the motive for going through one of these phases for recontextualising.

During the *reflection* phase for recontextualising, students are invited to compare and explicate the differences and similarities between descriptions of a concept in different contexts. Focusing on the *differences* between the context-based descriptions allows the students to see that a different context can involve an actual change of certain conceptual elements (like the products involved in cellular respiration), as well as bring other elements in or out of view. Focusing on the *similarities* allows students to see how certain elements of the concept remain similar across different practices, possibly allowing them to identify a 'conceptual core' of the concept: a combination of conceptual elements that is more or less consistent and unchanging between contexts. In the case of cellular respiration, such a conceptual core can be identified by combining the elements of energy-release (function) and breakdown of an energy-rich substrate (form).

Testing for recontextualising

In the LT-strategy specific for cellular respiration, this phase is represented with the recontextualising-test (see table 7.1). However, this test had more a summative than a formative function during the case studies in both design-research cycles (despite earlier formulated intentions). This was because it also served as a research instrument for purposes of assessing students' use of the concept in other contexts. In retrospect, it would have been better to incorporate this phase more prominently in the LT-strategy by adding a final series of LT-activities where students would be allowed to compare and discuss their solutions to the problems presented in the test. The addition of such a final reflection phase following a test for recontextualising provides students with a number of extra chances to *explicitly recontextualise* the concept and compare its use among different contexts.

The results from the recontextualising-test in the previous section have shown that knowledge of the different elements of a concept is not enough for successful recontextualising, but that students also need sufficient other, context related knowledge in order to do so. Although they can never be expected to have sufficient knowledge of all possible contexts, additional practice with recontextualising in a variety of contexts and organisms can help students to improve the flexibility of their conception. This can help students develop a better understanding of a conceptual core for a concept, as well understand the questions that they need to ask in order to get the context-specific information needed to properly solve a context-related problem. This touches on the tension between including context-specific information to provide students with a detailed view on a context; and limitations on the amount of new information in order to prevent confusion (see chapters 1 and 3, and the description of other experts' views on the recontextualising-test in section 6.1). Because this problem is also strongly related to the identification of conceptual elements, this discussion will be continued in section 7.2.

Discussion of the generalised structure for recontextualising

The description of the structure for recontextualising in relation to the concept-specific LT-strategy in this section shows that preparation and recontextualising-phases accompany every step in the (intended) conceptual development for cellular respiration. This is also true for steps that do not explicitly involve a step from one context to another, as with the step from CR_3 to CR_4, which takes place within an exploration of the biotechnology-context. A strict interpretation of recontextualising as adaptation of a concept for use in another social practice would contradict the identification of a 'recontextualising'-phase here (see chapter 3). However, the view on recontextualising as described by van Oers (van Oers, 2001) allows for a broader interpretation (see also: chapters 1 and 3). Within this view, recontextualising occurs when the concept needs adaptation due to changes in the *activity*. The example of the step from CR_3 to CR_4 in the LT-strategy for recontextualising cellular respiration, clearly involves a change in activity that required an adaptation of the concept. The series of LT-activities related to the practical experiment provided new context-based information (i.e.: differences in speed of carbon dioxide production by yeast under aerobic and anaerobic conditions), which triggered the need for a perspective on the concept that would allow for an explanation of these differences (i.e.: differences in speed between aerobic and anaerobic respiration). As such, any explicit step in students' (intended) conceptual development in an LT-strategy can be considered as an act of recontextualising.

This does not mean that an LT-strategy for recontextualising can do without an exploration of several contexts and that it can be limited to a single context. The other steps in conceptual development in the LT-strategy for recontextualising cellular respiration do involve changes in context and activity. An exploration that would be limited to the biotechnology context would not allow for a view on all elements for the concept. For instance, the exploration of cellular respiration in yeast only provides an example of alcoholic fermentation as a variant for anaerobic respiration. It neither provides a view on the function of mitochondria in cellular respiration. A change in context allows for another perspective and (reflecting van Oers' description of the abstraction process) adds new information that can be related to the concept.

The exploration of more contexts thus leads to more perspectives on that concept, which can be used in creating abstractions such as definitions. Referring to chapter 1, it should be noted that such definitions usually tend to describe the similarities between a concept's meanings in different activities, and are a product of the activity of *defining the concept*. In itself, a generalised definition that is intended to describe a concept in a variety of different contexts (such as the description of cellular respiration for this thesis, see box 1.1) cannot be expected to enable students develop a broad view on the concept. However, if students take part in activities for explicitly defining a concept's meaning(s) in one or more contexts, they have to review their context-specific perspectives by themselves in an attempt to relate these among each other. This involves a review of how the differences between contexts, which in turn allows for an identification of the similarities (Marton, 2006).

The LT-structure for recontextualising described in this section explicitly incorporates the *activity of defining* a concept during the preparation and reflection phases. During a preparation-phase, students described the concept as they understand it in the relation to the context in which it is explored. Due to differences between the personal perspectives and prior knowledge that students bring into the classroom, it may be expected that different students will recognise other (conceptual and contextual) elements that are required for an accurate, context-specific description of the concept. Therefore, by subsequently inviting students to compare each other's descriptions and come to a jointly accepted description, the chances of an accurate (and correct) description can be improved. Following this preparation, students can participate in LT-activities that introduce new, context-specific information that can be related to the concept (recontextualising), and trigger a modified perspective on the concept. Their descriptions of the concept before this new perspective was introduced, provides students with an explicit view on their current conceptual development. Furthermore, these descriptions can be used in reflection phases for recontextualising. Reflection phases for recontextualising are intended to allow students to explicitly compare context-specific descriptions for a concept, and attempt to produce a generalised description, forcing them to focus on the similarities *and* differences between these. Therefore, these two phases (preparation and reflection) should involve discussions (or similar activities) that are structured is such a way that students are allowed to contribute equally and voice their individual perspectives without these being (immediately) corrected. When they are allowed to produce their own descriptions for a concept instead of being handed a definition by an authority like the teacher or textbook, students can be held more *accountable* for the descriptions they produce.

This accountability can help them to develop an authoritative perspective on the concept, reflecting insights from a study on transfer by Engle (2006). In his commentary on this study Greeno (2006) describes transfer (pg. 538) as an authoritative action that requires an authoritative and accountable position towards the knowledge that is to be transferred. This is in line with the perspective on recontextualising used in this thesis, which involves the need for a *flexible* conception of a concept as a tool that can be re-evaluated and changed if the need arises. In Greeno's terms, people who have developed a flexible conception of a concept can act with *conceptual agency* with regard to that concept. Although this idea of an authoritative positioning of the knowledge emphasised by Greeno and an example of this is given in Engle's study, Greeno's is not clear on how this can be achieved, limiting his description of this by stating that in order for a student to act with 'conceptual agency', he or she should be allowed to develop a participatory identity with a strong conceptual agency (p.539). Although the structure for recontextualising described here is not expected to be the only possible solution to the problem, it does provide a framework for holding students accountable for the knowledge they produce, and it allows them to participate in *activities for defining* a concept, based on new information that is brought into view with the exploration of a specific context. Participation in these activities for defining is considered to be crucial for developing a flexible conception of a concept that can be re-evaluated and changed, depending on specific, contextual needs and circumstances. An integral part of this activity is the importance for allowing students to view the differences as well as the similarities between context-specific perspectives on a concept, and develop their own descriptions for a concept for which they can be held accountable. The importance of viewing both the differences and similarities is emphasised by Marton's study (2006), which was also a part of the review in Greeno's (2006) commentary.

Although the use of the word 'phases' in this description of a structure for LT-strategies for recontextualising biological concepts might suggest that they should always be sequenced in the same order, it should not be interpreted in that sense. It is conceivable that with other concepts different sequences are fruitful. However, it is expected that LT-strategies that aim at students to develop a flexible conception on a biological concept can be effectively designed using these four phases. Also, it is expected that reflection phases aimed at identifying a possible conceptual core are most fruitful after several steps in students' conceptual development. The preparation and recontextualising phases provide structure to the intended steps in conceptual development for an LT-strategy (see table 7.1).

For the identification of the intended steps in development for a concept in a particular context-based 'storyline', this research project has illustrated how it can be fruitful to identify conceptual elements for a concept that needs to be developed. This brings us to the identification of conceptual elements for the concept of cellular respiration. These can be used in the design of context-specific test-items for recontextualising a biological concept, and allow for a systematic analysis of the elements that students recognise and use in solving test-items. The usefulness of these conceptual elements and their generalizability for other studies on recontextualising, are described in the following section.

7.2 Using conceptual elements

Having made a case for a generalised structure for an LT-strategy focusing on recontextualising, we turn to the second part of the answer to the main research question: the identification of conceptual elements of a concept. These elements are described in chapter 2, because they are considered as important instrument used in this design research project. Despite differences with descriptions for cellular respiration in educational resources (i.e.: incorporation of the difference in speed as a specific element, see also: chapter 4), these elements do not provide any new information from a biological perspective. They can however, be useful for structuring the *storyline* for a given LT-strategy or be used to get a better view of students' understanding of a biological concept.

Using conceptual elements for structuring an LT-strategy

Using conceptual elements we can make the steps in conceptual development explicit; not only for the students, but also for ourselves as teachers and/or designers of biology education. The descriptions of differences between the α- and β- versions of the LT-strategy (see chapters 5 and 6) provide an example of how a clear view of these steps in the second design-research cycle allowed for a more consistent structuring of contexts and their related LT-activities. Although the α-version of the LT-strategy did allow for an explication of the concept by students as preparation for the first and final steps in the intended conceptual development, it did not include such activities for the steps in between. The β-version included more LT-activities for explicating the concept in preparation of important changes or additions to the current (intended) perspective on the concept. Similar to the identification of conceptual elements in this study, many other design-research projects at FIsme have identified specific steps in the intended conceptual development for a specific LT-strategy (Klaassen, 1995; Knippels, 2002; Lijnse, 1995; Lijnse, 2007; Westra, 2008).

Similar to these studies, this study emphasises the importance of context-specific descriptions for a concept. The approach described in this thesis is different, because despite of the importance of context-specific descriptions it also stresses the need for identifying which elements of a concept can be related to, or left out of a contextual perspective (see chapter 3). Such a description can keep the intended conceptual development in focus, and guide the design process. Without this focus, the designer's expert view on the context may lead to too much focus on the context. Too much focus on a context may result in a highly contextualised view on the concept that is not flexible. An example of this can be found in a recent design-study for a context-based LT-strategy for understanding animal behaviour[2] (van Moolenbroek, 2012). In his thesis (p. 179), he describes students' performance as poor with regard to an LT-activity in which they wrote an essay on human hooligan behaviour in relation to their newly developed notions on animal behaviour. This might be attributed to an over-contextualised view on animal behaviour on part of the students, although this does not need to be caused by the LT-strategy in itself. Like the students in that study, society in general has a highly contextualised view on animal behaviour, which is not commonly used in explaining human behaviour. In fact, most psychology practices focus solely on explaining the behaviour of this one species (i.e.: humans) and have developed their own distinct concepts for this. There are of course numerous examples of shared ideas between these practices and animal behaviour practices in their cultural history, for example: ideas from I. Pavlov and B.F. Skinner have influenced both biological and psychological practices. However, these practices have developed their distinct sets of rules, concepts, instruments, etc. based on these ideas for studying either human or (other) animal behaviour.

Another result of too much focus on a context (or rather: an entire social practice) can be the introduction of too many new concepts at once. Explorative case 1 (see chapter 3) showed how this led to confusion for students, and did not provide them with a chance to develop each concept separately. Rather, the vast number of new concepts introduced resulted in the teacher providing them with a set of generalised, ready-made definitions for the concepts involved. As noted before (see section 7.1 and also: chapter 3 and section 6.1), this also illustrates the tension between the amount of context-specific information needed to understand a context in detail, and to limit this amount in order to prevent confusion. The advantage of specifying the elements that make up a concept is that this can make clear how a concept is used in a particular context and allow us to

[2] Although the explorative case study 2 (see chapter 3) also involved a version of van Moolenbroek's LT-strategy for animal behaviour, the example described here is from another version of that LT-strategy that was intended for pre-university secondary education (VWO) and therefore, not a part of the exploration that focused on senior general secondary education (HAVO).

identify the context-specific information that is needed for a sufficient understanding of the *concept and the context*. As such, this can help relieve the tension between too much or too little information and find the proverbial *'Goldilocks-zone'* for just the right amount of context-specific information needed, without causing too much confusion and dilute a proper focus on a concept.

This name is of course derived from the well-known fairy-tale "The story of the three bears", but more specifically: from astronomy. In astronomy, a Goldilocks-zone specifies an imaginary zone around stars other than our Sun where a planet might be found that can sustain (water based) life. In astronomy, the specifics of any Goldilocks-zone are very dependent on the type of star and as such; context-dependent. This is reflected in the use of the same name here. The specific information needed to understand and successfully use a concept in context is very dependent on the context in which that concept is to be used. The specification of conceptual elements for a concept reflects (but is not the same as) astronomers trying to identify the specific conditions needed to sustain life. It allows us to describe what kind of context-specific information is needed to 'sustain' a concept in a specific context. In that sense, this can tell us where to look in order to find a possible Goldilocks-zone for successful recontextualising of a concept in a specific context. But aside from the specifics of a concept (life) and a context (star), what also needs to be taken into account are the learning goals for a concept in an LT-strategy and students' expected prior knowledge that may be connected to a concept in context. To keep with the metaphor of a Goldilocks-zone, it requires some extension (or: recontextualising). This means that this should not only indicate the possibility for life in general, but to indicate the possibility for different types of life (for instance, organisms of varying levels of complexity).

Conceptual elements used by students in different contexts

The identification of conceptual elements for a specific concept can provide a more pronounced view on the context-specific peculiarities for a concept, and allows us to identify what aspects (elements) of the concept were made available during a series of LT-activities (see chapter 6). In that sense, it allows us to make any test-items for recontextualising more *consistent* with what was actually being introduced, discussed and described during the LT-process. Chapters 1 and 3 both mention the disappointing results of many studies regarding the transfer of knowledge to different contexts. A major part of that problem is the difficulty with identifying exactly *what* *was being transferred*. Bransford & Schwartz (1999) described how the questions people ask when trying to use knowledge in new and unfamiliar contexts could be used as an indication of someone's conceptual understanding. They described an experiment that showed how experts in a particular field were able to ask the right questions that would allow them to find the information needed to use their expert knowledge in an unfamiliar context, but which was related to their field of expertise. The results from the recontextualising-test described in chapter 6 showed that students also need a sufficient understanding of a context in order to successfully use cellular respiration in that context. Both these observations (from Brandsford & Schwartz, and those described in this thesis) relate to the need for sufficient contextual information for successful recontextualising. The identification of conceptual elements allows us to infer what contextual knowledge is needed to do so, and provide indications of the questions that need to be asked for successful recontextualising. The examples provided by the recontextualising-test and the analysis of students' answers to these items (see chapters 2 and 6), show that it is possible to identify separate elements that make up a concept, and which of these are needed in a specific context. As such, the identification of conceptual elements cannot only help us to identify *what* is being transferred; it may also help us to improve our understanding of *how* it can be recontextualised to allow for transfer to occur.

This analysis of the results from recontextualising-test also revealed that students did not have enough context-specific information for a number of items and were not able to recontextualise their view of cellular respiration successfully to contexts involving unknown or unfamiliar biological objects. Although the conceptual elements needed for each item were identified eventually, this was not yet the case at the start of the first case study (β1) in the second design cycle. One item had been added to the test before the start of case study β2, but it was decided not to change the other items in the test in between these two case studies in order to be able to compare the results. However, a detailed investigation like the one presented in chapter 6 does provide the opportunity to more easily identify the context-specific information needed to find a correct answer. For instance: items 7 and 11 were related to different contexts (bacteria and humans) and elicited different responses from students. The analysis in section 6.3 has shown that a plausible explanation for these differences is not only found in the differences between students' familiarity with bacteria and humans. Another possible explanation provided was the idea that item 11 (which elicited more correct answers from students than item 7), also clearly stated a consequence (symptom) of dysfunctioning mitochondria that students could relate to element A. Item 7 did not provide a similar consequence for bacteria when robbed of the ability to respire, but instead asked students to make a prediction by themselves. In this latter item (no.7), the students had no clear connections to element A, preventing them from seeing such a connection.

This example illustrates that in order to design proper tests for recontextualising we also need to identify which hand- and footholds students are expected to need in order to successfully recontextualise a concept. Again, this is related to the tension between providing too little or too much context-specific information. Conceptual elements can allow us to design a consistent LT-strategy that provides students with the information needed, but not so much that students get confused or 'over-contextualise' a concept. In other words: these elements help us to identify a *Goldilocks-zone* for a concept in context. However, this research project only concentrated on one concept and it has not been made clear if and how these conceptual elements can be related to other concepts. Returning to the example of the use of a Goldilocks-zone in astronomy earlier in this section, this illustrates the difference between a Goldilocks-zone for a biological concept, with the perspective in astronomy. Where astronomers only needed to define such a zone for one idea or concept (i.e.: life). In biology education however, we might need to define such a zone for a variety of different concepts. Not only that, but the contexts used to explore and develop a concept in an LT-strategy, the level of detail of a concept described in the learning goals, and students' expected prior knowledge all need to be taken into account as well. The metaphor of a Goldilocks-zone is therefore (like any metaphor) not completely fitting in itself. But it does emphasise the situated and context-specific character of using conceptual elements.

The final part of this section moves on to this question and discusses possibilities for identifying conceptual elements in other concepts.

Conceptual elements in other concepts

The generalizability of conceptual elements as a research instrument for research on recontextualising possibly depends for a great deal on the peculiarities of a specific concept. For instance: concepts that describe specific biological processes (for instance: photosynthesis or reproduction) or structures (for instance: cell or protein) across different organisms often have a well-agreed, generalised meaning across a variety of these practices. Such concepts may also allow for the identification of a *conceptual core*: a combination of several conceptual elements that together describe the similarities between a concept's context-specific meanings. This thesis (see chapter 4) described the core for cellular respiration as the idea that organic substrates that can be broken down to release energy that is needed for powering other biological processes. As such, it describes the primary function (energy-release) and general form (breakdown) of the process.

Another example may be provided with a look at another concept: 'protein'. It is different from cellular respiration in that this concept describes structures in biology, not processes. However, similar to cellular respiration it refers to numerous different processes; the concept of 'protein' also includes a variety of different structures that are essential for any living organism. In addition, there is a large variety of possible functions for proteins: they can be hormones, pheromones, neurotransmitters, part of the cytoskeleton, receptors, gateways, pheromones, antibodies, toxins, enzymes, etc. The inclusion of all these different structures and functions within a concept of 'protein' is allowed because aside from all these differences, they are structured by large chains of amino-acids with different sequences, folded into an almost endless variety of different three-dimensional structures that allow connections to other substrates, including other proteins. The similarities and differences in molecular structure (*form*) do *not describe* the *function* for these types of biological structures, but they do *determine* the *function* of these structures. The description of a generalised *form or structure* with these molecular structures is self-explanatory; the generalised *function* lies in their ability to connect to other organic and inorganic substances. This explains the large variety of possible functions for proteins, especially when combined with the idea that the basic structure for these proteins is encoded in genes. Possible footholds for identifying a series of conceptual elements for such molecular structures can be found in a description of a framework for reasoning at molecular levels of biological organisation provided in a study by van Mil, Boerwinkel, and Waarlo (2011) which (among others) identifies spatial and temporal elements that describe the organisation and interactions of biological molecular structures at different molecular levels.

Other concepts might prove more difficult when it comes to the identification of a stable core. An example of such a concept is provided in a study on the concept of biodiversity (van Weelie, 2001; van Weelie, 2002). In this study, van Weelie showed how that concept eluded any single, generalised description. Similar concepts that are not as generally agreed upon between different (biological) practices might not allow for the identification of a single, conceptual core. Despite this lack of a conceptual core, the recontextualising process still involves the explicit comparison of different, context-specific descriptions for the concept. The only difference is that students (although they might try) are not invited to try and provide a single, generalised description, but rather use different descriptions for different contexts. This is essentially no different from recontextualising complex concepts (like cellular respiration) that do allow for the identification of a conceptual core. In fact, the perspective on recontextualising in this thesis stresses the importance of comparing contextualised descriptions in activities for defining the concept. Although the activity of creating such generalised descriptions is considered to be crucial for developing a flexible view on a concept, the description in itself is not (see also: section 7.1). Van Weelie's example of biodiversity shows how students engaged in a series of context-based LT-activities, and described the concept specifically in each context. Eventually, they were able to develop a description for the concept that explicitly stated these contextual differences.

This concludes the discussion of the use of conceptual elements as a design-instrument for designing LT-strategies that aim at a stepwise, and flexible development of a concept. Combined with their use as an instrument for determining if and how students manage to recontextualise a concept, the identification and description of these elements, in relation to their use in specific contextual perspectives provides a detailed view on the process that is recontextualising. With this second part of the answer to the main research question now described and established, it is considered to have been answered.

The final two sections of this chapter describe the implications for education that can be inferred from this research project (7.3), and some suggestions for future research on the recontextualising-process (7.4).

7.3 Possible implications for education

The structure for recontextualising that has been presented in section 7.1 is expected to be applicable for designing LT-strategies that aim at students to develop biological concepts in a flexible manner. This section describes how it can be used in combination with other structures for designing other such LT-strategies for biology education.

Designing other LT-strategies for recontextualising biological concepts

This structure for recontextualising is not intended to be the only structure needed to design a coherent LT-strategy. Chapter 5 in this thesis described how an LT-strategy for recontextualising cellular respiration was designed using a number of other structures and strategies as well. Together, these structures were woven into one, central storyline with the concept of cellular respiration as its protagonist.

A problem-posing structure (Klaassen, 1995; Lijnse, 2007) was used to stimulate students to develop a motive for studying a particular concept. The development of a motive for recontextualising (design criterion 3, see chapter 4) can be seen as an extension of this problem-posing structure. In a sense, the original context-related problem is extended because the information needed to solve it stems from other social practices. This allows for an extension of the original motive as well, and the needed information can be developed in an exploration of another context that is based on other social practices. This problem-posing structure was originally developed for physics education (Klaassen, 1995) and has been used successfully in a number of other LT-strategies for chemistry and biology education (Knippels, 2002; Prins, 2010; Verhoeff, 2003; Westbroek, 2005). The use of a problem-posing structure can stimulate students to develop a motive for learning a concept, which can then be extended to a motive for recontextualising that concept by weaving it in a storyline that spans different contexts. This can, for instance, be achieved by the need for a more detailed description of a concept to satisfy the original motive, but which is not directly apparent from its use in the original context. The original motive can then develop into a motive for exploring the concept in more detail in another context in order to finally return to the original context and solve the original problem.

Another structure with a strong influence on the design of the LT-strategy described in this thesis is the yoyo-strategy (Knippels, 2002) that was developed for navigating the different levels of biological organisation. This structure was needed to allow a step-by-step exploration of the physiology and structure of human skeletal muscles down to sub-cellular levels of biological organisation. From there, students could move on to study the cells of other organisms and observe the effects of aerobic and anaerobic respiration in yeast cells. During the final series of LT-activities, they returned to the original context and the organism level of biological organisation (again: step-by-step). Because biological knowledge is structured using these levels of biological organisation, the yoyo-structure is expected to be applicable to most other LT-strategies for developing and recontextualising biological concepts.

Finally, the LT-strategy that is developed here used the idea of developing a context for education that is based on social practices. Many professional and scientific biological practices have a complex structure and use a large variety of biological concepts in order to satisfy their needs. For students to develop an intricate view on the relations between biological concepts in these practices, they cannot be introduced to all of these different concepts at once. Instead, context-based LT-strategies should introduce these concepts in a step-by-step process and not focus on too many concepts at once. However, this does not mean that it should completely focus on only one concept. The LT-strategy for recontextualising cellular respiration also included an exploration of muscular physiology and development of concepts related to that, and the use of model organisms in biological and medical research practices. However, the focus for the LT-strategy was cellular respiration. As such, the context is described as the focus on a particular problem in that social practices, related to the goals and motives from that social practice. To allow students to develop a new context, a series of orientation LT-activities should then introduce the social practice as a whole and then focus on a particular problem in that practice. A similar view has been described in a study on authentic modelling practices for chemistry education (Prins, Bulte, & van Driel, 2008).

These structures can be used together with the structure for recontextualising for designing LT-strategies that aim for students to develop biological concepts in a step-by-step process, while exploring different biological practices.

Chapter 5 in this thesis provides an example of how these phases can be intertwined with phases from other structures in an LT-strategy for recontextualising cellular respiration. The preparation-phase and reflection-phase are intended to engage students in activities for defining such concepts and were intertwined with orientation and reflection-phases from other structures. The recontextualising phase, intended for the introduction of new information regarding the concept, is consistent with the information gathering phase from the problem-posing cycle. Finally, the test-phase is part of any eventual LT-strategy that also intends to assess students' progress in terms of a flexible development for a concept. Ideally, this phase functions as an LT-activity and method for formative assessment, aside from the mostly summative function it had during the enactment of the LT-strategy in cases β1 and β2.

Using conceptual elements to describe students' intended conceptual development

The design-research project in this thesis included the use of conceptual elements for cellular respiration to identify specific steps in students' intended conceptual development during the LT-activities in the lesson module. Other complex, biological concepts can possibly be described similarly (see section 7.2). This can aid the design of domain-specific LT-strategies and provide a perspective on the specific steps students are expected to take during the course of their conceptual development. This allows us to better describe the learning goals for an entire lesson module, but also for the individual LT-activities included in such an LT-strategy. In many biology education practices, it is still very common to describe such goals using a single label for a concept (personal observation); we are often not specific in what parts or elements of a concept students are intended to develop and how they can get to these insights. By identifying the specific elements that describe a concept and possible combine to a conceptual core, we can specify these steps for students' intended development of a particular concept. This detailed perspective allows for the design of more consistent LT-strategies that provide students with enough, but not too much context-specific information needed to understand a concept in context (*the Goldilocks-zone*). As such, this idea can also be applied to designing consistent test for summative *and* formative assessments of students' ability to recontextualise a particular concept to other contexts.

More concept-specific LT-strategies

Designing LT-strategies like the one presented in this thesis requires a lot of time and resources that are probably not available for most teachers with a full-time appointment. Therefore, teachers cannot be expected to design

LT-strategies in an extended design-research process such as the one described in this thesis if not also provided with the resources needed to do so. Instead, teachers should have access to a variety of different LT-strategies which they can adapt for use in their own teaching practices. Ideally, a collection of such LT-strategies would be developed by design-teams, possibly consisting of teachers, professionals from biological practices, and researchers. This would allow for the teachers to concentrate on parts of the design-process and the implementation of LT-strategies in practice, while researchers can devote their resources to analysing the enactment and effects of such LT-strategies. A first step towards this ideal was made with the design-teams that have designed examples for context-based lesson modules that were based on the concept-context approach (see also: chapter 2). However, that project is finished and there seem to be no plans for similar projects in the immediate future.

7.4 Suggestions for future research

Exploring the process of recontextualising for other concepts and contexts in (biology) education, allows us to *recontextualise* this view on recontextualising, adding new elements to our perspective with each subsequent contextualisation. Although the idea of transfer has been studied extensively, the same cannot be said for this perspective on the process as recontextualisation. This section provides a few suggestions for further research on the recontextualising process.

Further research on LT-strategies for recontextualising biological concepts

The structure for recontextualising and the identification of conceptual elements have been described as the major outcomes of this design research project in sections 7.1 and 7.2. These sections included arguments for possible generalisations of these findings for developing LT-strategies and tests for recontextualising other biological concepts. However, these findings are still based on a design-research project that involved a single LT-strategy that aimed at one biological concept. For empirical proof that might support or refute the possible generalisation of these findings they need to be used in designing other LT-strategies for other biological concepts. In addition, there might be other possible solutions for the problem of recontextualising in secondary biology education. Thus, next to using - and testing – these findings for designing similar LT-strategies for other biological concepts, it can also be fruitful to compare the solution suggested in this thesis with other possible LT-strategies for recontextualising.

Further research on students' performance with recontextualising biological concepts

In order to test and possibly even compare the effectiveness of such LT-strategies, the identification of conceptual elements can help in the design of test-items that test for students' ability to recontextualise biological concepts. The test-items developed for this research project (see appendix I) provide an example of how such items can be designed to reflect similar uses of a concept in different contexts and organisms. These items were developed during the first design cycle and redesigned based on an analysis of students' written answers and numerous discussions with experts in (biology) education. The analysis of students' answers during the second design-research cycle provide an example of how these can be used to determine if an how students are able to recontextualise cellular respiration. However, this analysis included only 44 students in two different case studies. A large-scale use and analysis of these and similar test-items for recontextualising biological concepts would provide more insight into the fruitfulness of such test-items, and the use of conceptual elements for determining students' ability to recontextualise biological concepts. Finally, it would be very interesting to see if more test-items can be designed and used for other biological concepts and contexts, using a similar logic of identifying the conceptual elements for a concept.

Further research on students' individual learning trajectories while recontextualising

The analysis of students' learning trajectories and use of specific conceptual elements described in chapter 6 of this thesis looked at how many students managed to use a particular conceptual element in their answers to the different items in the recontextualising-test. It did not include an analysis of individual students' performance on the different test-items. For developing a better understanding of the recontextualising-process and *how* and *why* students are able to develop a biological concept and use it in different context, an individual view might be needed. This might be gained from detailed analyses of students' individual learning trajectories during an LT-strategy like the one described here, and combine these with individual performance to different context-based tests for recontextualising. Such an analysis of individual students' performance can provide additional insights in why students apparently identify and use a particular element successfully in one context, but fail to do so in another context with a similar problem.

Although there are possibly numerous other avenues for future research on the recontextualising-process, we end this discussion here with the final observation that in order to develop our understanding of it, we need to engage in numerous different activities where we attempt to use and define it in a variety of different, educational practices. If the findings from this design-research project and insights from other sources are combined (for instance: Greeno, 2006; Bransford & Schwartz, 1999), our perspective on recontextualising may be developed further. By repeatedly taking part in combined activities of (re)contextualising and defining our understanding of this idea, we can progress in our perspective and – possibly – develop a more flexible concept of recontextualisation. However, we should not lose sight of the fact that – similar to developing biological concepts – it is not the definition but the activity of defining that is the key.

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Summary

This thesis reports on a design-research study on recontextualising biological concepts that was carried out between 2007 and 2012 at the Freudenthal Institute for Science and Mathematics Education (FIsme). It adopted a design research approach to answer the following research question:

How can a learning-and-teaching (LT-) strategy, aimed at the flexible use of biological concepts through recontextualising, be structured?

Chapter 1 describes the theoretical framework that introduces the idea of recontextualising as an alternative perspective on the use of concepts in different contexts. In addition, it describes how the concept of cellular respiration is defined for purposes of this research project. The term *recontextualising* is based in cultural historical activity theory and was proposed as a change of perspective on the idea of knowledge-transfer. Within this view concepts are tools to be used in activities or contexts. A possible explanation for disappointing results from previous transfer-research is the idea that concepts are used – and described – differently by participants in different contexts. This means that knowledge cannot be easily transferred from one context to another, but needs to be re-evaluated and adapted for each new use in another context. This process of re-evaluation and adjustment of a concept to fit context-specific needs is termed recontextualising.

The concept of cellular respiration was selected as a main topic for the LT-strategy developed in this project. Within this thesis, it is defined as a biochemical breakdown of energy-rich substrates in order to release energy, which is needed in other biological processes. Aerobic respiration and anaerobic respiration are used to distinguish between the breakdown of a substrate with and without the use of oxygen, respectively. Typical examples of anaerobic respiration include alcoholic and lactic acid fermentation.

The methodology for this research project is described in **chapter 2**. The explorative phase of this research project included a theoretical and empirical exploration of context-based biology education, recontextualising, and cellular respiration. The empirical exploration involved the observation and analysis of two context-based lesson modules for senior general secondary education in practice. Insights from the explorative phase were used to design an LT-strategy for recontextualising cellular respiration. During the following, cyclic research phase, the LT-strategy was implemented in two different classes for senior general secondary education (case studies α1 and α2). The data from the implementation of the LT-strategy was analysed to describe the implemented learning trajectories in both cases. These were compared with the intended learning trajectory that was described in a scenario, with the objective of improving the LT-strategy.

The improved LT-strategy was then tested in case studies β1 and β2 during the second research cycle. In addition to the data collection for describing the implemented learning trajectories in cases β1 and β2, data from a pre- and post-test served to determine students' knowledge of cellular respiration before and after participating in the lesson module that was part of the LT-strategy. Also, a recontextualising-test was designed to test students' ability to use the concept of cellular respiration in various contexts. Data from the pre- and post-tests, and the recontextualising-test were analysed by identifying specific elements of the concept of cellular respiration. These conceptual elements formed an integral part of the design of the LT-strategy and for the analysis of students' answers to items in the recontextualising-test.

Chapters 3 and 4 describe the results from the explorative phase of this research project, which was guided by the following two (sub-) research questions: RQ I: *Which design criteria for an LT-strategy for recontextualising biological concepts can be identified from an empirical and theoretical exploration of recontextualising?* RQ II: *Which design criteria for an LT-strategy for recontextualising cellular respiration can be identified from a theoretical exploration of cellular respiration?*

Chapter 3 describes the development of design criteria related to recontextualising biological concepts, based on the empirical and theoretical exploration of transfer and recontextualising in relation to context-based biology education. This chapter finishes with an answer to RQ I by summarising design criteria for an effective LT-strategy for recontextualising biological concepts: It should focus students on a specific context related to the concept in a social practice (1-1); it should focus students on the conceptual elements needed in a context and allow for a stepwise conceptual development (1-2); it should invite students to explicate a concept in context (2-1); it should invite students to reflect on a concept in different contexts (2-2); and it should incite students to develop a motive for recontextualising a concept to different contexts (3).

Chapter 4 provides arguments for the choice for cellular respiration as the biological topic in this research project. It describes common problems with learning and teaching of cellular respiration, derived from science education literature. It also provides a description of how the concept is approached in Dutch textbooks for biology education. This chapter answers RQ II with a set of design criteria for an LT-strategy that aims at students to develop the concept of cellular respiration: It should clearly connect the molecular level to more familiar levels of biological organisation (4-1); it should use representations that emphasise the breakdown of carbon chains at the molecular level of biological organisation (4-2); it should invite students to compare aerobic and anaerobic respiration (5-1); it should invite students to compare lactic acid and alcoholic fermentation (5-2); it should include contexts that use the conceptual core of the concept (6-1); and it should include contexts that use different variants of cellular respiration and connect these in a single storyline (6-2).

Chapters 5 and 6 describe the cyclic research phases in this research project that were guided by the following research questions: RQ III: *How can we determine students' ability to recontextualise cellular respiration to other contexts?* RQ IV: *To what extent can the LT-strategy be considered adequate for promoting students' understanding of cellular respiration and their ability to recontextualise cellular respiration to other contexts?*

Chapter 5 describes the LT-strategy that was designed during the first research cycle, starting with the three contexts that were explored during the lessons in the LT-strategy. These were related to social practices of sports physiology, biotechnology, and biological research. Included in this description is an argumentation for the use of these contexts and how these can be used to design an LT-strategy that adheres to the design criteria described in chapters 3 and 4. This chapter continues with a description of the storyline in the intended learning trajectory for the LT-strategy. This storyline also guides the subsequent description of the implemented learning trajectory in cases α1 and α2. Finally, this chapter describes weaknesses in the design of the first (α-) version of the LT-strategy and their related solutions in the β-version of the LT-strategy.

Chapter 6 starts with a detailed description of the implemented learning trajectories in the second research cycle, including the results from- the pre- and post-test for determining students' understanding of cellular respiration before and after taking part in the LT-strategy. The chapter continues with the results from the recontextualising-test that was designed to determine if and how students were able to use cellular respiration in other contexts. These results provide answers to RQ III: although students develop a conception of cellular respiration for the contexts explored during the lesson module, they still had difficulty with recontextualising it to other contexts. A comparison of the results from different items in the recontextualising-test revealed two possible explanations for students' apparent difficulties, related to *students' (un-) familiarity with a biological object of focus* in a context, and *the actions that are performed on a biological object of focus* in a context.

Finally, this chapter discusses the effectiveness of the LT-strategy in answer to RQ IV and concludes with a description of a third version of the LT-strategy. This third version (not tested) includes additional LT-activities following the recontextualising-test, which are intended for students to reflect on their own answers to the different test-items.

Chapter 7 relates the findings from this design research project to other sources in an attempt to develop additional, theoretical insights in the process of recontextualising. The first part of the answer to the research question is provided with the identification of four different phases related to recontextualising. These phases describe specific phases for structuring an LT-strategy for recontextualising biological concepts. Although no specific order for these phases is prescribed, a *preparation-phase* can probably best precede *recontextualising-phases*. Thus, students can first develop a description of a concept in one context (*preparation*), before exploring the concept in a different context (*recontextualising*). The *reflection-phase* is expected to be fruitful after students have had a chance to develop descriptions of the concept in at least two different contexts. The *test-phase* can be used to determine students' ability to recontextualise a concept, its formative function is emphasised by a subsequent reflection phase. The order described here is not meant to be set in stone. In fact, the *storyline* that guides an LT-strategy is expected to be the primary guide in determining whether or not a particular phase is to be included at a specific moment in an LT-strategy.

The second part of the answer to the main research question in this final chapter is described as the use of conceptual elements. These can be used for designing successful LT-strategies for recontextualising and help to connect different contexts in a single storyline that describes a gradual development for a concept in an LT-strategy. Conceptual elements are not only specific for a concept, but also depend on the contexts and learning goals in an LT-strategy, and student' expected prior knowledge of a concept. In addition to their use in designing LT-strategies for recontextualising, conceptual elements can also be used for designing test-items to determine students' ability to recontextualise a concept. Conceptual elements can provide a clear view of how a concept is intended to be used and described in response to particular context-based test-items and as such, can be used to find possible explanations for students' performance with recontextualising biological concepts in different contexts. Finally, this chapter describes possible implications for education that stem from this research project, and concludes with some suggestions for further research.

Samenvatting

Dit proefschrift rapporteert over een ontwerponderzoek naar het recontextualiseren van biologische concepten. Dit ontwerponderzoek was uitgevoerd tussen 2007 en 2012 aan het Freudenthal Institute for Science and Mathematics Education (FIsme) en was gericht op de volgende onderzoeksvraag:

Hoe kan een onderwijsleerstrategie die is gericht op een flexibel gebruik van biologische concepten door recontextualiseren, worden gestructureerd?

Hoofdstuk 1 beschrijft de theoretische achtergrond en introduceert *recontextualiseren* als een alternatief perspectief op het gebruik van concepten in verschillende contexten. Daarnaast beschrijft dit hoofdstuk het concept *dissimilatie* binnen dit onderzoeksproject. De term *recontextualiseren* heeft een basis in cultuurhistorische activiteitentheorie en biedt een alternatief perspectief op de transfer van kennis. Dit perspectief beschrijft concepten als kennisgereedschappen die worden gebruikt in activiteiten of contexten. Een mogelijke verklaring voor teleurstellende resultaten in voorgaand onderzoek naar transfer kan worden gevonden in het idee dat concepten verschillend worden gebruikt en beschreven in verschillende contexten. Dit houdt in dat kennis niet eenvoudigweg kan worden gekopieerd van een context naar een andere, maar dat deze kennis moet worden geëvalueerd en aangepast voor gebruik in de andere context. Dit proces van evaluatie en aanpassing van een concept wordt *recontextualiseren* genoemd.

Het concept *dissimilatie* is gekozen als onderwerp voor de onderwijsleerstrategie die in het kader van dit onderzoeksproject is ontwikkeld. Dit proefschrift beschrijft dissimilatie als een biochemisch afbraakproces van een energierijk substraat om er energie uit vrij te maken, die nodig is om andere biologische processen te doen verlopen. Aerobe en anaerobe dissimilatie onderscheiden verschillende dissimilatieprocessen, met en zonder het gebruik van zuurstof. Typische voorbeelden van anaerobe dissimilatie zijn melkzuurgisting en alcoholgisting.

De methodologie voor dit onderzoeksproject wordt beschreven in **hoofdstuk 2**. De explorative fase van dit onderzoek bestond uit een theoretische en empirische verkenning van context-gebaseerd biologie onderwijs, recontextualiseren en dissimilatie. De empirische verkenning bestond uit de observatie en analyse van het ontwerp en de uitvoering van twee lesmodules voor context-gebaseerd biologie onderwijs in het HAVO. De inzichten uit het exploratieve onderzoek werden gebruikt voor het ontwerpen van een onderwijsleer-strategie voor het recontextualiseren van dissimilatie. Tijdens de hierop volgende, cyclische onderzoeksfase werd deze onderwijsleerstrategie uitgevoerd in twee verschillende klassen in het HAVO (casestudies α1 en α2). De data die tijdens de uitvoering werd verzameld, zijn geanalyseerd om het uitgevoerde onderwijsleertraject in beide casestudies te beschrijven. De uitkomsten daarvan zijn vervolgens vergeleken met het geplande onderwijsleertraject dat was beschreven in een scenario, met de bedoeling om de onderwijsleerstrategie te verbeteren.

De verbeterde onderwijsleerstrategie werd getest in casestudies β1 en β2 tijdens de tweede onderzoekscyclus. Naast de dataverzameling om de uitgevoerde onderwijsleertrajecten in deze casestudies te beschrijven, dienden een pre- en post-test om het begrip van dissimilatie bij de leerlingen voor en na deelname aan het onderwijsleerproces te inventariseren. Daarnaast werd er een toets ontworpen om de vaardigheid van leerlingen te toetsen om dissimilatie te kunnen recontextualiseren in verschillende contexten. Data uit de pre- en post-test en de recontextualisatie-toets werden geanalyseerd door specifieke elementen van dissimilatie te identificeren. Deze conceptuele elementen vormden een onderdeel van het ontwerp van de onderwijsleerstrategie en de analyse van de antwoorden van leerlingen op de vragen in de recontextualisatie-toets.

Hoofdstukken 3 en 4 beschrijven de resultaten uit de exploratieve fase van dit onderzoeksproject, welke was gericht op het beantwoorden van de volgende twee deelvragen. RQ I: Welke ontwerpcriteria kunnen worden geïdentificeerd aan de hand van een empirische en theoretische verkenning van recontextualiseren, voor het recontextualiseren van biologische concepten? RQ II: Welke ontwerpcriteria kunnen worden geïdentificeerd aan de hand van een theoretische verkenning van dissimilatie, voor het recontextualiseren van dissimilatie?

Hoofdstuk 3 beschrijft de ontwikkeling van ontwerpcriteria voor het recontextualiseren van biologische concepten, gebaseerd op een empirische en theoretische verkenning. Dit hoofdstuk besluit met een antwoord op deelvraag RQ I door deze ontwerpcriteria voor een effectieve onderwijsleerstrategie voor het recontextualiseren van biologische concepten op te sommen. Een dergelijke strategie moet leerlingen richten op een specifieke context die is gerelateerd aan het concept in een praktijk (1-1); moet leerlingen richten op de conceptuele elementen die in een context nodig zijn en een stapsgewijze ontwikkeling van het concept mogelijk maken (1-2); moet leerlingen uitnodigen een concept in relatie tot contexten te beschrijven (2-1); moet leerlingen uitnodigen om te reflecteren op de betekenis van een begrip in verschillende contexten (2-2); ten slotte moet een dergelijke strategie leerlingen stimuleren om een motief voor recontextualiseren te ontwikkelen (3).

Hoofdstuk 4 geeft argumenten voor de keuze van het concept *dissimilatie* als biologisch onderwerp voor dit onderzoek. Dit hoofdstuk beschrijft veel voorkomende problemen met het onderwijzen en leren van dissimilatie. Daarnaast beschrijft het de manier waarop het concept wordt beschreven in Nederlandstalige biologieboeken voor het HAVO. Dit hoofdstuk beantwoordt deelvraag RQ II met de volgende ontwerpcriteria voor een onderwijsleerstrategie voor het recontextualiseren van dissimilatie. Een dergelijke strategie moet de organisatieniveaus cel en molecuul, helder verbinden met de meer bekende organisatieniveaus orgaan en organisme (4-1); moet representaties gebruiken die de afbraak vak van koolstof-ketens benadrukken op het organisatieniveau molecuul (4-2); moet leerlingen uitnodigen om aerobe en anaerobe dissimilatie te vergelijken (5-1); moet leerlingen uitnodigen melkzuurgisting en alcoholgisting te vergelijken (5-2); bevat contexten die gebruik maken van de conceptuele kern van dissimilatie (6-1); ten slotte verbindt en verweeft een dergelijke strategie contexten waarbinnen verschillende varianten van dissimilatie worden gebruikt in een verhaallijn.

Hoofdstukken 5 en 6 beschrijven de cyclische onderzoeksfase, die was gericht op de volgende deelvragen. RQ III: Hoe kunnen we de vaardigheid van leerlingen vaststellen met betrekking tot het recontextualiseren van dissimilatie naar andere contexten? RQ IV: In hoeverre is de onderwijsleerstrategie effectief als het gaat om de ontwikkeling van het concept dissimilatie door leerlingen en hun vaardigheid dit concept te recontextualiseren naar andere contexten?

Hoofdstuk 5 beschrijft de onderwijsleerstrategie in de eerste onderzoekscyclus en begint met de drie contexten die hierin zijn gebruikt om het concept dissimilatie te ontwikkelen. Deze contexten zijn gerelateerd aan praktijken voor sportfysiologie, biotechnologie en biologisch onderzoek. Daarna volgen argumenten voor de keuzen voor deze drie contexten en hoe deze voldoen aan de ontwerpcriteria. Hierna wordt de verhaallijn beschreven voor het geplande onderwijsleertraject, die ook wordt gebruikt voor de daaropvolgende beschrijving van het uitgevoerde onderwijsleertraject in casestudies α1 en α2. Ten slotte beschrijft dit hoofdstuk zwakheden in het ontwerp van de eerste (α-) versie van de onderwijsleerstrategie en de oplossingen daarvoor in het ontwerp van de β-versie.

Hoofdstuk 6 geeft een gedetailleerde beschrijving van het uitgevoerde onderwijsleertraject in de tweede onderzoekscyclus en de resultaten van de pre- en post-tests. Dit hoofdstuk vervolgt met de resultaten van de toets om de vaardigheid van leerlingen vast te stellen met betrekking tot het recontextualiseren van biologische concepten in andere contexten. Deze resultaten worden vervolgens gebruikt om een antwoord te geven op deelvraag RQ III. Hoewel leerlingen een begrip van dissimilatie ontwikkelen tijdens het onderwijsleerproces, hadden zij naderhand nog steeds moeite met het recontextualiseren hiervan naar andere contexten. Vergelijking van de resultaten voor verschillende opdrachten in deze toets geeft hiervoor twee mogelijke verklaringen: de bekendheid van leerlingen met een biologisch object in een context en de wijze waarop een biologisch object in een context wordt gebruikt. Ten slotte wordt de effectiviteit van de onderwijsleerstrategie besproken aangaande de ontwikkeling van het concept dissimilatie door leerlingen en hun vaardigheid dit concept te recontextualiseren (deelvraag RQ IV). Dit hoofdstuk sluit af met een beschrijving van een derde versie van de onderwijsleerstrategie. Deze derde versie bevat aanvullende onderwijsleeractiviteiten voor een expliciete reflectie door de leerlingen op hun antwoorden op de vragen in de recontextualisatie-toets.

Hoofdstuk 7 verbindt de uitkomsten van dit ontwerponderzoek met andere bronnen in een poging om de theorie van recontextualiseren aan te vullen. De onderzoeksvraag wordt in twee delen beantwoord. Het eerste deel omvat de beschrijving van vier fasen voor recontextualiseren. Hoewel er geen specifieke volgorde wordt voorgeschreven, kan de *voorbereidingsfase* het beste voorgaan aan een *recontextualisatie-fase*. Zo beschrijven leerlingen eerst hun begrip van een concept (*voorbereiding*), voor ze het bestuderen in een andere context (*recontextualiseren*). Een *reflectie-fase* kan vruchtbaar zijn nadat leerlingen hun begrip hebben beschreven in twee of meer verschillende contexten. De *toets-fase* is bedoeld om de vaardigheid van leerlingen vast te stellen met betrekking tot het recontextualiseren van een begrip. Een daaropvolgende *reflectie-fase* kan bijdragen aan de ontwikkeling van een flexibel begrip van een concept. De verhaallijn van een onderwijsleerstrategie is uiteindelijk bepalend voor de beslissing of een bepaalde fase voor recontextualiseren wel of niet op een bepaald moment moet worden ingevoegd.

Het tweede deel van het antwoord op de onderzoeksvraag is beschreven als het gebruik van conceptuele elementen. Deze kunnen worden gebruikt om onderwijsleerstrategieën te ontwerpen voor recontextualiseren en het verbinden van verschillende contexten in een verhaallijn. Conceptuele elementen zijn niet alleen specifiek voor een concept, maar zijn ook afhankelijk van de contexten en leerdoelen in een onderwijsleerstrategie en de verwachte voorkennis van leerlingen. Naast het gebruik van conceptuele elementen voor het ontwerpen van onderwijsleerstrategieën, zijn ze ook goed te gebruiken voor het ontwerpen van toetsvragen om de vaardigheid van leerlingen met betrekking tot recontextualiseren te toetsen. Deze elementen geven een helder beeld van de verwachte of bedoelde wijze van gebruik van een concept voor specifieke vragen en opdrachten in contexten en kunnen zo worden gebruikt om mogelijke verklaringen te vinden voor de prestaties van studenten in het recontextualiseren van biologische concepten in verschillende contexten. Ten slotte beschrijft dit hoofdstuk mogelijke gevolgen voor biologieonderwijs en enkele suggesties voor vervolg onderzoek.

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Appendices

Appendix I: Contexts and items in the recontextualising-test

Context 1, item 1

Producing Yeast **A yeast producer (biological engineering)**

Today, one can easily buy yeast in the supermarket for home use. Bakers and beer producers use yeast in large quantities. These yeasts are produced by (for instance) the company “DSM Gist” in Delft (the Netherlands). They use large tanks in which the yeast cells can reproduce over time. The newly formed yeast cells are ‘harvested’ from a tank on a regular basis. The yeast cells require a lot of energy for their reproduction.

Imagine that you are a yeast producer who has to design a new facility for reproducing yeast on a large scale. The time it takes yeasts to reproduce is not an important factor. What is important is that the food supply for the yeast is used as efficiently as possible, meaning to gain as much yeast cells per kilogram of food substances. For your design, you have the choice between tanks that are deprived of oxygen or tanks in which oxygen is constantly bubbled through the yeast suspension.

1. Explain as thoroughly as possible which of the two tanks you would choose if you need the yeast to reproduce as much as possible.

Context 2, items 2 and 3

Differences between marathon and sprint runners **A sports physiologist**

During the previous series of lessons, you have studied and compared the structure and function of runners’ muscles, just like sports physiologists do, both during their education and in their practice.

2. The muscles of marathon- and sprint runners are built differently. What are the most important differences in muscular structure between sprint- and marathon runners?

3. The muscle fibres of marathon runners can perform with far greater duration than muscle fibres of sprint runners, while those of a sprint runner are capable of a fast release of energy for an explosive type of performance. Which processes of breakdown are responsible for providing the energy in these muscle cells? Describe these processes as thoroughly as possible.

Context 3, items 4 and 5

Producing wine by yourself **An amateur vintner**

A website for amateur vintners contains an explanation how you can brew your own wine at home. The website describes how yeast is added to grape juice in a large barrel or bottle. The yeast converts the sugars (like glucose) from grape juice to (among others) alcohol. De website's developers explain that it is ***very important*** that one seals the barrel or bottle with a 'water-lock' (see the picture on the right). This water-lock seals the bottle of from oxygen in the outside air.

4. Explain as thoroughly as possible why it is so important that the yeast and grape juice in the barrel or bottle are sealed off from oxygen.

The water-lock is constructed in such a way that it does allow gasses to exit the bottle.

5. What gas (or gasses) has to be released from the bottle? Explain the origin of this gas as thoroughly as possible.

Context 4, items 6 and 7

No more cavities **A dentist and a biological engineer**

A dentist and a bio engineer have developed an idea to put an end to tooth decay. Tooth decay is caused by so-called *lactic acid* bacteria. These lactic acid bacteria live in our mouths from food particles between our teeth. When these lactic acid bacteria break down the glucose from the food particles, lactic acid is produced. This lactic acid damages the glazing of our teeth, eventually creating cavities. The figure below depicts this process schematically.

Step 1: Food particles (containing glucose) are left behind in our mouth.	⇒	Step 2: Lactic acid bacteria in our mouth break down glucose and release lactic acid.	⇒	Step 3: The lactic acid damages the glazing of our teeth, so cavities can develop.

Lactic acid bacteria are simple, single-celled organisms without a nucleus or other organelles such as mitochondria.

6. The lactic acid bacteria break down glucose into lactic acid. Explain as thoroughly as possible why they cannot break down glucose completely to carbon dioxide and water.

The dentist and the bio engineer want to disrupt this process. Their idea is to engineer the bacteria in such a way that they produce alcohol instead of lactic acid when breaking down glucose. If a patient regularly washes his mouth with a solution of these engineered bacteria, they expect the engineered bacteria to replace the lactic acid producers over time. Thus, lactic acid is no longer produced and cannot damage any more tooth glazing. This is schematically depicted in the figure below.

Step 1:
Food particles (containing glucose) are left behind in our mouth.

→

Step 2:
The new bacteria in our mouth break down glucose and release ***alcohol***.

→

Step 3:
The alcohol does ***not*** damage the glazing of our teeth, so ***no*** cavities can develop.

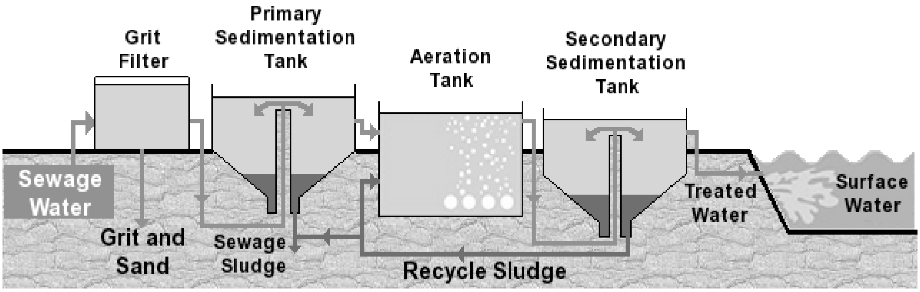
The alcohol evaporates and is exhaled for the most part and thus does not influence the patient in any way. The bio engineer explains that is very important to provide the engineered bacteria with another method for breaking down glucose, instead of removing this capability altogether.

7. Explain as thoroughly as possible what would happen to these engineered bacteria if they lost the ability to break down glucose completely.

Context 5, items 8 and 9

Wastewater cleaning **A process engineer**

In the cleaning of wastewater, we often use living organisms (bacteria). The process engineer is someone who designs, maintains and inspects wastewater cleaning facilities. An example of a commonly used cleaning process is given in the figure below (see next page). This cleaning facility removes most of the waste from the water so it can be released back into the environment.



Step 1 - Large pieces of dirt and grit are removed using huge reeks or mesh screens. From here, the water slowly flows onward, while sand settles at the bottom to be collected and re-used.	**Step 2 -** In the primary sedimentation tank, particles of dirt slowly settle at the bottom. This *sludge* is then collected and moved to another tank for further thickening. After a while, the sewage water flows on to the next tank.	**Step 3 -** In the aeration tank, bacteria are added to the water. These bacteria use the organic waste particles in the water as a food source and break them down. Also, oxygen is added to the water.	**Step 4 -** In the secondary sedimentation tank, the bacteria settle at the bottom. Part of them is returned to the aeration tank. Another part is returned as waste to the primary sedimentation tank.	**Step 5 -** When most of the particles and bacteria have settled, the water is clean enough to be released into the surface water.

Bacteria are added in step 3. Also, air is bubbled through the water, adding oxygen. This type of cleaning is called ‘aerobic cleaning’.

8. Explain as thoroughly as possible why oxygen is added in this step.

Another type of wastewater cleaning is *anaerobic* cleaning, in which bacteria break down glucose without using oxygen. Imagine that you are a process-engineer that has been asked to design a cleaning facility for breaking down the waste as much as possible. For this facility, you can choose between an aerobic or anaerobic cleaning phase.

9. Explain as thoroughly as you can which type of cleaning you would choose if you want the waste to be broken down as much as possible.

Context 6, items 10 and 11

Mitochondrial diseases **Physicians, nurses and medical lab technicians**

The university children's' hospital at the university medical centre St. Radboud in Nijmegen, has for over twenty-five years dedicated special attention to the care for patients with defective mitochondria in their cells: mitochondrial diseases. Several disciplines involved in the study and treatment of these diseases are incorporated in the Nijmegen Centre for Mitochondrial Diseases (NCMD), a unique centre for the Netherlands.

The website for the NCMD explains the symptoms for patients with mitochondrial diseases. The following quote describes one of these symptoms:

"Usually, patients' blood, urine and brain fluids show an elevated amount of lactic acid. Therefore, the measurement of this lactic acid (or lactate) is usually one of the first tests for identifying these diseases in patients."

10. The cells that compose these patients' bodies convert glucose to lactic acid. Describe as thoroughly as you can why they cannot completely convert glucose to carbon dioxide and water.

Other important symptoms are feelings of fatigue and apathy in a patient.

11. Explain as thoroughly as you can why a patient feels fatigued and apathetic.

Appendix II: Scenario example

This appendix describes a part of the scenario in case study. The scenario was used to describe the intended learning trajectory, and details the expected actions of students and the teacher for each LT-activity in the LT-strategy. This example describes episodes 1 through 5 (see table 5.14).

Abbreviations: Ep. = episode; LTA = learning-and-teaching activity; M = learning-and-teaching materials; Org. = organisation of an LT-activity; WBA = workbook assignment.

Ep.& LTA	Time (min)	LT-function and storyline	Expected teacher actions	Expected student actions
Ep.1; LTA 1	10	LT-function: orientation Storyline: orientation on professional athletes and sports physiology. Introduce a sports physiology perspective. Org. whole class discussion M: video from FC Utrecht TV*	Explains to the students that they are going to look at professional athletes from the perspective of a sports physiologist. Shows a video fragment from FC Utrecht TV (professional football club). Leads a whole class discussion on the role of a sports physiologist: goals, actions, knowledge, etc. Asks the students what aspects are important for proper development of athletes?	Comment on the video fragment. Identify the development of a proper training schedule and specific diet for athletes as an important goal. Identify that a sports physiologist needs an understanding of how an athlete's body and its organs (muscles, digestive system) function. as important knowledge
		Together, students and the teacher reach the following conclusions: A sports physiologist works with athletes and trainers in order to improve an athlete's performance. Part of this job is, for example, to develop a proper training schedule and a specific diet for an athlete. A sports physiologist needs biological (physiological) knowledge of how the body (and its organs, and cells) functions and is structured.		
Ep. 1; LTA 2	15	LT-function: orientation Storyline: Orientation on runners from a	[Hands out the workbook to the students] Informs students that they are going to watch	Write down the observed differences between

		sports physiology perspective. Differences between marathon- and sprint runners. Org: individual assignment and whole class discussion. M: photos, video fragments of sprint- and marathon runners; WBA no. 1	other video fragments and pictures of sprint- and marathon runners. Asks students to describe the differences that they observe between these athletes. Discusses answers from students in a whole class discussion, which leads to the conclusion below.	sprint- and marathon runners: in body structure; muscular structure; in performance. Describe differences in body structure, muscle structure, and type of performance between sprint- and marathon runners as important from a sports physiology perspective.
		Together, students and the teacher reach the following conclusions: Sprint runners have bigger muscles and a larger body structure than marathon runners, who have a more slender body structure. Sprint runners deliver a powerful and fast performance, but soon become exhausted. Marathon runners have more stamina than sprint runners, but deliver less powerful and slower performances as well.		

*Video online available at: *http://www.123video.nl/playvideos.asp?MovieID=539825*; 00m:56s to 02m:00s.

Ep. 1, LTA 3	10	LT-function: orientation Storyline: specify the knowledge needed to explain differences between marathon- and sprint runners from a sports physiology example in question 1. Org. individual assignment or in pairs. M: WBA no. 2.	Asks students what kind of (biological) knowledge a sports physiologist needs to explain differences between sprint- and marathon runners. Instructs them to first think of an answer for themselves and write it down in the workbook. Asks students to describe their answers and notes these on the blackboard. Leads students in a whole class discussion on the relevance of students' answers. The discussion leads to the	Write down their thoughts on the required knowledge in the workbook. Mention knowledge of muscular structure and function of human muscles; knowledge of the influence of training exercises on a muscular development; knowledge of the digestive system. Students may also mention knowledge that is not directly relevant.

<table>
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<td>conclusions below.
Rephrases students' remarks to finishes the discussion with a description of question 1 (see below).</td>
<td>Students identify the importance of physiological knowledge, although they are not expected to spontaneously formulate a question.</td>
</tr>
<tr>
<td colspan="3">Together, students and the teacher reach the following conclusions:
A sports physiologist supports trainers and athletes in, for example, developing specific training programmes and diets. This requires a sports physiologist to have a detailed understanding of the differences between power- and endurance-focused athletes (sprint- and marathon runners, respectively). This in turn, requires a detailed understanding of the structure and function of human muscles.
Question 1: How can we (a sports physiologist) explain the differences in performance and build between sprint- and marathon runners?</td>
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<tr>
<td rowspan="2">Ep. 2; LTA 4</td>
<td rowspan="2">20</td>
<td>LT-function: information and exploration: muscle physiology.
Storyline: find an answer to question 1 by studying muscle physiology.
Org. assignment in pairs
M: a set of pictures depicting muscle physiology (workbook); WBA no.'s 3a, 3b, & 3c.</td>
<td>Instructs students to study and describe a set of pictures depicting the structure and function of muscles at the organism and organ levels of biological organisation.
Visits each pair of students and asks them to explain the pictures in the workbook to stimulate them to provide a thorough description.</td>
<td>Describe the structure and function of human skeletal muscles at the organism and organ levels of biological organisation (see below).</td>
</tr>
<tr>
<td colspan="3">Students (with help from the teacher) describe the following aspects of muscle physiology:
Marathon runners have a more slender build than sprint runners, who have a notably large muscular build. A skeletal muscle consists of muscle fibre bundles, which in turn consist of red and white muscle fibres. Muscle fibres are long, fibre-like cells that have developed through a fusion of individual cells before birth, essentially becoming a single long cell with multiple nuclei. The fibre bundles of a marathon runner have a high number of red</td>
</tr>
</table>

		muscle fibres, while those of a sprinter have a high number of white muscle fibres.		
Ep. 2; LTA 5	15	LT-function: information and exploration: muscle physiology. Storyline: find an answer to question 1 by studying muscle physiology. Org. assignment in pairs or small groups M: a set of pictures depicting muscle physiology (workbook); WBA no.'s 3d, 3e.	Instructs students to study and describe a set of pictures depicting the structure and function of muscles at the organ and cellular levels of biological organisation. Visits each pair of students and asks them to explain the pictures in the workbook, stimulating them to provide thorough descriptions and develop their understanding.	Describe the structure and function of human skeletal muscles at the organ and cellular levels of biological organisation (see below).
		Students (with help from the teacher) describe the following aspects of muscle physiology: Muscle fibres or cells contain long, fibre-like structures: myofibril. These are organised lengthwise in microfilaments (made from the proteins actin and myosin). These microfilaments hook together and can decrease their overall length, thereby contracting the muscle fibre or cell. Groups of muscle fibre bundles work together, the strength of a muscle's contraction increases. White muscle cells (fibres) contain more microfilaments and can provide a more powerful contraction than red muscle fibres. Red muscle cells contain more mitochondria than white muscle cells.		
Ep. 3; LTA 6	20	LT-function: information and exploration: muscle physiology. Storyline: specify question 1 in questions 2, 3, and summarise	Asks students to describe their answers and notes these on the blackboard. Leads students in a whole class discussion for describing muscular physiology and identifying 'knowledge-gaps' for answering	Mention differences at different levels of biological organisation. Expected difficulties with formulating these differences are solved by a discussion or by the

		these in question 4. Org. whole class discussion M: a set of pictures depicting muscle physiology (workbook); WBA no. 4.	question 1. Rephrases students' remarks to finishes the discussion with a description of questions 2, 3, and 4 (see below).	teacher. Add to their written descriptions from LTA 4 and 5. Mention the differences in the need energy supply between white and red muscle cells (fast vs. slow) as requiring more explanation.
		Together, students and the teacher reach the following conclusions: **Question 2:** How are white muscle cells capable of a faster and more powerful performance than red muscle cells, although white muscle cells contain fewer mitochondria than red muscle cells? **Question 3:** How are red muscle fibres capable of delivering a performance over a longer time than white muscle cells? **Question 4:** From where and how does a muscle cell get the energy it needs?		
Ep. 4; LTA 7	15	LT-function: explicate prior knowledge (combustion). Storyline: find an answer to question 4 using prior knowledge. Org. individual assignment M: WBA no.'s 5a & 5b.	Asks students to write down their own thoughts on the energy supply in muscle cells. Stimulates students to provide a thorough description of their thoughts.	Students are expected to mention and describe (parts of) the 'combustion' process, but are expected to have difficulty with separating this from food intake, digestion, and respiration at the organism level of biological organisation.
Ep. 4; LTA 8	15	LT-function: explicate prior knowledge (combustion); information and exploration: muscle physiology. Storyline: find an answer to question 4 using	Asks students to describe their thoughts on the energy supply in muscle cells, inviting them to supplement and/or correct each other's descriptions. Helps students to rephrase their answers, while emphasising the	Students describe and discuss their thoughts. With help from the teacher, they are able to distinguish food intake, digestion, and respiration at the organism level of biological organisation, from combustion at the cellular level of biological

		prior knowledge. Org. whole class discussion M: WBA no.'s 5c & 5d.	release of energy by breaking down glucose molecules. The discussions leads to the conclusions described below.	organisation.
		Together, students and the teacher reach the following conclusions: *Glucose*, which is delivered to a muscle cell via the bloodstream after digestion, is *broken down* using oxygen in a combustion process that releases *water* and *carbon dioxide*. The *function* of combustion is to *release energy* that was previously stored in glucose, and temporarily store this energy as ATP. This can be used to power the contraction of a muscle cell. To distinguish this biological process from 'normal' combustion in a fire, scientists use the term: *cellular respiration*.		
Ep. 5; LTA 9	10	LT-function: orientation; *develop a motive for recontextualising*. Storyline: identify a direction for further study to find an answer to question 4. Org. whole class discussion M: WBA no. 6	Reminds students of questions 1 to 4 and asks them if they are now able to formulate fitting answers to these questions. Ask students where a sports physiologist might have retrieved this knowledge from. Asks students to describe the origin of the knowledge that has been made available for sports physiologists in books. Indicates biological / biomedical research the direction for further study of cellular respiration in order to find answers to questions 1 to 4.	Mention differences in performance and muscular structure between marathon- and sprint runners. Indicate that a sports physiologist probably develops a lot of this knowledge by studying specific textbooks during higher vocational education. Indicate biological or biomedical research as a probable origin for this knowledge. Students possibly also mention research using laboratory animals.

This is the end of this example of the scenario for the LT-strategy (episodes 1 – 5) in case study β2. A Dutch version of the complete scenario and the workbook for students will be made available on the website of the Freudenthal Institute for Science and Mathematics Education: *http://www.fisme.science.uu.nl/fisme/nl/materialen/index.php* .

Dankwoord

Dankwoord

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Curriculum vitae

Menno Wierdsma was born on July 14, 1976 in Eindhoven, the Netherlands. He grew up in Franeker, where he attended senior general secondary education (HAVO) at “CSG Anna Maria van Schurman”. He then moved to Dokkum and attended pre-university secondary education (VWO) there at “CSG Dockingacollege”. At the University of Groningen, he studied biology and received his Master’s degree in 2003, followed by a teacher training programme at that same university. After finishing that programme in 2004, he moved to Rotterdam to become a teacher of biology and general sciences at the secondary school “Krimpenerwaardcollege” in Krimpen aan den IJssel. From 2007 to 2010, he combined his teaching job with this PhD research project at the Freudenthal Institute for Science and Mathematics Education (FIsme) at Utrecht University, funded through the DUDOC-programme for science teachers doing education research. In 2010, he moved back to Groningen to become a (secondary school) biology teacher educator at the University of Groningen where he is still employed. In addition, he now works as a science teacher in (primary school) teacher education at Hanzehogeschool Groningen.

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