Systems thinking in biology amongst lower secondary students

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Abstract: In a scientific society, quality science education in secondary education is of great importance to prepare students for a possible future in science. In the Netherlands, one approach to increase learning achievements in science is the introduction of the crosscutting concept of systems thinking in lower secondary science education. In order to effectively implement systems thinking in lower secondary science didactics, it is important to investigate students' inherent awareness of systems thinking. The aim of this study is to investigate the extent to which lower secondary students describe systems thinking characteristics in solving complex biological problems. In a seven week lesson series, student metacognitive awareness was promoted through the use of a student journal and group discussions. Student formulated strategies were retrieved and analysed for metacognitive components. Four distinct categories of student strategies were found. The categories were analysed for systems thinking characteristics. The findings indicate that a majority of students formulate certain systems thinking characteristics in their approach to complex biological problems. This may have implications for systems thinking in lower secondary curricula, allowing for a more specialised didactical approach.

Key words: Crosscutting concepts, systems thinking, biology education

Introduction

Children receive science education from an early age to cultivate scientific literacy. This is required in a scientific society. The Programme for International Student Assessment (PISA) describes scientific literacy as the ability to apply scientific knowledge in different contexts, the acquisition of new knowledge, describing scientific phenomena and drawing conclusions from evidence. A readiness of students to engage with scientific ideas is also considered to be part of scientific literacy. These components of knowledge of, ability in and attitude towards science are derived from the PISA framework (OECD, 2013). Another such framework is the K-12 Science Education Framework, developed in the United States by experts in science education. This framework forms a fundament for the revision of science education to increase student achievements and attitude towards science from kindergarten until the end of high school (National Research Council, 2012).

In 2011 the ‘’Actieplan Beter Presteren’’, an action plan for better learning, has been proposed to the Dutch parliament by the Minister of Education, Culture and Science (OCW, 2012). The goals for this action plan are the reinforcement of ambition in lower secondary education and advancement of learning achievements of pupils. These goals are adapted from the PISA framework of scientific literacy and K-12 science education framework and function as benchmarks to keep science education at a sufficient quality level. Through further elaboration of this plan, the minister hopes to increase the PISA score of Dutch pupils in science by the year 2015 and 2018.

In a response to this proposal, the Dutch institute of curriculum development (SLO) has developed a curricular guideline called *Kennisbasis natuurwetenschappen en technologie voor de onderbouw VO*, which will be referred to as " Kennisbasis" in this thesis (Ottevanger *et al.*, 2014). The Kennisbasis is a document that helps secondary schools to put the ambitions of the Minister of Education, Culture and Science into practice. The goal of the Kennisbasis is to provide schools and teachers guidance in improving science education to increase learning achievements and to prepare students for higher secondary science education. Also, by providing more coherence in the curriculum of science subjects such as physics, chemistry, biology, physical geography and technology, the SLO hopes to stimulate students’ orientation towards science in higher secondary education.

The Kennisbasis subdivides the science subjects into three interwoven dimensions; subject-matter, crosscutting practices and crosscutting concepts. Subject-matter are the subjects that teachers are required to teach within a certain science discipline. These are adapted from a guideline earlier developed by the SLO; *Leerplan in beeld*. Crosscutting practices (werkwijzen) are common practices used by technicians, scientists and engineers alike, for example researching, designing and logic reasoning. By distinguishing these common practices in science related subjects, the Kennisbasis provides possibilities to increase the coherence of the science curriculum in secondary school. Crosscutting concepts (denkwijzen) are concepts that are characteristic for the field of science. Therefore these concepts can be taught in any science class, independent of the subject. Examples are patterns, scale, systems, cause and effect, structure and function and durability. By teaching these concepts in different science disciplines it is assumed that with the increased focus on interconnectivity of these concepts, the learning achievements of pupils will increase and a better orientation on a future in science is provided to reinforce pupils’ ambition for science.

The minister’s plans are ambitious. Even though SLO provides direction to teachers, the pupils are an important factor to take into consideration as well. New approaches to science curricula do not only require being of good quality, but also require to be adapted to the students’ ability and potential. As this new educational approach to science in lower secondary school is relatively young, very little is known about pupil’s perceptions and application of crosscutting practices and crosscutting concepts.

This study will focus on students' application of the latter with a precise focus on the crosscutting concept of systems. As this is an explorative study, it will focus on one subject in science education: biology.

In order to design effective strategies to teach crosscutting concepts we must know more about the ways students themselves use and formulate learning strategies when confronted with a situation that invites such strategies. By researching how students formulate learning strategies we can learn about their metacognition, and to what extent elements of the desired crosscutting concept are already present. The aim of this study is to evaluate how and to what extent students in lower secondary education formulate systems approach characteristics when asked for their approach in solving complex biological problems.

Theoretical Background

Metacognition in the science curriculum

As stated in the introduction, the SLO has adapted the fundamental three dimensions from the K12-Science education framework and used these to develop Kennisbasis. These three dimensions are crosscutting practices, core ideas and crosscutting concepts. By implementing of these three dimensions into the science curriculum of lower secondary education, the SLO aims to increase curriculum coherence. A better science curriculum coherence is expected to lead to better orientation of students towards higher secondary science education. One additional aim of the SLO is to use crosscutting practices and crosscutting concepts as a way to develop a science-specific metacognition for lower secondary education. Characterised by Boerwinkel (2003) as one of the five characteristics of metacognitive strategies, crosscutting practices and crosscutting concepts are used by experts to explain phenomena in their day-to-day profession. When explaining these phenomena, experts are not bound to one specific metacognitive strategy, but can use several strategies. This seems to be the characteristic that is used in the approach of the Kennisbasis.

Crosscutting practices are "the major practices that scientists employ as they investigate and build models and theories about the world and a key set of engineering practices that engineers use as they design and build systems" (National Research Council, 2012a p. 30). These practices form a common working method amongst experts in the field of science, for example: model development & model use, research, designing, information literacy, reasoning skills, computational & mathematical skills and appreciating & judging .

Crosscutting concepts are applicable in all disciplines of science and technology and provide a way of connecting across these disciplines. These crosscutting concepts are for example: patterns, cause & effect, scale, proportion & quantity, systems & system models, energy & matter, structure & function and stability & change (National Research Council, 2012a). These crosscutting concepts are adapted by the Kennisbasis as well. The Keniisbasis also adds two other concepts: sustainability and risk & safety.

By providing clear of crosscutting practices and crosscutting concepts, several studies have shown that interdisciplinary coherence and domain-specific metacognition allow students to detect similarities in different contexts more effectively (Boersma, Bulte, Krüger & Seller, 2010; Thijs & Van den Akker, 2009). However, it is important that we have a closer look at how these crosscutting practices and crosscutting concepts in particular help students form domain-specific metacognition and how teachers can actively support the growth of this metacognition.

Teaching and evoking metacognition

One of the aims of the Kennisbasis is to use crosscutting practices and crosscutting concepts to promote science-specific metacognition. The SLO states that the way to do this is to explicate the crosscutting practices and crosscutting concepts. However, it does not elaborate on teaching strategies that will help create science-specific metacognition in students. It is therefore important to look at research for ways to explicate these crosscutting practices and crosscutting concepts that promote metacognitive development in students. First however, it is important to consider what metacognition is, what students can use it for and how it can be taught to students.

Metacognition has originally been defined by John Flavell (1979) as the "cognition about cognitive phenomena". In a way, metacognition can be seen as thinking about thinking and it consists of knowledge considering the acquisition of knowledge. Flavell stated that metacognitive knowledge is knowledge about acting and interacting of factors or variables that affect the course and outcome of cognitive processes. Over the years metacognition has become an umbrella for many metacognitive terms such as metacognitive skills, metacognitive awareness, metacognitive beliefs or learning strategies (Veenman et al., 2006). In this study, metacognition is defined as a set of strategies one can use to approach, reflect on and improve one's learning.

Much research has been done on how metacognitive strategies can be taught by teachers. It has shown that teachers should emphasise how these strategies should be used and when and why students should use them. By pointing out the value of a specific strategy, students can be motivated to use this strategy strategically and independently (Cross & Paris, 1988; Kramarski & Mevarech, 2003; Schneider & Lockl, 2002; Schraw, 1998).

Further literature research leads to more specific ways to teach metacognitive strategies. Joseph (2009) writes about ways to teach middle and high school students metacognitive strategies and about a lack of attention to metacognition in middle and high schools. This may be due to a content focused approach in many subjects. Another reason may be that due to demands of the curriculum guidelines there is much time needed for instruction and little is left for teaching metacognitive strategies.

Now, seven years later, metacognition is a much more important point in curriculum guidelines such as the K-12 Science education Framework or the Kennisbasis and educators must find a way to teach metacognitive strategies to students. Since we are interested in how students implement metacognitive strategies, we will have to investigate on ways to evoke the application and explicitation of metacognitive strategies by students. Joseph (2009) proposes seven teaching strategies that teachers can use to enable students to recognise, develop and foster metacognitive strategies. Although some strategies are mainly focussed on teacher behaviour, other strategies offer student activities in which students' metacognitive strategies are developed and fostered. Discussions about thinking, self-assessment and problem solving activities are such strategies. Jayapraba & Kanmani (2013) studied the effects of different teaching strategies on metacognitive awareness amongst students in higher secondary education. Results show that cooperative learning leads to higher metacognitive awareness compared to strategies that focus on individual learning. The aim of this study is to evaluate to what extent elements of crosscutting concepts are present. This study will take place in the classroom and the aforementioned teaching strategies can be used to evoke students to use metacognitive strategies and increase their awareness and explicitation of these metacognitive strategies.

Science specific metacognition in this study

As the Kennisbasis offers many different crosscutting practices and crosscutting concepts which may require different approaches, contexts or subjects we will only focus on the crosscutting concept of systems & system models as a way to promote and foster science-specific metacognition.

Over the years, especially in the field of biology, several studies have been conducted regarding the use of systems and system models in secondary biology education. Knippels (2002) proposed the use of systems thinking as a metacognitive strategy to tackle the abstract nature of genetics in higher secondary biology education. Verhoeff (2003) addressed the introduction of systems thinking into secondary school cell biology education. In this study, the types of learning and teaching strategies based on systems thinking, resulting in an adequate and coherent understanding of the cell as a basic and functional unit of the organism were researched. Riess & Mischo (2010) were more focused on teaching methods concerning systems thinking in biology education. In their research, the effect of different teaching methods to promote systems thinking on achievement score results was studied.

In each of these studies, different biology subjects are taught and the target group differs as well. Also the way systems thinking is applied to the lessons given to the students shows small, but noteworthy differences. To narrow the scope of this research, a clear definition of systems thinking as a crosscutting concept is needed.

Systems as a crosscutting concept in lower secondary education

For this study, a clear definition of the crosscutting concept of systems is needed that allows it to be applicable and serve the purpose of increasing science curriculum coherence in lower secondary education and student learning achievements. The framework for K-12 Science Education (Schweingruber, Keller & Quinn, 2012) introduces the use of crosscutting concepts in education towards the 12th grade. The goal of this framework is to promote attitude towards, knowledge of and capability in science of students and it has been used by several educational institutes worldwide. Educational guides with comparable goals such as Next Generation Science Standards (NGSS) in the United States and the Kennisbasis in the Netherlands built on this framework and offer definitions that are less abstract, but still rather unspecified. For example, the NGSS defines the crosscutting concept systems as: "Defining the system under study-specifying its boundaries and making explicit a model of that system – provides tools for understanding and testing ideas that are applicable throughout science and engineering". Though this is a very applicable definition, it allows for a very broad interpretation from educators. In this study the student use of systems approach in biology is under research. It is therefore important that the definition of this crosscutting concept still allows it to be used in other subjects. In order to do that, a closer look at possible systems theories in biology is required. In the following section, we will discuss the three system theories in the field of biology that offer a different perspective on biological phenomena: Cybernetics, General Systems Theory and the Dynamic Systems Theory. An introduction of the system theory will be given, its applicability in biology and relevance and possible applicability in other subjects in the science domain.

Cybernetics

Introduced by Norbert Wiener (1948), Cybernetics is the science of control and communication in the animal and the machine. It offers a multidisciplinary approach to regulation of systems with an emphasis on the (self-)regulatory characteristics of closed systems such as mechanical systems or biological systems. In biology, characteristics of living systems such as maintaining a dynamic equilibrium through feedback mechanisms and control circuits can transcend towards non-living systems in other sciences. A living system for example could be homeostasis in organisms, where, through feedback and control, the balance of important variables such as salt or sugar levels in blood is maintained. In a non-living system feedback and control can be seen in a climate control system for example in which humidity and temperature are maintained. Although cybernetics offer a systems perspective on biological phenomena that transcends to phenomena in other science subjects, it is important to keep in mind that systems as a crosscutting concept will be taught to lower secondary students. Living systems that allow for a cybernetic approach are limited and within the curriculum of students predominantly offered to higher secondary students in the form of homeostasis and ecosystems.

General Systems Theory

GST is a theory of general models in multiple scientific disciplines, and as such, it is more suitable to approach the GST from a subject specific perspective and then broaden the scope to other subjects in lower secondary education. As this study will focus on biology, elaboration on GST in the field of biology is required. Verhoeff (2003) states that the contents of GST relevant for the field of biology can be summarised in five points:

(1) One can see biological objects as a system with an internal and external environment with a system boundary separating these environments.

(2) There is a continuous exchange of material, energy and information between the living system and

the external environment.

(3) Characterisation of living systems can be done by their form, function and behaviour and

(4) living systems are hierarchical.

(5) At each level of organisation, organised sublevels which are functional to higher-level subsystems can be distinguished.

Especially the model of hierarchical order and distinguished living subsystems within the living system as features of GST may hold promise for application in biology in lower secondary education. Several studies report on the lack of coherence in students' understanding which leads to conceptual problems at organism level subjects, for example digestion (Ramadas & Nair, 1996) or human nutrition (Nuñez & Banet, 1997). Roebertsen (1996) states that higher secondary students in biology hardly integrate knowledge of bodily processes such as uptake or transport with the organs concerning these processes.

When knowledge about a certain subject is offered to students in a fragmented way at different levels of biological hierarchy (e.g. organ level, cellular level and molecular level), the lack of interrelatedness can result in student conceptual problems in other biological subjects (Nuñez & Banet, 1997; Roebertsen, 1996).

Applying components of GST in biology education at secondary school could increase the subject coherence and as a result lead to higher learning achievements. Moreover, the interrelatedness of systems over different levels of organisation, living or non-living, could result in higher learning achievements in other science subjects and lead to a more interrelated science curriculum.

Boulding (1956) suggests that the hierarchical component of GST is a crosscutting concept that can even be used as a framework to conjoin subjects from different science disciplines. Systems can be distinguished from the smallest subsystem of atoms in a molecule to subsequent subsystems such as cells, organisms and ultimately to highest subsystem of the universe.

Dynamic Systems Theory

The Dynamic Systems Theory (DST) also called 'chaos theory' (Prigogine & Stengers, 1984) is a theory that is orientated more towards non-linear processes. The systems that are dealt with in this theory are characterised as open and are lacking a stable equilibrium. The lack of equilibrium is caused by the continuous exchange of materials and energy with the surrounding environment. In their book, Priogine & Stengers (1984) apply the DST mostly to non-living systems of force and energy. As for living systems, the focus is on ontogenesis and evolution.

Verhoeff (2003) summarises the perspective that DST offers on living systems in two main points. First, living systems are viewed as self-organising systems that maintain themselves in an unstable state due to the continuous energy and material exchange with the external environment. Second, these living systems go through ontogenetic and evolutionary changes, which causes them to transit from one attractor state to another. In this process, complex forms of organisation emerge spontaneously.

The application of DST in biology education in lower secondary education is somewhat limited, as the obvious subjects ontogenesis and evolution are mainly taught in higher secondary education. Also, the unpredictable systems that can be viewed from the perspective of DST, offer limited opportunities to study for students at that level.

Cybernetics, GST and the DST offer different perspective on biological phenomena. For different subjects, different theories can be used as a crosscutting concept. As this study focuses on lower

secondary students studying biology, the biological subjects that these students learn are limited. Cybernetics has been shown as a theory applicable to the self-regulation of systems such as ecosystems and homeostasis. These subjects however, are taught at higher secondary biology education. The theory however is very applicable as a crosscutting systems theory, but the researcher sees it as applicable higher secondary education. The DST is a theory that offers a perspective towards more chaotic systems in biology, such as ontogenesis and evolution. These subjects are also taught in higher secondary biology education and their applicability in secondary biology education is somewhat limited. In this research, components from the GST will be used to define the crosscutting concepts of systems in lower secondary science education. The main reason for this is that the GST offers applicability for both students and teachers. As it is a broad theory with a hierarchical nature, it allows itself to be applicable to various subjects that students encounter in the first years of high school. The lower secondary biology education is mainly focused on organisation within organism such as organs systems, organs, tissues and cells.
Now that GST is used to define the crosscutting concept of systems, we will focus on the appliance of the definition. In order to evaluate how and to what extend students use systems thinking, they will need to be induced to apply it. In the following section, the characterisation of these problems will be investigated.

Characterising problems connected to a systems thinking approach

In this research, it is important that students are induced to talk about their approach when faced with problems of multiple biological levels. To investigate the forms of systems thinking that students might call upon when facing these problems, we have to characterise these problems further. These forms of systems thinking will be referred to as naive systems thinking. Boersma, Waarlo & Klaassen (2011) identified the system characteristics of different system theories. As the General Systems Theory is used to define the systems as a crosscutting concept in lower secondary education, we will focus on the associated characteristics. Five characteristics of the GST were identified; the identity of systems, systems can be and consist of partial systems which require a form of biological organisation, the function of partial systems within the system, interaction between partial systems and the openness of the partial systems which allow an exchange of matter, energy and information with the environment. In this section we will elaborate on how these characteristics can be used to design a framework for creating biological problems that may induce students to use a naive systems thinking approach (fig. 1**)**.

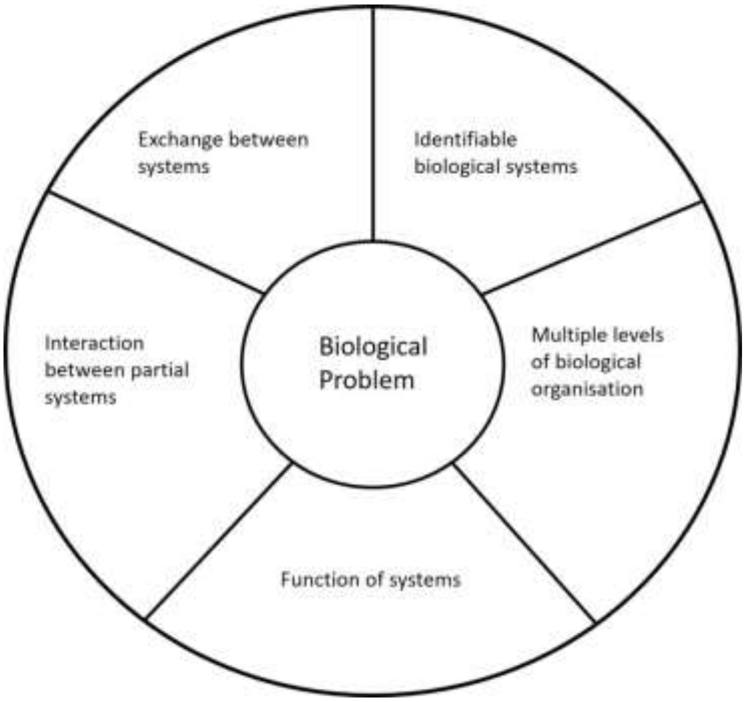

Figure 1. Framework of characteristics related to biological problems that require a systems thinking approach

The identity of biological systems can be characterised through seeing them as objects. Although not all systems are confined to a certain boundary such as an ecosystem, other systems such as cells, tissue and organs are. Therefore, biological problems must consist of identifiable biological systems. As biological systems consist of partial systems, there is a biological organisation of identifiable biological systems. Students may be stimulated to organise conceptual knowledge into systems of a different scale when faced with problems that cover multiple biological systems. Partial systems perform functions in the system. Biological problems that deal with the function or dysfunction of a partial system should not be confined to that particular system. For example, students can be asked to explain why the system of an organism is functioning or dysfunctioning based upon normal or alternative behaviour of a system of a different order, such as tissue or the cell. Partial systems within a higher system are interacting with each other. Biological problems should allow students to either recognise the interaction between partial systems or treat each system as an isolated concept. The openness of biological systems is characterised by the exchange of matter, energy and information with the environment. Biological problems in which the exchange of matter (think of oxygen or carbon dioxide), energy or information (hormones) may stimulate students to use a systematic perception on the cells, organs, organisms, etc. that play a role in the problem.

Further definition of the characteristics in the framework is required to be able to explore and indicate naive systems thinking in lower secondary students. So far, very little on systems thinking by students in lower secondary education has been researched. Some research has been done on applying systems thinking in biology education, but criteria of what encompasses systems thinking differs broadly as most research has not been done in the classroom. To investigate any use of naive systems thinking in lower secondary education, it is crucial to define the five characteristics of systems thinking. In higher secondary biology education however, some research in the classroom has been conducted on the use of specific systems thinking characteristics in teaching a specific biological topic. In the following section we will investigate this research to create clear criteria to help indicate student naive systems thinking. From these criteria for biological problems that will require students to use a naive systems thinking approach, complex biological problems can be created that invite students to use naïve systems thinking.

Identifiable biological systems

Verhoeff (2003) developed and executed a learning and teaching strategy (LT-strategy) for teaching the cell as a system. For this LT-strategy, several criteria that will enable students to develop cell biological knowledge and develop systems thinking competence were set. Based on an extensive literature review, five different criteria were formulated. Although this LT-strategy is a synthesis of systems thinking and cell biology, we can derive criteria for other biology subjects from this. The first criterion used by Verhoeff is that the cell should be introduced to students as a free living organism. From this we can derive that systems in themselves must be distinguished. Also students should be provided with the opportunity to distinguish autonomous systems within biological problems.

> * Students are able to distinguish borders between systems explicitly.
>
> * Biological problems must consist of multiple systems and encourage students to formulate answers in which multiple systems require to be distinguished.

Multiple levels of biological organisation

Knippels (2002) has developed an LT-strategy for higher secondary students on genetics in biology class that uses a systems thinking approach. Students were taught to switch back and forth between levels of biological organisation while dealing with biological problems. The learning goals of this LT- strategy consisted not only of conceptual knowledge, but also the ability to approach these biological problems from multiple levels of biological organisation. The first learning goal was the ability to distinguish all levels of biological organisation. The second learning goal was the ability to descend along these levels towards the molecular level and last the ability to interrelate the different levels and concepts to a molecular level.

> * Students are able to link biological concepts to the connected level of biological organisation while ascending/descending along levels of biological organisation.
>
> * The solution of biological problems should not be confined to the problem's level of biological organisation.

Function of systems

Verhoeff (2003) states that to combine systems thinking in cell biology learning and teaching strategy for higher secondary students, cells must be described as functional systems within the organism. It is important to note that describing the function of systems solely as its role towards other systems the mechanism behind the function is overlooked. In biology however, the question of how systems work or influence other systems also concerns the mechanisms of these functions. When mechanisms are overlooked, students fail to connect system properties and structural knowledge to phenomena taking place in systems or in systems of higher organisation (Van Mil, Boerwinkel & Waarlo, 2013). Lira & Gardner (2017) propose that the concept mechanisms should be at a core position within systems thinking, because mechanistic reasoning plays such an important role in understanding the relationship between different systems. Mechanistic reasoning is defined as "a cognitive strategy that involves utilising knowledge about relevant entities and their properties and interactions occurring at a lower level of organisation to predict and explain emergent properties at a higher level of organisation". Though limited, in secondary education students still obtain knowledge about systems that they can apply in mechanistic reasoning. Therefore it may be interesting to investigate to what extent lower secondary students describe the function and mechanism of any system within other systems. Students must be given the opportunity to describe the function and mechanisms behind identified systems within other systems.

* Students describe the function of a system within another system
* Students describe the mechanism behind the function of a system

* Biological problems must encourage students to identify specific systems and its function or mechanism of function within other systems

Interaction between partial systems

Evagorou *et al.* (2009) studied the development of 11-12 year old students at primary school. Seven aspects of systems thinking were investigated through a pre-post test. After the pre-test a learning environment was implemented. Post-test results indicated that students of this age have the potential to develop systems thinking skills. Although in this study students will not be subjected to a learning environment with the specific goal to develop systems thinking skills, the way this development of skills was measured by Evagorou *et al.* can be used for our criteria. The ability to identify the influence of partial systems on other partial systems or the whole system was investigated. Students are subjected to a problem with a certain cause and effect that requires systems thinking. While working though this problem, the students could elaborate on the size of the effect on other systems and the direct and indirect effect on partial systems and the system as a whole. From this, the following criteria were derived;

* Students are able to explain the influence of one partial system on another partial system. Effect size and affected components of influence is investigated.

* Biological problems should challenge students to explain the influence of one partial system over another partial system through the use of cause & effect problems.

Exchange between systems

Assaraf & Orion (2005) studied the progress of systems thinking skills in lower secondary students. Also in a pre-post test design, a learning environment on water sources was implemented. Progress was measured with the help of set characteristics of systems thinking. In the hydro-cycle system there is an extreme amount of exchange between systems. This provided enough opportunity to investigate the use of systems thinking to this subject. Although this exchange between systems is limited to water, Boersma, Waarlo & Klaasen (2011) provide a more general terminology. Exchange between systems is defined by the exchange of matter, energy or information with the environment. A clear distinction is made between closed systems and open systems that have input, throughput and output. This more general characteristic broadens the scope a bit, but it is important to keep in mind that in lower secondary biology education the exchange of energy or information between systems plays little to no role. However, students do have conceptual knowledge of matter in the form of molecules such as water, carbon dioxide, hormones, sugars or oxygen. Assaraf & Orion (2005) provide a good example of a molecule that students need to follow through systems, indicating when water is being put in, through or out of a certain system. In biological problems we can challenge students to follow certain molecules through several systems and thus identify the exchange between systems.

* Students are able to follow matter through different systems, explicating input, throughput and output

* Biological problems should enable students to elaborate on their ability to follow molecules

through and between systems

Now that the characteristics of biological problems that require systems thinking are more defined, what is necessary to solve them becomes more defined as well. As proposed by Joseph (2009), problem-solving activities can evoke, foster and increase awareness of metacognition. In this study the aim is to identify the extent of systems thinking students apply. Problem-solving activities can be one way to identify this and through characterisation of problems connected to a systems thinking approach the requirements of these problem-solving activities become clearer. In these problem-solving activities, students must apply a set of skills of which each is a part of systems thinking as it is defined in this study. Based on this, a framework for creating these types of problems can be designed (see fig. 2).

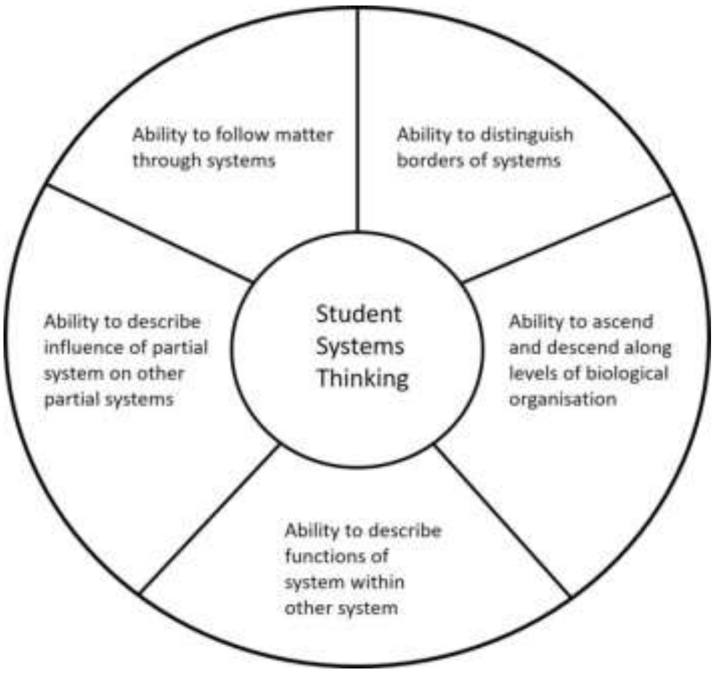

Figure 2. Framework of skills students need to apply in systems thinking

Aim of this study

Crosscutting concepts in lower secondary science education is one of the three dimensions in the Kennisbasis. However, the crosscutting concept of systems thinking is not defined thoroughly in this curricular guideline. Further research into system theories indicates that the General Systems Theory is the most suitable systems theory to serve as a foundation for systems thinking in lower secondary biology education. Although systems thinking is not a metacognitive strategy limited to only biology, this study will focus on one discipline in order to further define systems thinking. Characterisation of distinct components in the GST has led to the identification five distinguishable characteristics of systems thinking. (1) Identifying biological systems and the borders that bind the system. (2) Identifying multiple levels of biological organisation and linking conceptual knowledge to the systems while ascending/descending along levels of biological organisation. (3) Understanding the function of systems within other systems and understanding the mechanism behind this function. (4) Identifying the influence of partial systems on other partial systems, with influence being described as the effect size and the affected components. (5) Ability to follow matter through different systems, explicating input, throughput and output.

In order to increase the student achievements through teaching and fostering crosscutting concepts such as systems thinking, it is important to investigate the extent of naive systems thinking students formulate in their learning strategies. Through problem-solving activities that evoke students to apply learning strategies and the way they formulate their strategy we can learn more about student’s metacognition in lower secondary education. This will give us more insight into the extent to which the use crosscutting concepts are already present in their learning strategies. The aim of this study is to evaluate how and to what extent students in lower secondary biology education formulate systems thinking characteristics when asked for their approach in solving complex biological problems.

Methods

This study is a qualitative study on what strategies students formulate to apply whilst solving biological problems with multiple biological levels. In this study the extent to which students apply systems thinking in their formulated strategies is investigated.

Research Design

The design of this research is focused on promoting students' awareness of used strategies in dealing with biological problems of multiple biological levels and stimulating students to explicate their used strategy. The research was divided in four separate phases (fig **X**). During these phases, data was collected in the form of students' notes in a student journal, audio recordings of group discussions and interviews.

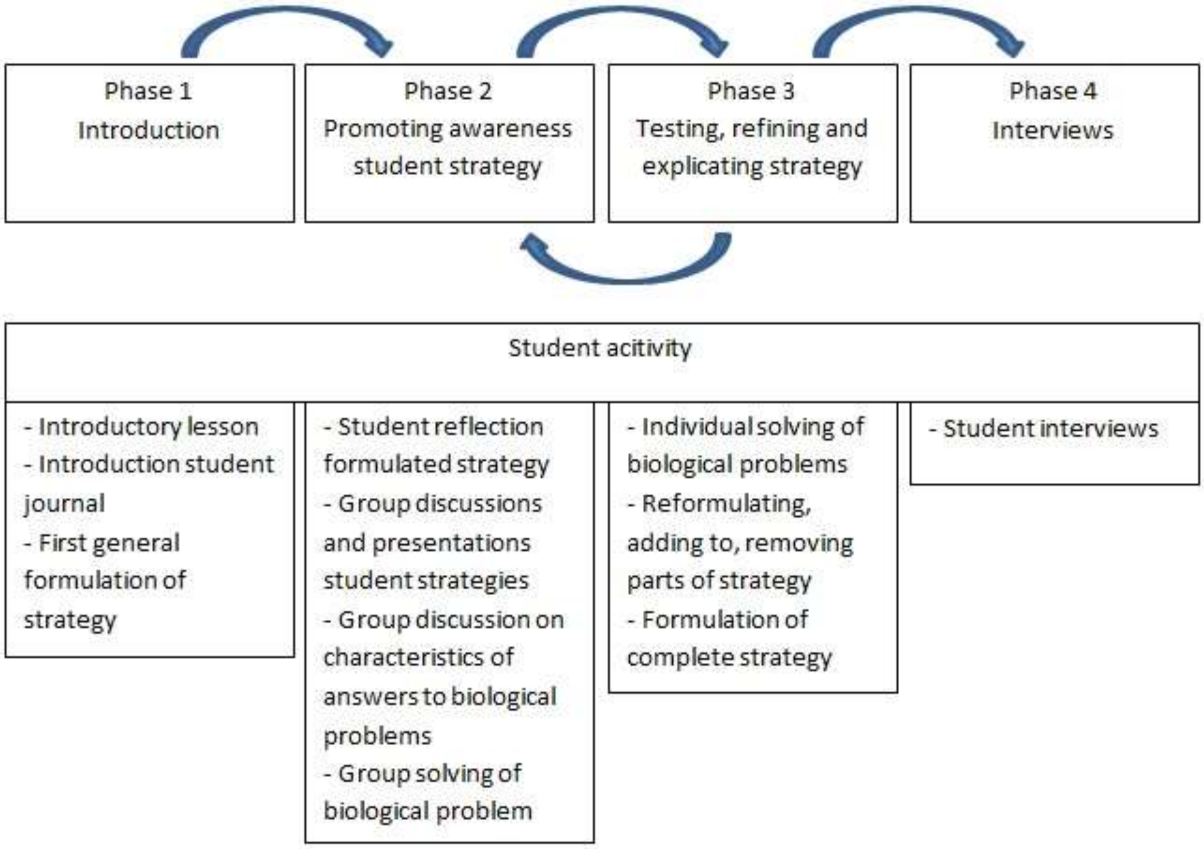

Figure 3. Phases of research

Phase 1 is the introductory phase of this research and consisted of two lessons during which students were introduced to metacognitive strategies, research planning and the student journal. At the start of the research, the research and – to some extent- tits goals were presented in a lesson. Students were told that the goal is to investigate what kind of strategies they used to solve difficult biological problems, also referred to as problems with multiple biological levels in this research. Students were also told that there is no such thing as a good or bad strategy, but that the goal was to ascertain the scope of strategies used by students. To get students to think about their strategies, different strategies from other disciplines not directly related to biology were presented and discussed. Strategies were presented in different ways to inspire students' future presentation of their own strategies. For example, two different strategies for mathematics were presented to the students in a text form. Strategy one was to type the numbers in the math problem into the calculator until a number arises that looks like a suitable solution. A fair number of students recognised this to be their strategy from time to time. The other strategy was to link the numbers in the math problem to things in their own life to increase the comprehension of the problem. This strategy also received a fair amount of recognition.

In the second lesson the students received a student journal (appendix A). The student journal is divided in different sections. First, students were given several test questions from previous test that consisted out of multiple biological levels of organisation. They were given the opportunity to write down what they find typical and hard about these questions. It is important to let students differentiate between different biological problems, as their strategy for problems concerning multiple biological levels may be different from problems concerning anatomy for example. At the end of this section, students were asked to write down or create a model of their general strategy to the offered problems.

Phase 2 consisted of nine lessons. This phase focused on the promotion of student awareness of one's applied strategy or strategies. During this phase, students used the student journal to solve problems that consisted of multiple biological levels. These problems were developed in this way so that students were probed to think about their strategy concerning problems that had the same attributes. These problems were meant to induce naive systems thinking so that students can evaluate and elaborate on their approach. These problems were created using the framework of characteristics related to biological problems that require a systems thinking approach (fig. 1). Prior to each lesson, the student journals were handed out to the students. After the plenary section of the lesson was finished, students were given 15 minutes to finish the biological problem that was embedded in the subject of the lesson. During this time, students reflected on their strategy and were asked if they applied the same strategy as noted before or if they applied a different one. If so, students were asked to explicate in what way they adapted their strategy and write this down in the student journal.

In order to stimulate the students ability to explicate their own strategy, students were grouped together during the second lesson of this phase and were given the time to present their own strategy to one another. Students were asked to write any adjustments they made to their strategy in the student journal. Research performed by McCrindle & Christensen (1995) indicates that the use of a learning journal promotes among other things metacognitive awareness amongst first year biology students. Presentations of student strategies were audio recorded for analysis. Analysis showed that many students were more explicit about their strategy when presenting it verbally. Therefore alterations were made to the lesson series that allowed students to communicate with each other more about their strategy, in order to increase awareness and explications of one's strategy.

During the fourth lesson of this phase, students from the two different groups were presented four different answers to a biological problem they had solved themselves in the third lesson. The answers were taken from student journals of the other group and were presented anonymously. All answers were right, but a selection had been made to allow differentiation between answers. During a group discussion students were given the opportunity to vote for the best answer and argue why they thought a certain answer was better than other answers. Notes of this discussion were made for further analysis.

During the eighth lesson of this phase, students were grouped into groups of four and were asked to solve the biological problem in lesson eight together. Students were asked to think of a solution that completely solved the problem. Students were told explicitly that their answers had to be complete, but that they had to discuss amongst themselves what they saw as the characteristics of a complete solution. All answers were presented to the student groups, but no feedback was given from the teacher on which was the best answer, in order to prevent students from adapting ways of answering that were not a result of their own strategy.

Phase 3 is about the testing, refinement and explication of student strategies. To a certain extent, this phase overlaps with phase 2 as the testing and refinement of the students' strategy takes place during the student journal activity in the lessons. Apart from the overlap, phase 3 consisted of two lessons in which the students finish formulating their strategy and use it during the final test.
Students use the last fifteen minutes of each lesson to finish a biological problem. During this time, students also use the time to reflect on the strategy they formulated earlier and are asked to note in the student journal if they have made any adaptations. Adaptations do not necessary mean that strategies were changed; students were also encouraged to reformulate their strategy so they were able to explain it better to others. For the test, students were given the opportunity to write down their developed strategy in the student journal on a paper that they received during the test. In the test, the questions that consisted of a biological problem with multiple biological levels were marked. This was done to prevent unnecessary application of the strategy at questions concerning anatomy for example. After the test was administered, the papers with the formulated student strategies were retrieved for later analysis.

Phase 4 starts when coding of formulated student strategies and categorisation of categories is complete. After categorisation of formulated strategies, two students of each categorised strategy were randomly selected for a semi-structured interview. In this interview, students were asked to elaborate on their strategy. This elaboration included the explaining to the researchers what their strategy entailed, how they used it in dealing with biological problems and how or if they changed their strategy during the lesson series. Also, students were asked to explain what was meant with certain formulations. Data from these interviews was used to create a more defined picture of each student strategy that was categorised.

Complex biological problems in the student journal

In phase 3, students followed normal lessons but spent the last fifteen minutes of every lesson trying to solve a complex biological problem. These problems were created using the framework of skills students need to apply in systems thinking (fig. 2). The five skills in this framework were combined with subject matter of each lesson in order to create ten biological problems that require these skills to solve. Depending on the subject, different skills are necessary to solve these problems with a minimum of three skills per problem. For example, in lesson three students learn about the process of fertilisation. At the end of the lesson they try to solve the following biological problem:

In the STD presentations you have heard that chlamydia may lead to infertility amongst women. This is the result of inflammation caused by bacteria that leads to damage of the fallopian tubes. Create a theory how this can lead to infertility amongst women.

To solve this problem, students need to apply several skills of systems thinking. First, they need to identify all systems that play a role in this problem. The fallopian tubes are a given, but the egg cell, sperm cell and uterus also play an important role. In addition to that, students need to ascend and descend along multiple levels of biological organisation in order to recognise that the damage in the fallopian tube is of cellular identity. The function of the fallopian tube in ensuring a fertilised egg cell reaches the uterus plays a key part in the solution and needs to be addressed by the students as well. Lastly, students must indicate that interaction between the fallopian tube and the uterus is changed due to the damage done by chlamydia, leading to infertility. Four of the five skills are needed to solve this biological problem, exchange between systems does not play an important role in the solution. Nine other biological problems were created differentiating in skills required to create a solution. See the student journal in the appendix A for other biological problems that were given to the students.

Sample and context of the study

The sample comprised of fifty-nine 13 to 14-year-olds, thirty-two girls and twenty-seven boys. The students are part of two different student groups, both in the eighth grade of VWO (pre- university education. The participants were students at an urban middle school De Passie (Utrecht, the Netherlands, with a religious denomination). The author of this research knows the students, as he is also the teacher of these two groups. Consent of participation of students in this study was asked from both the parents and the students. The students were free not to participate in this research. For those students who did not want to participate, different lesson program was available. In this research however, every student chose to participate. The research was conducted in four separate phases lasting twelve lessons over a period of seven weeks, during which the researcher gave two lessons a week to the students. The last two weeks were used for interviews.

Data collection and analysis

Data was collected in the form of audio tapes from the group discussions during which students presented their own strategy to one another, of the developed, written student strategy in the student journal and the interviews. All the data collection took place between March and June 2017. The audiotapes were collected in the second week of the research, after the first lesson of phase 2. The developed and written student strategies were collected in the seventh week of the research, at the end of phase 3 after the twelfth lesson of the lesson series. The interviews were taken and transcribed in phase 4 during the last two weeks of the research.

Group discussions

At the beginning of phase 2, group discussions were held during which students in groups of five students each presented their own strategy. Students were grouped and a recording device was placed in the middle of the group. Audiotapes from group discussions were analysed for metacognitive components students used in the presentations of their strategy. Metacognitive components that were mentioned in the student presentations but not formulated in the student strategy were added to the individual student strategy. This information was used to create a better picture of the student strategy in order to successfully categorise student strategies. In addition to this, newly found metacognitive concepts from group discussions were presented to students in interviews, in order to verify whether they were rightly added to the student strategies.

Categorisation

At the end of phase 3, formulated student strategies were gathered by the researcher. All student strategies were screened for metacognitive concepts. A list of all available metacognitive concepts was created. Comparable metacognitive concepts were grouped together. Such groups were for example metacognitive concepts concerning sorting information, understanding the subject, specific ways to approach the problem or specific ways of formulating solutions. Student strategies were compared to each other for metacognitive concepts and through back-and-forth comparison an initial categorisation was made. A coding system was created to assign student formulated strategies to different categories. The coding system was formed by grouping formulations of metacognitive components and thereby creating distinctive strategies that were grouped in different categories. The coding system can be found in the appendix B. Data from group discussions and interviews was used to further refine the categories and formulate distinct subcategories. Final coding was done by the researcher. After this, a colleague researcher coded 20 randomly selected student strategies in order to validate the accuracy of the coding process. After comparison, 90 per cent of the student strategies were similarly coded.

Interviews

After initial categorisation, semi-structured interviews were conducted with students whose formulated strategies were represented in all categories. Transcripts of these interviews were used to analyse student formulation of personal strategy in order to further refine student strategies and categories of student strategies. When students proposed different or adjusted strategies in the interviews, they were asked to elaborate on the differences between their written strategy and verbalised strategy. After students explained their strategy to the researcher, their written strategy in the student journal was presented and students were asked to elaborate on their choice of words. During this section of the interview, students were asked to explain what they meant with generalising phrases or words. Data from interviews was used to further refine individual student strategies and categories of student strategies.

Results

Group discussions

After the third lesson in the lesson series, the researcher gathered the student journals, to investigate differences in answers to the given biological problems. Out of each student group, four different answers were selected to present to the other student group. Incorrect answers or answers that did not answer the question were excluded. Students were given the opportunity to vote on what they thought was the best answer and give arguments in a group discussion as to why they felt this way. The voting process was guided by the researcher, the group discussion was guided by the students. The results can be seen in table 1. The answers given by students allow for analysis of characteristics of systems thinking. The group discussion can provide insights into the student responses to these characteristics.

Problem: In the STD presentations you have heard that chlamydia may lead to infertility amongst women. This is the result of inflammation caused by bacteria that leads to damage of the fallopian tubes. Create a theory as to how this can lead to infertility amongst women.		
Student answers	**Votes**	**Argumentation (+/-)**
1. The egg cell must travel through the fallopian tube to the uterus. If the fallopian tube is damaged or inflamed, the egg cell can't be transported by the fallopian tube. The egg cell dies and can't be fertilised.	13	''It's step by step, I like that, it doesn't skip anything.'' (+) ''It gives a clear cause and effect relationship.'' (+) ''The answer ends with why women are not fertile anymore, what comes before explains that.''(+)
2. If the fallopian tube is partly damaged, the egg cell can't travel to the uterus anymore. The egg cell does not have enough nutrients and dies. It may also be possible that the sperm cell can't reach the egg cell anymore, but I think that happens way less because the sperm cell is very small and can get almost anywhere.	9	''To me it's not a right answer. The egg cell doesn't travel, it's the fallopian tube that pushes it forward.'' (-) ''I think it's good that this person mentions that the egg cell must travel to the uterus, just like in the other answer. The end goal should be explained.''(+) ''It's complete, it gives follows the two important players in the process; the egg cell and the sperm cell.'' (+)
3. When the fallopian tube is inflamed, it might swell and block the egg cell	0	''Answer is not complete. This doesn't explicitly explain why women become infertile.'' (-) '' Too short, feels like it needs more text.'' (-) '' It doesn't really explain anything.'' (-)
4. If the fallopian tube is damaged, the sperm cell can't reach the egg cell anymore possible due to a lack of moisture or because of a blockage.	5	''This may be so, but the sperm cell is way smaller than the egg cell, so it makes more sense to me to address that.''(-) ''Considering that you don't know what is damaged, this answer provides different options. It can be the mucous cells that are damaged or because of swelling of blood vessels causing a blockage.'' (+) ''I think it is vague, what exactly is blocking the egg cell now?'' (-)

Table 1. Student answers to a biological problem, voting and argumentation

Characteristics of systems thinking in student answers

First we should compare the answers given to the characteristics of systems thinking. Although metacognition of the students providing these answers was not measured in any way, their given solution provides insights into the application of naive systems thinking. In the following section the characteristics of systems thinking in the student answers and the extent to which students respond to these characteristics is analysed.

Identification of biological systems is actively done in answer 1 and 2 and partly in answer 4. Answer 3 does identify the fallopian tube and the egg cell, but it does not address any other systems that play a part in this biological problem. Students note that answer 3 is lacking completeness but do not explicitly state that this is due to biological systems not being addressed.

Multiple levels of biological organisation are addressed in all answers, except for answer 3. In answer 1, 2 and 4 the egg cell and/or sperm cell is identified as a cell traveling through organs such as the fallopian tube towards the uterus. Again, students do not actively make note of the fact that this identification of biological organisation is lacking in answer 3.

Function of systems and mechanisms behind those systems are addressed in answers 1, 2 and 4 as well, although in answer 4 it remains implicit to a certain extent. Answer 1 and 2 both address the function of the fallopian tube but fail to provide the mechanism. In these answers the malfunction of the fallopian tube is linked to infertility. Answer 4 does not provide the function of the fallopian tube but does explain a possible mechanism as to why it is not functioning anymore. The responses of students show that function plays an important role in deciding whether or not they feel that an answer is complete.

Interaction between partial systems is given in answers 1, 2 and 4 and is lacking in answer 3. Yet, the levels of biological organisation on which these interactions take place differs. Answer one explicitly notes that the fallopian tube interacts with the uterus through transport of the egg cell towards the uterus. In answer 2 there are two levels of interactions addressed; again the interaction between fallopian tube and uterus, but also the interaction between egg cell and sperm cell. Answer 4 only provides the latter interaction. In response to the answers, students note that the interaction between systems is an important part to address in a solution. Students note that it's important that answers are written down in a step-by-step order in which each steps is logically followed by the next step. Logic in their sense is that steps explain future steps to address in the solution.

Exchange between systems is neither noted in any of the answers nor in the comments of the students. It is important to note that this biological problem does not address any exchange of matter, energy or information.

Interviews

In phase 4, after the student journals were submitted to the researcher and first categorisation of student strategies was done, students with formulated strategies belonging to different categories were interviewed. The purpose of the student interviews was to investigate the language students used to describe their strategies and respond in group discussions. By further investigation of terms and phrases often used by students to formulate their strategy, a second more explicit categorisation could be done. In the following section we will investigate three common uses of language in formulated student strategies that require further investigation for meaning.

Generalising terms

In many strategies formulated by the students, words like ‘’things’’, ‘’parts’’, ‘’words’’, or ‘’terms’’ were used to describe certain concepts. Students use these words to make a certain generalisation, but which concepts are indicated by this generalisation is not specified. In order to investigate what students meant by these words, several students with formulated strategies from different categories were interviewed and asked to elaborate on their choice of words. In the following section, three fragments of interviews with three different students concerning the use of generalisations are transcribed.

Researcher: Can you explain in your own words what your approach is to these biological problems?
Arjan: If I don't know the answer straight away, I try to understand parts of the question
R: What do you mean with parts?
Arjan: For example, meiosis or mitosis what we talked about this morning, I might know those but other parts not. Or it could be organs as well.

Renske: First I read the question and if I don't know words, I think what they mean
R: What do you mean with words?
Renske: Like concepts you find in the textbook, which you may have learned but then forgotten about them
R: Can you give an example of such a concept?
Renske: Diffusion for example or stomata, then I think about what I know about them and what I read about it in the book and learned in the lessons.

Larissa: I look for important things in the question
R: Can you give an example of such important things?
Larissa: Hormones for example, then I think what they are exactly and if the question is about muscles for example I try to think where the muscles are located.

Many students describe in their strategy to be checking the biological problem for certain things, parts, words or terms. With these words, they refer to biological concepts and biological processes. In the initial phase of their approach, no clear distinction between concept and process is made. An interesting observation is that one of the students makes a distinction between what is and what is not relevant to recall concerning these concepts. For hormones, it is important what the hormones are, and for muscles the location is of importance.

Step-by-step formulation of the solution

Some of the categorised student formulated strategies share the same metacognitive concept of step-by-step formulation of a solution. Many students use the words 'step-by-step' as a description of how they formulate the answer. Students were asked to elaborate on this process in order to find out which factors students consider while going through this process.

Researcher: You mentioned that you answer the question step-by-step, what do you mean by that?
Esther: For example, when a guy eats a banana, you've got to provide the answer step by step.
R: Can you elaborate on that with your example?
Esther: Well, first it goes through the teeth where it is being made smaller, and then it goes through the oesophagus where it is being pushed to the stomach. In the stomach there are enzymes to digest it further.

R: You noted in your strategy that you put the answer in the right order, what do you mean by that?

Sam: How does glucose go through the body for example, then it is important that you must put it in the right order.

R: And what do you mean by putting it in the right order?

Sam: Well first it goes into the mouth, between the teeth, then the oesophagus and eventually to the small intestine. There it is being taken up by the blood and then through the blood it can go anywhere, but in the end it goes to one cell. But I do check if I didn't forget anything. Let's say that the glucose must go to a leg muscle cell, it is important to note the veins which it travels through.

Louise: I'm quite sloppy and when I write things down I tend to skip a step, so I need to write down an answer step by step.

R: So in answering biology questions, what does this step by step mean exactly?

Louise: When you have a cycle for example, then I write down in detail what comes first, what comes after that and after that and so forth.

Step by step formulation of a solution is elaborated on by students as describing a process that is taking place at different times and different places of biological interest. Students describe the solutions to difficult biological problems to be causal explanations of phenomena happening on a temporal scale. There are small differences in the descriptions of the students however. Esther for example not only notes where and when the banana is going through the body but also the functions of the organs which the banana is going through. Sam on the other hand only notes the organs and cells the glucose is going through.

Using logic

Many students note that using logic is part of their strategy. They usually apply logic during the formulation of a solution. In the student strategies no explicit explanation of what logic entails was given. Students were asked to explain what they meant with applying logic to their strategy.

Researcher: You describe in your strategy that when you are not able to answer a question, you try to think logically, what do you mean by that?

Sam: Looking for connections. With thinking logically I mean that things should make sense, they must be right. For example if a plant is walking, that obviously isn't very logical. So I check the options I have and then try to exclude what isn't possible.

Joel: I look for things I know, like organs for example. Then I think about what they do in the body I try to create a solution but if that isn't possible I make up things to make it more logical

R: What do you mean by logical?

Joel: Take blood for example, when your question concerns things that travel all through the body, then it is probably transported by the blood.

R: What do you see as logical?

Arjan: I use like rules; when it goes in your blood, it goes everywhere. So when there is something that is going everywhere in the body, it probably travels through the blood.

Categorisation of formulated student strategies

At the end of phase 3, students were asked to formulate their strategies in the student journals. Student journals were retrieved by the researcher and all formulated student strategies were analysed for metacognitive components. Examples of these components include: understanding the problem, accessing knowledge about the topic, accessing knowledge about the biological concepts, remembering the function of identified concepts, searching for cause and effect relations, step by step formulation of an answer. For a full overview of the identified metacognitive components in the formulated strategies see appendix B**.** Based on the occurrence of these metacognitive components, seven formulated student strategies were distinguished and categorised into four different categories. In the section below the categorised formulated student strategies and the associated metacognitive concepts are presented.

Category 1a. Read & Write

Strategies in this category consist of few metacognitive concepts that remain rather inexplicit. Students formulate their strategy for biological problems to be reading and understanding the problem, deciding on the biological subject and giving the solution to the problem. No further explanation is given by the student as to what entails understanding the biological problem or on what basis the subject of the biological problem is decided. How or on what basis the solution is formed is also not explained.

Category 1b. Read, Write & Check

Although very similar to category 1a, formulated strategies in category 1b are extended with one metacognitive concept; checking. When the solution to the biological problem is given, it is checked to be fitting, complete or logical. What students define as logical is elaborated on in the student interview section of the results.

Category 2a. Indicate, Access knowledge & Combine

Strategies in the second category compared to the first category are more elaborate and consist of more metacognitive concepts. For this specific category, students formulate their strategy to start with the indication of biological concepts such as organs, tissue, cells or matter. Once indicated, these concepts are identified through the access of knowledge about these concepts. Students think about what they know about these concepts through learning, classes and the textbook. This knowledge about the concepts can be processes in which these concepts perform a function The solution to the biological problem is created through the combination of this accessed knowledge. The formation of the solution is a process in itself, during which unnecessary knowledge about biological concepts is excluded and the solution is formed step by step.

Category 2b. Indicate, knowledge and take into account lacking knowledge & Combine

Strategies in this category are formulated with the same metacognitive concepts as category 2a. The only addition to category 2a is that students formulate to actively consider what conceptual knowledge they lack for solving the biological problem. To deal with the gaps in identified necessary knowledge, students mention to use logic or try to access knowledge considering these concepts.

Category 2c. Searching analogous problems

Strategies in this category have the same metacognitive concepts in the initial phase of dealing with the biological problem as category 2a. Once the biological concepts are indicated and identified, students search for analogous problems that they have dealt with in class, the textbook and in their workbook. Once an analogy is found, students try to recall how the solution was found in the analogous problem or situation and use this knowledge to solve the biological problem they are dealing with now.

Category 3. Connectivity approach

Although many metacognitive concepts in this category are also being formulated in category 2, the connectivity approach distinguishes itself through the focus on causal biological relations between biological concepts. Students note that after reading the question, biological concepts are first to be indicated and identified. After this is done, processes attached to these biological concepts are recalled and possible causes or effects are identified to formulate a cause and effect relationship. Once the normal cause and effect relationships are established, a check for any deviant effects or causes is done and deviant processes are identified. Identification of the deviant cause or effect combined with knowledge of how processes normally go then forms the basis to formulate a solution.

Category 4. Who, Where, What-approach

Students analyse a biological problem in three consecutive steps. The first step is what students describe as the "who-question". This step is the indication and identification of all biological concepts in the biological problem. After the first step, the "where-question" is asked and students try to recall the location of all the identified biological concepts and the spatial relation these concepts may have based on the location. When the biological concepts are identified and located, the "what-question" is asked. Students recall any processes they know in which the identified biological concepts play a role. Students create an overview in their mind of the biological concepts in their place and their function working together. To create a solution, all the available information is reviewed and suitable information is selected. This selected information is used to solve the biological problem and formulate an answer in which 'who', 'where' and 'what' questions are fully answered.

A total of fifty-nine formulated strategies were categorised into these seven distinct strategies. Strategies in category 2a were found to be the most occurring. For an overview of the occurrence of categorised strategies see table 1.

Table 1

Occurrence of categorised strategies with characterising quotes

Category	Student strategies (%)	Characterising quote
1a	14	"Read the question – If I know the answer I write it down, if I don’t know the answer I read the question again."
1b	10	"I think what I know already and write down an answer, after that I check for errors."
2a	32	"I search for the most important words and think what about what I know of these words. I search for connections between these words and write those down. Last, I write down the answer step-by-step in the right order. "
2b	15	"I take the things I know and try to solve the problem, the things I do not know, I try to fill in with logic or other knowledge about biology."
2c	9	"Check what they need to know and compare that to assignments in the work book and textbook."
3	17	"I read the question and try to create a picture of the situation in my head. I try to remember the task or the effect of things in the question."
4	3	"Is it important what substances are involved? - Is it important what process is involved? – Is it important where in the body it is located?"

Interpretation of the results

Systems thinking is not defined as one metacognitive strategy that students either do or do not apply. As systems thinking is an umbrella for multiple metacognitive concepts, we can investigate the extent to which students apply systems thinking by looking at these isolated metacognitive concepts. In this study, these metacognitive concepts have been identified into a framework of five characteristics of systems thinking (fig. 1). Each category consists out of a group of metacognitive concepts that can be compared with the framework to assess the extent of systems thinking used in student strategies.

Strategies in Category 1 show no metacognitive concepts that are associated with systems thinking. This category consists of the Read & Write approach and the Read, Write & Check approach. Students formulate their strategy as to be mainly reading and understanding the question in order to give a solution. There appear to be no characteristics of systems thinking in these metacognitive strategies (fig 1.). Students do not actively identify biological systems of different biological organisation, functions and influence of systems or consider matter that may travel through systems.

Student strategies that have been categorised in the second category show a moderate extent of systems thinking characteristics. Students start by indicating and identifying what they call biological terms, words, concepts or things. Student interviews indicated that the meaning of these words can be compared with that of biological systems. Once indicated and identified, knowledge about these biological concepts is accessed considering functions and processes that these concepts play a role in. Students with strategies ascribed to category 2b explain that they use logic to assign functions to systems they do not know the function of. This logic is based on the relationship between systems or properties of systems. This shows that students consider the functions of systems and are, to some extent, able to describe the influence of partial systems on other partial systems. In the formulated strategies in this category, no note is made of identifying levels of biological organisation.

The connectivity approach is a category of student strategies that shows a high extent of characteristics of systems thinking. Students formulate their strategy to start with the indication and identification of the biological concepts that play a role in the biological problem. When identified, these concepts are connected to processes in which these concepts perform a specific function. Influence of concepts on other concepts in the biological problem is correlated to knowledge of how processes and influence is normally taking place. When discrepancies are found between the norm and the situation in the biological problem, students search for causes or effects. This shows that students are able to ascribe functions to specific systems and understand the influence of systems on other systems. Identified biological systems are in some way organised in to a form of biological organisation that is based on shared function. Student interviews show that students use general function such as digestion to link several biological systems to each other, not necessarily a level of biological organisation based on system complexity.

Student strategies which have been categorised as the ‘Who, Where, What approach’ show a very high extent of characteristics of systems thinking. Students describe that once they have read the biological problem, they identify the important biological concepts in the question. The next step is to localise these biological concepts and thereby setting these biological concepts apart from other biological concepts. This shows that students attempt to distinguish borders of what they refer to as biological concepts. Although the interviews showed that some students consider biological systems and biological processes both to be biological concepts, the what-question that is still to follow in this strategy shows that students in this category do make this distinction. After the identification and localisation, students attend to the processes that are taking place in the biological problem. Knowledge about the processes in which the identified biological concepts play a role is being accessed, which shows that students actively try to describe the functions or mechanisms of systems. Students do not explicitly make the distinction between functions and mechanisms, but mainly focus on systems affecting other systems. This indicates that students with strategies in this category have the ability to describe the influence of a system on other systems. A characteristic of systems thinking is the ability to describe the influence of a partial system on other partial systems. Yet, even though students apply this strategy, they do not describe a distinct investigation of horizontal relations between partial systems or vertical relations between systems of different biological organisation. Nevertheless, the student journals that include strategies belonging to this category show that students have the ability to identify and describe these horizontal and vertical relations between systems. This ability is shown in the biological problem of lesson nine for example. Students are asked what the effect of errors cancer suppressing genes in intestinal cells may have on an individual. In the solution, attention is paid to the effects on cellular, tissue, organ and organ system level indicating that they ascend along levels of biological organisation. Next to this, the effects of a less efficient intestine on other organs in the digestive system are mentioned, noting the effect of partial systems on other partial systems. The ability to follow matter through systems is very evident in this student strategy. Students actively try to create a picture of all the biological systems connected through processes that take place between them. Student interviews indicate that the biological concepts that are identified in the beginning of the approach are not limited to systems of the cellular level and higher. Students consider molecules that they have learned in earlier lessons such as oxygen and glucose to be of interest as well. These molecules are incorporated into the overview of interaction between systems and allows students to follow such molecules through systems.

Conclusion

Eighth grade students were studied for the extent to and way they formulate systems thinking characteristics in their strategy for solving complex biological problems. Five characteristics of systems thinking for biology in lower secondary education were identified. Formulated student strategies were categorised and analysed for systems thinking characteristics. Categorisation of the formulated student strategies resulted in four distinct categories.

Out of fifty-nine students, fourteen students formulated strategies that were categorised in category 1. This category shows no characteristics of systems thinking. Forty-five students did formulate systems thinking characteristics to a certain extent in their strategies.

The systems thinking characteristic of distinguishing borders of systems is found in all categories but category 1, indicating to a high extent that this characteristic is formulated as part of a student strategy. Ascending and descending along levels of biological organisation is not formulated in any student strategy and therefore not part of any category of student strategies. Describing the functions of systems within other systems is also found in all categories but category 1.Thirty-three student strategies in category 2 consider functions of systems as knowledge connected to the identified biological concepts. Twelve strategies in category 3 and 4 clearly state the importance of identifying and describing the functions of identified biological concepts in order to indicate causes, effects or processes that are taking place in complex biological problems. Describing the influence of a partial system on other partial systems is found in category 3 and category 4. A total of twelve out of fifty-nine students reported this characteristic as a part of their strategy, indicating that this systems thinking characteristic is found in student strategies, but to a low extent. Following matter through systems is only found as a part of formulated strategies belonging to category 4, to which two student strategies were assigned. This indicates that this systems thinking characteristic is formulated to a low extent in student strategies.

To formulate a clear conclusion on the extent of which systems thinking characteristics are formulated in student strategies, all characteristics must be considered separately. Distinguishing borders of systems, describing functions of systems and describing the influence of partial systems on other systems are systems thinking characteristics that are found to a high extent in formulated student strategies. Ascending and descending along levels of biological organisation and following matter through systems are found in a low extent in formulated student strategies.

Discussion

Eighth grade students were studied for the extent to and in which they formulate systems thinking characteristics in their strategy for solving complex biological problems. Students show significantly different approaches to complex biological problems. Categorisation of the formulated student strategies resulted in four distinct categories. Category 1 showed no characteristics of systems thinking. Category 2 to 4 showed a moderate, high, to very high extent of systems thinking characteristics in the formulated strategies.

Very little research has been done concerning systems thinking as a metacognitive strategy amongst secondary school students. And even less research has been done when it concerns lower secondary school students. Assaraf & Orion (2005) researched the development of systems thinking skills in lower secondary education. Characteristics of systems thinking in the context of the hydro-cycle were investigated and indicated. Results in that study indicate that most students initially showed minimal systems thinking abilities. Results in this study indicate that most students do formulate systems thinking characteristics in their strategies to solve complex biological problems. These results seem to contradict each other, but a distinction must be made. Assaraf & Orion (2005) focus on systems thinking abilities in a specific context and note a high dependence on student cognitive abilities and involvement with the subject-matter. In this study, students were asked to formulate a strategy to complex biological problems in general. The results in this study clearly indicate that a majority of lower secondary students is aware of systems thinking to a certain extent. Linking awareness to ability might be interesting for future research.

Limitations

First, it should be noted that researcher, school and students may not provide generalisable data. The school is not a public school, but of Christian denomination. These schools are a minority school in the Netherlands. The pre-university students showed great enthusiasm to participate in the research throughout all the phases of research. The researcher in this study is also the teacher of the students in day-to-day school life. All of this could be of influence on the results and replication of this study on other schools is necessary to provide generalisable data.

The assignment of formulated student strategies to the right category is of great importance to the interpretation of the results of this study. Through the development of a coding system that focusses on the presence of metacognitive concepts in student strategies, we could make between student strategies. This distinction allowed for categorisation of student strategies. It is important to note that the coding system and coding process also provide limitations. Coding of 20 random selected student strategies by the researcher and second coding by the colleague researcher resulted in 90 per cent agreement. The 10 per-cent of strategies that were coded differently was discussed. Discussion of the different coding showed that there are multiple ways to evaluate student strategies. When we consider the categories to which the strategies are assigned, there appears to be a certain build-up. Student strategies in category 1 mostly consist of understanding the subject of the biological problem and answering the question. Strategies in category 2 show an expansion of variables that are considered in understanding the biological concepts and a step-by-step formulation of the solution. Category 3 strategies share this approach, but students note an extra focus on processes, causes and effects that are taking place in the biological problem. Student strategies in category 4 show to be more extensive by also focussing on the spatial relations place between the biological concepts. This build-up of student strategies, based on the presence of metacognitive concepts has an effect on the coding system that has to be taken into consideration. To code strategies, one can look at requirements: certain metacognitive concepts have to be present in the student strategy in order to advance to a higher category. In some student strategies however, metacognitive concepts from different categories are present. Formulated student strategies can for example show little attention to biological concepts in the biological problem, but much attention for step-by-step formulation of the solution. In that situation, more information is needed to assign the student strategy to the right category. In this study, the formulated student strategy was the primary source of retrieving student strategies. Interviews and group discussions were used to further investigate these student strategies. In future research, other ways of retrieving student strategies may help to create a clear picture of the types of student strategies are being used by students in lower secondary education.

Implications

When we consider the metacognitive nature of the categories of student strategies, we can see a significant variety of approaches to complex biological problems. When systems thinking characteristics are considered, this variety is visible as well. It is interesting to see is that some students already implement a moderate to very high level of systems thinking into their strategy. One of the goals of the kennisbasis is to improve science education through teaching crosscutting concepts such as systems (Ottevanger *et al.*, 2014). According to this research, some students already formulate this crosscutting concept as part of their strategy, only the extent of which can differ. Out of fifty-nine students, forty-five students formulated a student strategy that showed characteristics of systems thinking, twelve of these student strategies showed a large extent of systems thinking. Further research with larger samples is required to establish a better understanding of the fraction of students that formulate systems thinking characteristics in their strategy. Nonetheless, a refinement of the kennisbasis considering the teaching of systems thinking may be prudent. Analysis of characteristics of systems thinking in formulated student strategies shows that certain characteristics are found more frequent then others. Distinction of framed systems, description of function of systems within other systems and description of influence of partial systems on other systems are characteristics that are found in strategies of the majority of students. Ascending and descending along levels of biological organisation and the ability to follow matter through systems is found considerably less.
Depending on the systems thinking characteristic, different awareness is found amongst lower secondary students. Further research is necessary to investigate ways to increase awareness of systems thinking characteristics amongst lower secondary students. This is the first step for implementation in their strategy and may lead to application of systems thinking in science. As this specific field of science concerning systems thinking amongst secondary students is relatively young, very little is known on how to increase awareness of systems thinking amongst these students. Some research however, indicates that students in secondary school are able to acquire the ability to apply systems thinking characteristics. In higher secondary education, students are able to acquire the competence of ascending and descending along levels of biological organisation. Knippels (2002) has shown that through the application of the yo-yo LT strategy, students are able to attain this competence. In her research, the yo-yo LT strategy is used for genetics lessons in higher secondary education. However, the application of this LT strategy is suitable for lower secondary biology subjects such as evolution and behaviour as well. The second characteristic that is not found often in student strategies is consideration for the flow of matter through systems. Earlier research by Asharaf & Orion (2005) shows that students in lower secondary education with minimal systems thinking abilities can develop skills in systems thinking. One of these skills is the ability to follow matter through systems. The development of this skill is done in an educational setting using laboratory education and inquiry-based activities. These educational settings are present in lower secondary education as well, providing chances to develop required systems thinking skills.

This research has focussed on student strategies of pre-university students in lower secondary education. Results indicate that systems thinking, to some extent, is formulated in student strategies. This may have implications for the way the crosscutting concept systems are being implemented in the lower secondary curriculum for pre-university students. The use of crosscutting concepts in the curriculum is not limited to pre-university education however. The Kennisbasis is written for lower secondary education, also including lower and higher general secondary education. Investigating the extent to which students in lower and higher general secondary education use systems thinking in their strategy to solve biological problems will provide interesting insights. First, these insights will help in designing effective strategies to teach crosscutting concepts on these levels of lower secondary education. Second, it may provide insights to differences and similarities in student strategies of students in different levels of lower secondary education. The methods designed in this study can be used in future research to gain these insights.

Next to investigation of the extent to which systems thinking is formulated by students at any level of lower secondary education, these methods allow for the investigation of any other crosscutting concept. The kennisbasis provides for eight other crosscutting concepts (Ottevanger *et al.,* (2014). Through student journals, group discussions and interviews, the use of crosscutting concepts in student strategies can be investigated. This in turn will lead to more understanding of student naive understanding of crosscutting concepts that will help designing more effective teaching strategies.

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Appendix A

Studentendagboek Biologie

Naam:

Klas:

Appendix A

Toetsvragen uit eerdere toetsen

Hayo is een uur aan het hardlopen geweest
Hij is uitgeput en zijn spieren willen niet meer. Hij eet een banaan en heeft na een poosje weer energie om verder te gaan. Beschrijf wat er in Hayo's lichaam gebeurt na het eten van de banaan.

Eline heeft de mazelen. Haar broer heeft deze ziekte ook ooit gehad. Waardoor wordt haar broer niet weer ziek? Leg je antwoord uit.

José klaagt dat ze het steeds koud heeft en zich niet goed kan concentreren op school. Haar vader zegt dat ze om te beginnen wat beter moet ontbijten. Leg uit dat José een goed advies krijgt van haar vader.

Roy is in de tuin aan het werk. Hij heeft net de hele groentetuin omgespit. Zijn hoofd is rood en hij hijgt en zweet ervan. Een aantal organen in zijn lichaam zijn hard aan het werk om de samenstelling van het bloed constant te houden.
a. Schrijf twee voorbeelden op van organen die afvalstoffen van de verbranding uitscheiden en leg uit hoe ze de samenstelling van het bloed constant houden.
b. Welk uitscheidingsorgaan scheidt geen afvalstoffen van de verbranding uit, maar zorgt wel voor voldoende brandstof voor de verbranding? Leg je antwoord uit.

Wat vind je typerend aan dit soort vragen in vergelijking tot andere toetsvragen?

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Wat vind je lastig aan dit soort vragen?

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Appendix A

Heb je een speciale aanpak wanneer je dit soort vragen krijgt? Probeer in je eigen woorden op te schrijven hoe je deze vragen benadert. Voel je vrij om een stappenplan of model te maken

Stappenplan / Model

Zou je aan de hand van de bespreking met klasgenoten nog een aanpassing willen maken aan je aanpak? Welke?

Appendix A

Les 1 Vruchtbaarheid

Oefenvraag: Hypopituïtarisme is een zeldzame aandoening aan de hypofyse die bij mannen kan leiden tot een verminderde aanmaak van zaadcellen. Leg stapsgewijs uit hoe dit effect bij een man tot stand kan komen.

Wat van je eigen aanpak die je eerder omschreven hebt heb je succesvol gebruikt?

Wat van je eigen aanpak heb je niet gebruikt? Waarom?

Zou je je eigen aanpak iets beter kunnen maken?

Appendix A

Les 2 De menstruatiecyclus

Oefenvraag: Progesteron heeft een remmende werking op de hypofyse zodat er geen rijping van nieuwe eicellen plaats vindt. Probeer uit te leggen door het signaal te volgen hoe de rijping precies volgens jou geremd wordt.
Progesteron gaat ……..

Wat van je eigen aanpak die je eerder omschreven hebt heb je succesvol gebruikt?

Wat van je eigen aanpak heb je niet gebruikt? Waarom?

Zou je je eigen aanpak iets beter kunnen maken?

Appendix A

Les 3 Bevruchting

Oefenvraag: In de SOA presentaties hebben jullie gehoord dat chlamydia onvruchtbaarheid bij vrouwen kan veroorzaken. Dit komt doordat de onstekingen als gevolg van de bacterie de eileider beschadigen. Maak een theorie hoe dit er toe kan leiden dat een vrouw onvruchtbaar wordt.

Wat van je eigen aanpak die je eerder omschreven hebt heb je succesvol gebruikt?

Wat van je eigen aanpak heb je niet gebruikt? Waarom?

Zou je je eigen aanpak iets beter kunnen maken?

Appendix A

Les 4 Zwangerschap voorkomen

Oefenvraag: In de pil vind je de hormonen oestrogeen en progesteron. Wanneer een vrouw deze pil slikt komt deze in het verteringsstelsel. Leg stapsgewijs uit hoe deze hormonen vervolgens bij hun eindbestemming komen en wat daar precies gebeurt waardoor de vrouw niet zwanger kan worden.

Wat van je eigen aanpak die je eerder omschreven hebt heb je succesvol gebruikt?

Wat van je eigen aanpak heb je niet gebruikt? Waarom?

Zou je je eigen aanpak iets beter kunnen maken?

Appendix A

Les 5 Zwangerschap

Oefenvraag: Marleen heeft een leverafwijking waardoor de afbraak van alcohol ernstig vertraagt wordt. Ze is een paar maanden zwanger. Op een avond drinkt ze een aantal glazen witte wijn. Volg de alcohol door haar lichaam vanaf het moment dat ze het glas leeg drinkt en benoem wat er gebeurt.

Wat van je eigen aanpak die je eerder omschreven hebt heb je succesvol gebruikt?

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Wat van je eigen aanpak heb je niet gebruikt? Waarom?

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Zou je je eigen aanpak iets beter kunnen maken?

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Appendix A

Les 6 Bloedsomloop & Bevalling

Tijdens de zwangerschap neemt de baarmoeder met foetus en vruchtwater veel ruimte in. Leg uit welke onderdelen van het lichaam van de moeder hierdoor het met minder ruimte moeten doen. Zou je enkele effecten hiervan kunnen verzinnen en uitleggen?

Wat van je eigen aanpak die je eerder omschreven hebt heb je succesvol gebruikt?

Wat van je eigen aanpak heb je niet gebruikt? Waarom?

Zou je je eigen aanpak iets beter kunnen maken?

Appendix A

Les 7 De eerste erfenis

Oefenvraag:Een gen is de DNA-code voor één eiwit of speciale stof (zoals bijvoorbeeld hormonen of andere stoffen). Probeer zoveel mogelijk genen te bedenken die voor de taken van witte bloedcellen bepalend zijn. Leg zo precies als je kan uit waar deze genen verantwoordelijk voor zijn.

Wat van je eigen aanpak die je eerder omschreven hebt heb je succesvol gebruikt?

Wat van je eigen aanpak heb je niet gebruikt? Waarom?

Zou je je eigen aanpak iets beter kunnen maken?

Appendix A

Les 8 Erfelijke eigenschappen

Oefenvraag: Leg uit waarom een beschadiging in het DNA in een eicel grote gevolgen kan hebben voor voor de baby. Geef een voorbeeld van een gen en het effect van deze beschadiging

Wat van je eigen aanpak die je eerder omschreven hebt heb je succesvol gebruikt?

Wat van je eigen aanpak heb je niet gebruikt? Waarom?

Zou je je eigen aanpak iets beter kunnen maken?

Appendix A

Les 9 Cellen en chromosomen

Oefenvraag: Jamil woont in Jemen en heeft geen toegang tot een dokter of een ziekenhuis. Door een fout in de mitose ontbreken er een aantal regelgenen die de vorming van kanker tegen gaan in een darmcel van Jamil. Leg uit wat er de komende dagen, weken en maanden allemaal gaat gebeuren in Jamils lichaam.

Wat van je eigen aanpak die je eerder omschreven hebt heb je succesvol gebruikt?

Wat van je eigen aanpak heb je niet gebruikt? Waarom?

Zou je je eigen aanpak iets beter kunnen maken?

Appendix A

Les 10 Afsluiting

In dit onderzoek ben je bezig geweest met je eigen aanpak van inzichtsvragen in de biologie. Een aantal weken geleden heb je je eigen aanpak omschreven, deze is misschien veranderd of hetzelfde gebleven. Schrijf in je eigen woorden je aanpak op. Voel je vrij om een stappenplan of model te maken.

Wat vind je effectief aan je eigen aanpak

Zou je deze aanpak ook gebruiken voor inzichtvragen op de toets. Leg uit waarom wel of niet.

Appendix B

Categorisation of formulated strategies	Metacognitive components formulated strategy	Student formulation of metacognitive components
1a. Read & Write	- Taking time to understand the biological problem	: Reading the problem : Understanding the problem : Checking the biological subject
	- Preparing a suitable solution	: Thinking of a solution : Writing down what is known about the subject
1b. Read, Write & **Check**	- 1a.	
	- Checking solution for applied logic	: Asking oneself if the solution is logical : Checking if the solution is right
2a. Indicate, Access knowledge & Combine	- Taking time to understand the biological problem	: Reading the problem : Understanding the problem : Checking the biological subject
	- Identifying biological components in the problem	: Identifying important concepts : Identifying the subject(s) in the problem : Recognising subjects that have been learned : Exclusion of unnecessary information : Selecting information that is important in the question
	- Accessing knowledge about identified biological components in the problem	: Remembering what is known about the concepts /subject(s)/important information : Remembering what is read about concepts/subject(s) /important information : Remembering information that is linked to the identified concepts
	- Combining necessary identified biological components and accessed knowledge to formulate solution	: Asking oneself how the information can be combined to an solution : Combining what is known to formulate a logical answer
	- Step by step formulation of solution through reassessment of inclusion/exclusion of biological components and accessed knowledge	: Formulation to a story : Creating an solution that gives an overview : Creating a solution that must be logical : Checking the answer for missing information

Appendix B

2b. Indicate, Access known and **unknown** & Combine	- 2a	
	- Indicating and dealing with gaps in accessed knowledge	: Checking if accessed information is sufficient enough to formulate an answer : Applying logic for what is unknown
2c. Indicate, Access known and search for analogous problem	- Taking time to understand the biological problem	: Reading the problem : Understanding the problem : Checking the biological subject
	- Identifying biological components in the problem	: Identifying important concepts : Identifying the subject(s) in the problem : Recognising subjects that have been learned : Exclusion of unnecessary information : Selecting information that is important
	- Accessing knowledge and memories for visual, auditory or experiences in which identified biological components play a role	: Comparing the biological problem with text book and work book biological problems : Comparing the biological problem with teacher explanation
	- Combining identified biological components and accessed knowledge to formulate a solution	: If comparison is any found, formulate answer
3. Connectivity approach	- Taking time to understand the biological problem	: Reading the problem : Understanding the problem : Checking the biological subject
	- Identifying biological components in the problem	: Identifying important concepts : Identifying the subject(s) in the problem : Recognising subjects that have been learned : Exclusion of unnecessary information : Selecting information that is important in the question
	- Active arrangement for cause and effect relations between identified biological components	: Trying to look for any consequence/effect in the biological problem : Trying to look for any cause for the biological problem

Appendix B

		: Remembering the function of concepts in order to indicate possible malfunctions : Looking for relations between identified functions, processes and concepts
	- Identification of biological component behaviour of all identified biological components	: Looking at what plays what part in the cause of the biological problem : Trying to find the function of the identified concepts
	- Analyse logic of component behaviour with identified cause and effect relations	: Asking oneself how things/processes would normally go : Asking oneself how deviant processes are taking place
4. Who, Where, What approach	- Taking time to understand the biological problem	: Reading the problem : Understanding the problem : Checking the biological subject
	- Identifying biological components in the problem	: Identifying important concepts : Identifying the subject(s) in the problem : Recognising subjects that have been learned : Exclusion of unnecessary information : Selecting information that is important in the question
	- Allocation of identified biological components in the greater system	: ‘’Where is this biological problem taking place?’’ is being asked to oneself : Checking whether the location of the components in the biological problem is of importance
	- Allocation of processes that take place between the components	: ‘’What process is going on?’’ is asked to oneself : Checking whether the processes that take place in the biological problem are of importance
	- Formulation relation between identified located biological components and processes that take place between them	: Write down the process that is taking place : Write down the location of the biological subject and what exactly happens there : Draw conclusion of gathered information