What strategies do high and low achieving students use when reading a biological process diagram?

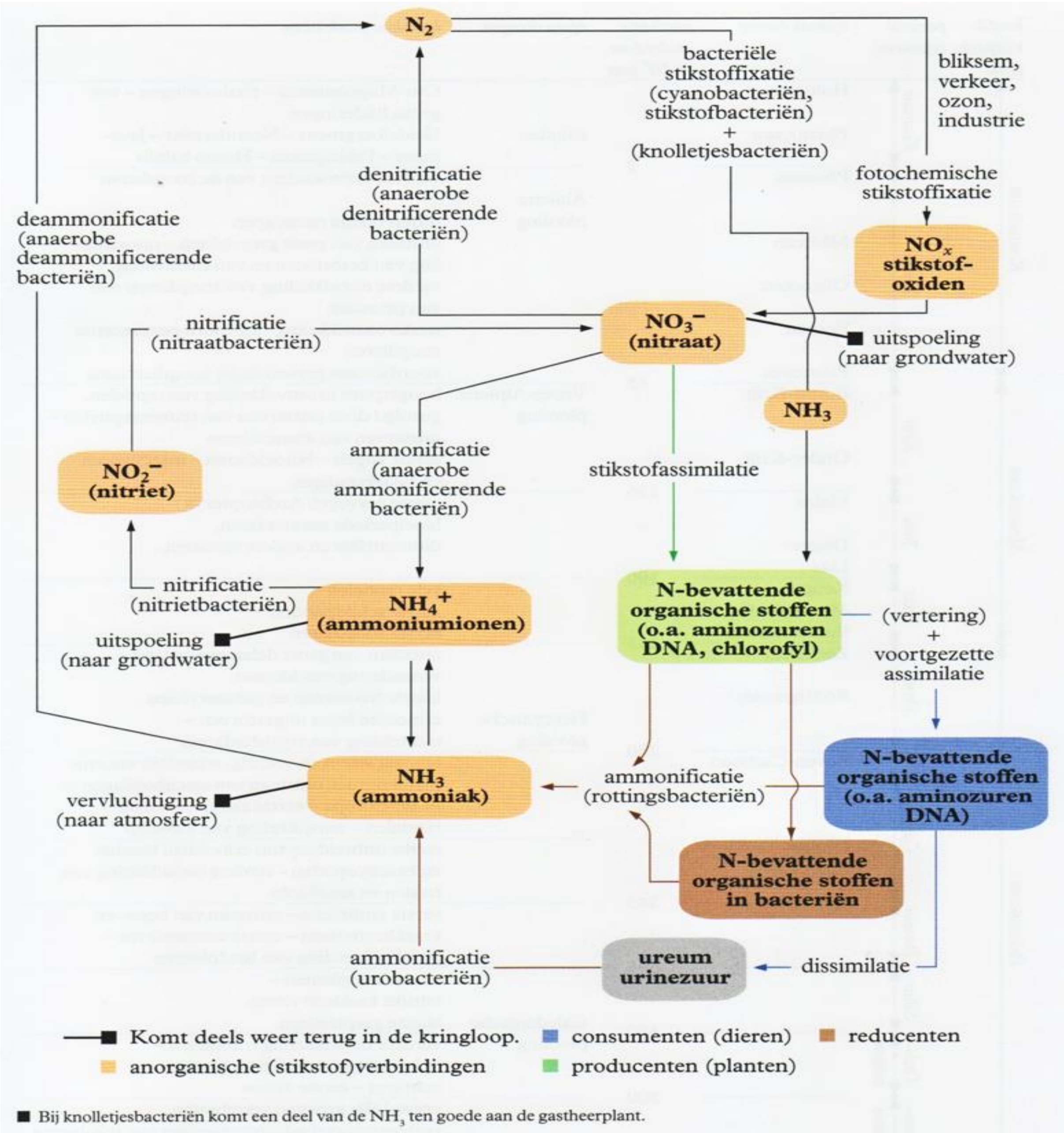

Figure 1 Example of a complex process diagram (NVON, 2013). In this process diagram, the nitrogen cycle is being displayed. It is one of the process diagrams in the BINAS, a book high school students in the Netherlands can use when taking a test.

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Abstract

In biology education in the Netherlands, students are often confronted with visual representations of biological concepts. These visualizations are intended to make complex concepts easier to understand for students and to summarize a lot of information in a compact figure. However, such figures are not always well understood by students. Especially a special kind of diagrams, process diagrams, require a lot of effort from students to understand them.

This study therefore investigated which strategies students use when studying two process diagrams: the menstrual cycle and the nitrogen cycle. Students were asked to look at visual representations of each of these process diagrams for 5 minutes and then use the think-aloud method to explain what they saw in the figures. These interviews were subsequently transcribed and analyzed with the use of an adapted version of the coding scheme established by Kragten et al. (2015).

A total of eleven different strategies have been identified. The results show that students mainly read labels regarding the organizational level and give meaning to process arrows. From the quality of the answers given, it can be concluded that students generally describe a figure very superficially and often do not really understand what the process diagram is about. There is no notable difference between havo and vwo students and high-performing students and low-performing students. Vwo students, however, are in general better able to explain what the process diagrams were about, and they made use of prior knowledge more often.

Introduction

As a biology teacher, visual representations of biological concepts are probably easy to understand. But unfortunately, high school students within the age of 15 to 18 can struggle with them a lot. In empirical research, it appears that students generally understand various types of visualizations very poorly (Bergey et al., 2015; Cromley et al., 2013). Students often lack prior knowledge and they do not understand different parts of figures. Therefore, they cannot draw correct conclusions from the figures (Cromley et al., 2013). Students also find it difficult to draw a connection between figures and texts. Even when there are explicit references to the text, they often pay little attention to the corresponding figure (Bergey et al., 2015; Cromley et al., 2013). Sometimes this can even lead to students skipping figures altogether (Bergey et al., 2015). Furthermore, in a study that was conducted with high school biology students, Cromley et al. (2013) found that students do not use knowledge gained from one figure for the next figure (Cromley et al., 2013).

In Dutch high school level, the subject biology is characterized by the wide range of diagrams, charts, images, and visualizations of biological concepts (Kragten et al., 2015). Especially within the field of ecology there is a high variety of figures. To perform well in biology, it is therefore important that students learn to understand and interpret visualizations. A subcategory within the broad term visualizations are process diagrams. A process diagram is a diagram in which relationships of different parts of a dynamic process are shown. An example of a process diagram is the carbon (figure 4) and nitrogen cycle (figures 1 and 3) within the field of ecology. These process diagrams show how the elements carbon and nitrogen are transported from one component to another. Another example of a complex process diagram is the menstrual cycle (figures 2 and 5). This process diagram consists of many details that are interrelated. In the process diagram of the menstrual cycle, for example, four different hormones are shown that regulate the cycle. These hormones are dependent on each other, for example: from the point when the concentration of LH is highest, the progesterone concentration starts to increase. And when the concentration of estradiol rises, the LH concentration also rises. Furthermore, it can be seen how the concentration of these hormones affects the thickness of the endometrium, the development of a follicle and the woman's body temperature. In addition, the exact relationship between all components is not explicitly present in the process diagram. For example, it is not explicitly visible what the influence of a high estradiol concentration is on the thickness of the endometrium. Another process diagram, as shown in figure 2, makes these relationships between the different parts much clearer. However, students in the Netherlands are not allowed to use this figure when taking tests. They can find the separate functions of each hormone in the BINAS, but this requires additional effort from students. In conclusion, what makes these process diagrams so hard for students to comprehend is the many details that are present within the process diagram. These include, among others, names of different biological concepts, various chemical formulas of molecules and a diverse array of graphic symbols and figures. This poses a significant chance of cognitive overload.

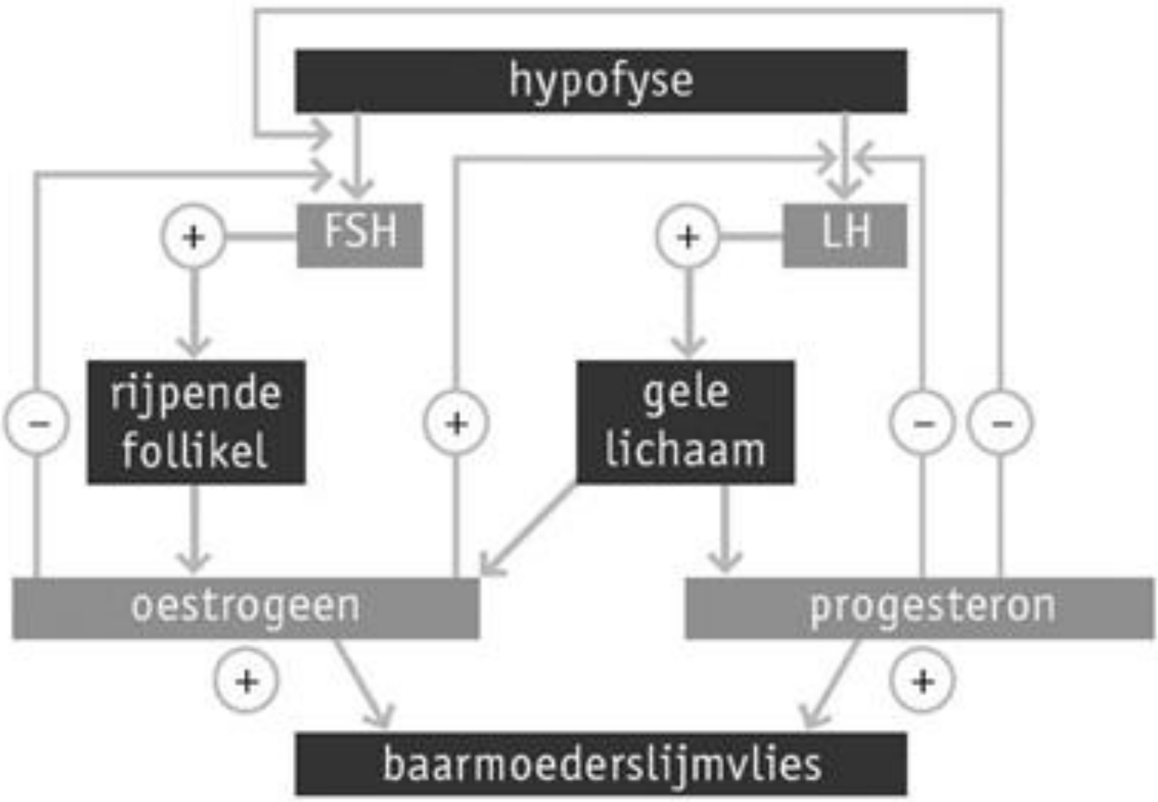

Figure 2 Example of a complex process diagram (Bijsterbosch, 2017). In this process diagram, the interrelationships of various hormones of the hormonal regulation of the menstrual cycle are visible.

Problem analysis

Biology exams are becoming more and more characterized by long texts (Kapteijn et al., 2018). The subject of ecology in secondary school biology is characterized by long texts and a wide variety of figures (Kapteijn et al., 2018). Ecology texts often contain figures, whether it is in the biology textbook, the BINAS or exams. As a teacher, these figures are probably easy to understand, but students struggle with them a lot. This struggle can go so far that they often end up skipping figures altogether (Bergey, Cromley, & Newcombe, 2015; Cromley, Snyder-Hogan, & Luciw-Dubas, 2010). An analysis of vmbo and vwo exams between 2012 and 2017 made it clear how important it is for students to be able to work with figures (Kapteijn et al., 2018). It regularly happens that students must use figures in the BINAS to answer questions. However, the lack of knowledge of the BINAS figures often proves to be an obstacle to properly answering questions. (Kapteijn et al., 2018).

As mentioned before, two complex ecological figures are the carbon and nitrogen cycles. These cycles are exam topics for both havo and vwo students who are expected to be familiar with the content concerned. While the carbon cycle is still somewhat related to the student's experience due to the increasing interest in climate change, this applies to a lesser extent to the nitrogen cycle. Partly because of this, the nitrogen cycle is described by students as particularly difficult (Kapteijn et al., 2018). Students must know and be able to explain the following concepts: (in)organic matter, biomass, autotrophic, heterotrophic, photosynthesis, (an)aerobic dissimilation, (de)nitrification, putrefaction/ammonification, and nitrogen fixation (CvTE, 2018). However, it remains to be seen to what extent the nitrogen crisis, which has been current in the Netherlands since 2019, contributes to ecological understanding among students. One possibility is that this crisis has brought the nitrogen cycle closer to the experiences of students.

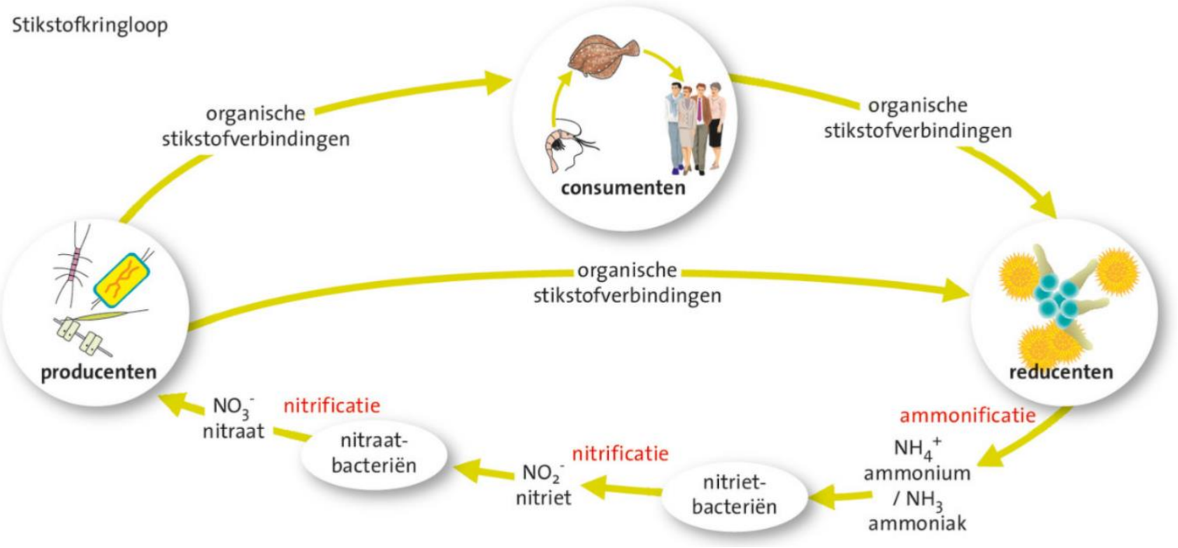

Figure 3 The nitrogen cycle in Nectar's biology textbook from havo 4 (Bijsterbosch, 2017). You can see the separate groups of organisms in the circles, the types of nitrogen compounds between the arrows and the names of the biological processes in red.

Students' difficulties

Problems students have with figures such as the nitrogen cycle are often overlooked by teachers (Kapteijn et al., 2018). Understanding these figures requires substantive prior knowledge. Firstly, about organisms and organizational levels (bacteria, plants, animals), secondly about biological processes (nitrification, denitrification & ammonification) and thirdly they need to know chemical terms such as NO3- and NH4+. In addition, they often need to notice and understand the shapes, arrows, sizes, and captions. The meaning of these graphic designs eludes the students. Finally, there is also a big difference between the figures from the textbooks and from the BINAS (figures 1, 4 and 2). The nitrogen cycle should evoke a cycle in the students. In the BINAS, on the other hand, this figure consists of straight lines and angles, which also all intertwine, which makes it unlikely that the students see a cycle in it (figure 1) (Kapteijn et al., 2018).

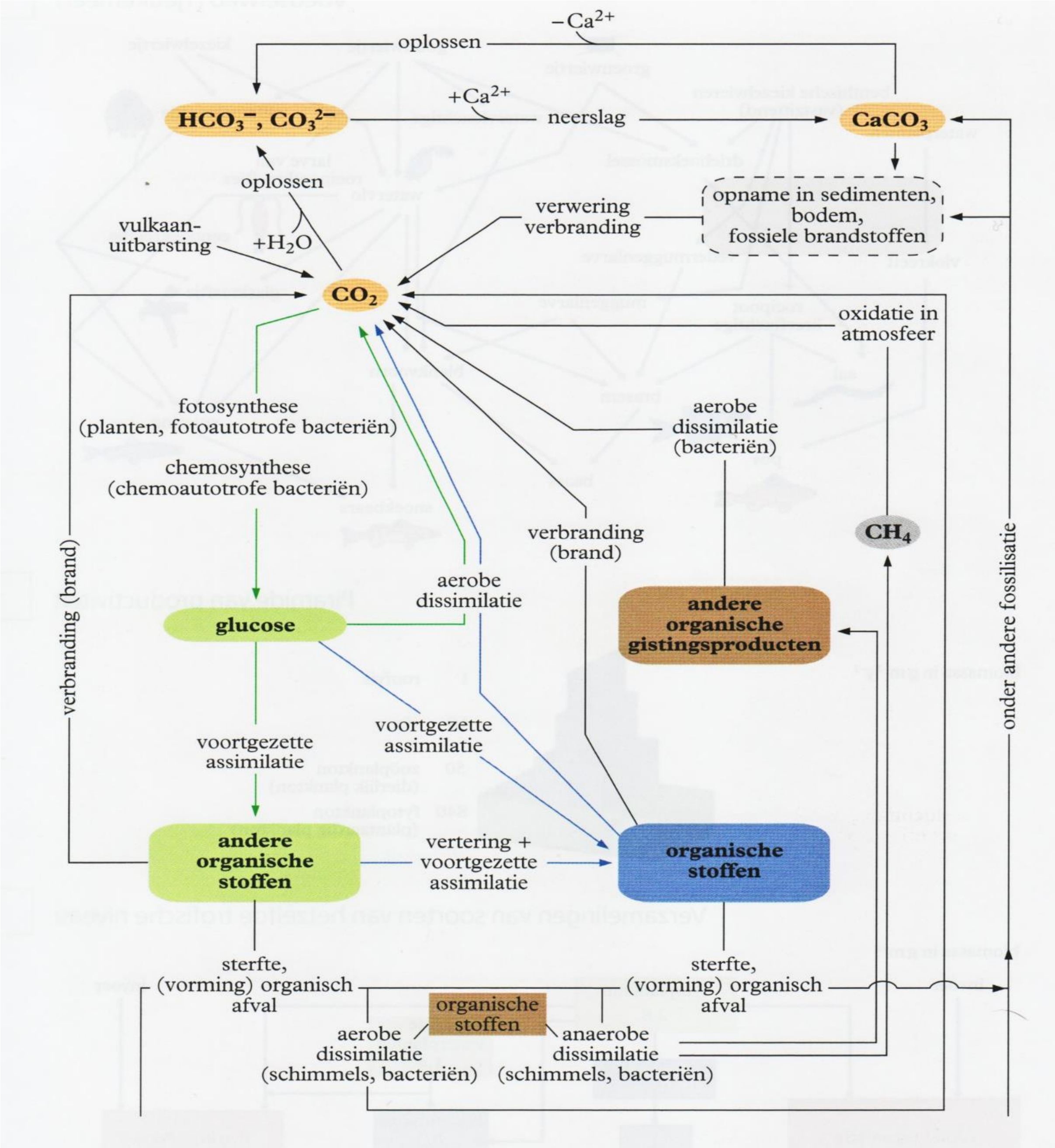

Figure 4 The carbon cycle in the BINAS (NVON, 2013). The individual groups of organisms can be seen between the arrows, the types of nitrogen compounds in the coloured blocks and the names of the biological processes in brackets between the arrows.

From different perspectives, obstacles can be described that students may have to learn and develop sufficient insight into biological cohesion (Eilam, 2002). First, students find it difficult to recognize and use different organizational levels. Complex cycles such as the nitrogen cycle vary from processes at the molecular level to major biological processes in ecosystems. This makes it relatively difficult for students to understand that the nitrogen cycle, for example, is the driver of all kinds of ecological processes. In general, students are relatively well able to understand the individual processes in a cycle, but they have difficulty placing these processes in a larger whole and seeing the interrelationships (Ummels, 2014). For example, a study in the Netherlands among havo 4 students shows that students have difficulty with the concept of energy in relation to photosynthesis, aerobic dissimilation, and continued assimilation (Ummels, 2014). In addition, students find it difficult that different components in the nitrogen cycle have different time periods. Some chemical processes are relatively fast while others can take centuries. Students also find it difficult to understand that organic molecules contain energy and that a change in molecular structure is accompanied by changes in that chemical energy (Kapteijn et al., 2018). Finally, the complexity perspective plays a role. It is important to understand the mutual influence in complex systems. For this, it is important to think in systems, the so-called systems thinking. When these different perspectives are not or insufficiently developed, the student's biological thinking remains too incoherent (Eilam, 2002).

Another problem with biological thinking can be that students can name the definitions of important concepts, but they don't really know what it means exactly. They are therefore unable to apply and use the concepts for biological reasoning (Kapteijn et al., 2018). Another problem in understanding complex biological systems is the limited 'working memory' of students. In general, students can only work with a limited number of elements when mastering complex biological systems (Millar, 1956). When a system becomes too complex, a student loses the overview. Characteristic of many biological figures, however, is that they make great demands on the working memory of students (Kapteijn et al., 2018). It is therefore important that the cognitive load remains limited to prevent overload. Interviews with Dutch secondary school students show that this cognitive (over)load is one of the biggest reasons that many students have difficulty interpreting complex figures, such as those of the nitrogen cycle and the menstrual cycle. The large amount of information available makes this scheme cluttered (Vertelman & Kunst, 2016).

In empirical work, therefore, it appears that students generally use and understand figures very poorly (Bergey et al., 2015; Bowen & Roth, 2002; Cromley et al., 2013; Kragten, Admiraal, & Rijlaarsdam, 2013). For example, before a student can understand a figure from the BINAS, he or she will first have to understand the individual components of the figure. The individual concepts are also necessary to understand what is happening (Winn, 1991). Not only are substantive prior knowledge and the understanding of underlying concepts important, but also understanding a figure in relation to other figures and with text in the textbook or with an assignment is important. All in all, understanding and interpreting a figure is a considerable mental effort (Kragten et al., 2013). A problem in understanding and interpreting figures that students often have is that teachers often do not give explicit instructions on how to read or interpret process diagrams, such as in the nitrogen cycle (Kragten et al., 2013; Quillin & Thomas, 2015). The use of the BINAS by teachers is often limited to only referring to the BINAS and having students practice looking for the correct BINAS figure (Vertelman & Kunst, 2016). The problem described above is not limited to process diagrams only. In general, there is hardly any instruction on how students can best use and interpret data from the BINAS (Vertelman & Kunst, 2016). It should be noted here that even teachers who do pay attention to reading and interpreting figures do not yet achieve the maximum learning outcome. By letting students practice making figures themselves, a much higher learning outcome can be achieved (Ainsworth, Prain, & Tytler, 2011; Bowen & Roth, 2002). In general, the following applies: the greater and more varied the effort, the greater the learning yield (Bowen & Roth, 2002). In practice, it appears that students often lack prior knowledge, do not understand essential parts, or cannot draw correct conclusions from the figures (Cromley et al., 2013). For example, students who lack the prior knowledge that atoms cannot disappear in a cycle, do not follow the atoms well in cycles and lose them especially during the transition to the gaseous form, such as N2 in the nitrogen cycle (Wilson et al., 2006; Hesse & Anderson, 1992; Stavy, 1990).

Students also appear to find it difficult to make connections between figures and texts. Even when there are explicit references to the text, they often pay little attention to the accompanying figure (Bergey et al., 2015; Cromley et al., 2013; Schmidt-Weigand, Kohnert, & Glowalla, 2010). Complicating matters even more is that students do not use knowledge gained from one figure or even another subject in the next figure (Cromley et al., 2013). In the nitrogen cycle, however, great demands are made on prior chemical knowledge. So, this is an important problem in students' understanding of these cycles.

Nitrogen cycle: An example of a complex process diagram

To understand the nitrogen cycle, students must have knowledge of all kinds of organisms (bacteria, fungi, plants, and animals) that perform different functions in the cycle. In addition, students should have knowledge of biological processes (photosynthesis, assimilation, aerobic and anaerobic dissimilation). Students must also know and understand all kinds of chemical terms such as CO2, HCO3 and CH4. In addition, students should know and understand concepts such as organic and inorganic material. Especially for students without a chemistry background, it will be difficult to distinguish between these biological and chemical terms, but students with a chemistry background also experience problems (Kapteijn et al., 2018). Finally, students must notice and understand the boxes, shapes, colors, arrows, sizes, and captions.

Figure designers try to shape these different things in such a way that they help in understanding the figure (Winn, 1991; Kragten et al., 2013). In practice, however, it appears that this does not always get through to students. For example, many students forget to read the legend carefully. What also does not help is that different figures are used for the same biological concept. The nitrogen cycle is represented differently in BINAS than in, for example, Nectar's textbooks (figures 1 and 3 respectively). As a result, students must learn and understand a figure twice. This will not make a big difference for students who understand the nitrogen cycle very well already, but this certainly does not make it more understandable for students who have more difficulty with the nitrogen cycle (Kapteijn et al., 2018). Also, not all figures in the BINAS are completely well designed. The nitrogen cycle is represented in the BINAS in straight lines and angles, making it unlikely that students will immediately see a cycle in it (figure 1) (Kapteijn et al., 2018). In addition, teachers often overlook that apparently simple concepts cause difficulties for students. Often, not so much attention is paid to what different language elements such as the prefix an- (as in anaerobic), or the suffix -ification (as in ammonification) mean. However, students are better able to understand such complex figures when they are given more attention (Kapteijn et al., 2018). Research shows that if students are familiar with the design of a figure, they perform better (Kragten et al., 2013).

Research methods

Purpose and research question

In conclusion from the problem analysis described above, it is therefore important for educators to learn what learning activities improve students' comprehension of complex process diagrams, so that they can help students in their learning process. In short, students have difficulty with the design of process diagrams, activating prior knowledge and recognizing and understanding different parts of process diagrams. As a biology teacher myself, the problem outlined above has piqued my interest to know more about the strategies used by students when studying a biological process diagram. By gaining insight into the strategies used by students when studying process diagrams, a teacher can more easily intervene in students' erroneous study of process diagrams and gain more insight into which strategies are particularly helpful when studying process diagrams. When a teacher is aware of the learning process of students, he or she can actively manage this, so that students are helped in their learning process.

To create more depth in this study, I have also looked at the strategies used by high-performing students and moderate to low-performing students. By examining which strategies are used by high-performing students, a teacher may be able to make these strategies explicit and teach them to students who have more difficulty studying and learning complex process diagrams. The question I asked myself in this study is therefore formulated as follows:

> *"What strategies do high and low achieving students use when studying a biological process diagram?"*

To answer this question, I used two process diagrams and asked students to explicitly articulate their thinking process: the menstrual cycle (figure 5) and the nitrogen cycle (figure 1). These process diagrams are described in detail in the problem analysis, as are the difficulties students experience when studying them.

Hypotheses

I hypothesize that students will generally employ superficial strategies when viewing and studying both process diagrams. Examples of this include reading the title, naming different parts of a process diagram, and viewing and locating items from the legend. Students will also try to give meaning to the various processes they observe. But this will lack depth and students will not actually understand what a particular process from the process diagram really means. Activating and using prior knowledge will be limited to recognizing and naming different concepts in the process diagram that were discussed earlier in biology lessons. I do not expect students to be able to actively use this prior knowledge in understanding and explaining the process diagrams. This is in line with the finding of Cromley et al (2013): students often lack prior knowledge and they do not understand different parts of figures. Therefore, they cannot draw correct conclusions from the figures. These are in general moderate to low expectations. These expectations are based on the fact that the process diagrams in the BINAS are complex for students to study and understand. For example, the nitrogen cycle is represented in the BINAS in straight lines and angles, making it unlikely that students will immediately see a cycle in it (figure 1) (Kapteijn et al., 2018). Furthermore, the menstrual cycle in the BINAS (figure 5) does not show cause-effect relationships, which will prevent students from understanding the effect of one hormone on another. However, the process diagram of the menstrual cycle is designed in a way that students may compare different parts of the diagram more thoroughly. The process diagram consists of five separate diagrams that are placed beneath each other, which may provoke comparisons between the different areas of interest. I also expect that high-performing students generally employ more and more diverse strategies when studying process diagrams. I think they will especially take more time to study the process diagrams well. Finally, I expect that vwo students will make more active use of their prior knowledge, which will make them better able to understand and explain the process diagrams.

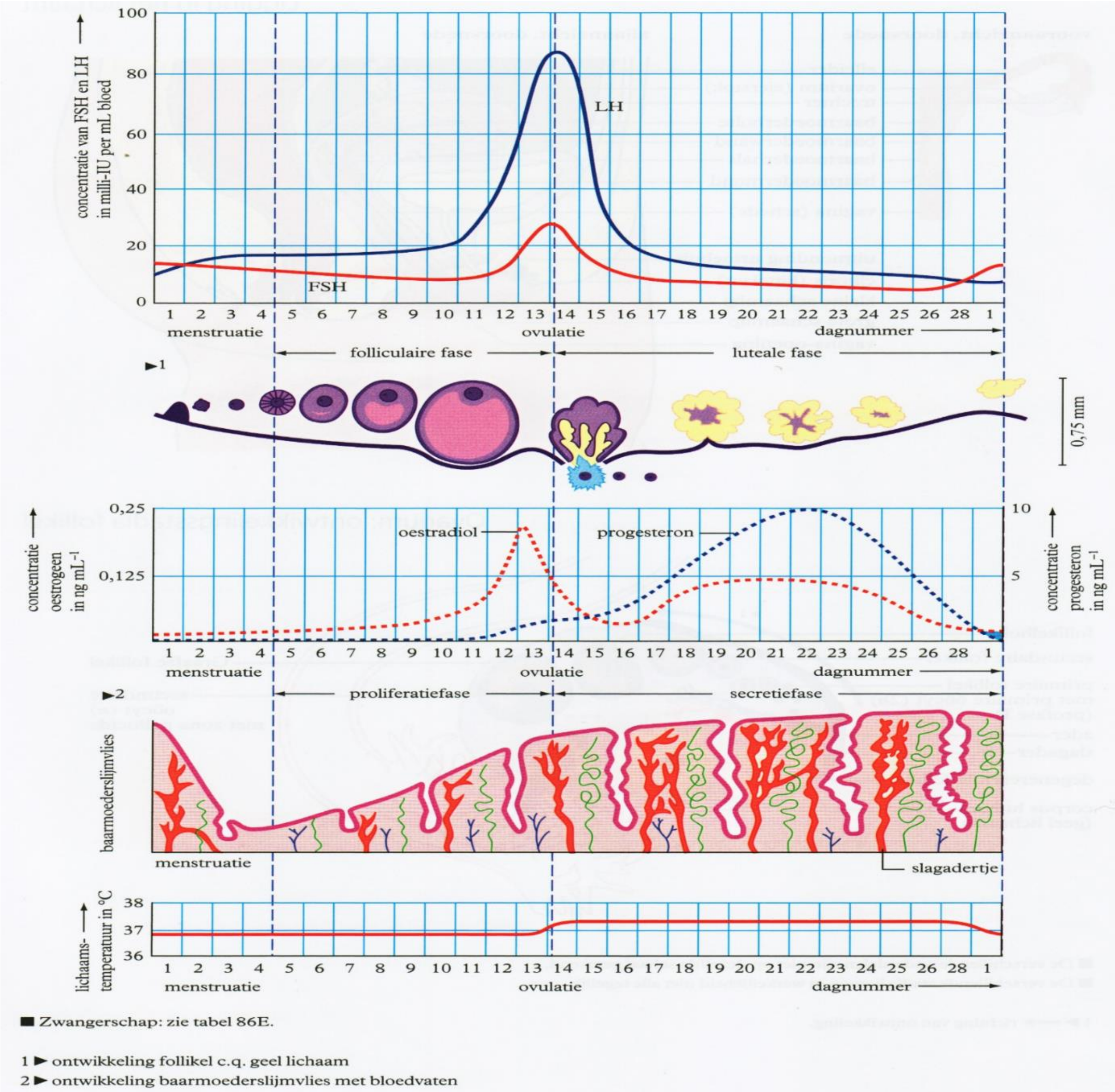

Figure 5 Example of a complex process diagram. In this process diagram, the menstrual cycle is being displayed. It is one of the process diagrams in the BINAS, a book high school students in the Netherlands can use when making a test (NVON, 2013).

Participants

The study took place at a high school in the central province of Flevoland in the Netherlands. Participating students were drawn from the 4th year of pre-university education (vwo) and higher general continued education (havo). These students were around 15 to 16 years old. Students in four classes were asked if they were willing to participate in the study. A brief overview was given of the design and purpose of the study, and what would be asked of the students. It was emphasized that the privacy of the students would be safeguarded throughout the study. It was made clear to the students that the recorded audio and video would only be used by the researcher and that no other person would see it. Furthermore, all data resulting from the interviews would be anonymized; nowhere the names of students would be mentioned. All data would also be deleted once the study has been completed. A total of around 80 to 90 students were asked if they were willing to participate in the study, of which a total of 20 students eventually participated. These students were drawn from four different classes: 4Hbiol_2 (2), 4Hbiol_4 (1), 4Hbiol_6 (11) and 4Vbiol_10 (6). 4Hbiol_6 was taught by the researcher itself (teacher 1). 4Hbiol_2, 4Hbiol_4 and 4Vbiol_10 were taught by another biology teach (teacher 2). In total, 11 students were taught by teacher 1 and 9 by teacher 2. Furthermore, four students in the class of teacher 2 were in the class of teacher 1 in a previous year. In total, 14 students of the havo-level participated and 6 of the vwo-level. At last, 12 of the participants were females and 8 were males. To make a distinction between high and low achieving students, the average grades of each student was used. On average, the students' average grade was a 5.97 (out of 10), which roughly corresponds to a B/B-/C in the American and Canadian school system. The havo students hereby had an average grade of 6.03 and the vwo students an average grade of 5.82. To pass a subject, high school students in the Netherlands need to have an average grade of 5.5.

Table 1 Participants in this study. In this table, the participants of this study are listed. For each student, the class, teacher, level of education, average grade and sex are displayed.

Participant	Class	Teacher	Level of education	Average grade	Sex
Student 1	4Hbiol_6	Teacher 1	HAVO 4	5,5	Male
Student 2	4Vbiol_10	Teacher 2	VWO 4	5,2	Male
Student 3	4Vbiol_10	Teacher 2	VWO 4	6,5	Female
Student 4	4Vbiol_10	Teacher 2	VWO 4	7,1	Female
Student 5	4Hbiol_2	Teacher 2	HAVO 4	5,1	Female
Student 6	4Hbiol_6	Teacher 1	HAVO 4	6,8	Female
Student 7	4Vbiol_10	Teacher 2	VWO 4	5,6	Male
Student 8	4Hbiol_2	Teacher 2	HAVO 4	6,9	Female
Student 9	4Hbiol_6	Teacher 1	HAVO 4	6,6	Male
Student 10	4Hbiol_6	Teacher 1	HAVO 4	5,2	Female
Student 11	4Hbiol_6	Teacher 1	HAVO 4	6,7	Female
Student 12	4Hbiol_4	Teacher 2	HAVO 4	5,4	Female
Student 13	4Hbiol_6	Teacher 1	HAVO 4	5,0	Male
Student 14	4Hbiol_6	Teacher 1	HAVO 4	6,1	Male
Student 15	4Hbiol_6	Teacher 1	HAVO 4	6,8	Female
Student 16	4Hbiol_6	Teacher 1	HAVO 4	6,3	Female
Student 17	4Vbiol_10	Teacher 2	VWO 4	6,7	Female
Student 18	4Vbiol_10	Teacher 2	VWO 4	3,8	Male
Student 19	4Hbiol_6	Teacher 1	HAVO 4	5,6	Female
Student 20	4Hbiol_6	Teacher 1	HAVO 4	6,5	Male

The study was conducted within the context of the nitrogen cycle (ecology, figure 1 and 4) and the menstrual cycle (human physiology, figure 5). Both topics were introduced for the first time in the 4th year of both havo and vwo (that was the year the participants of this study were enrolled). The menstrual cycle was explained in the month December. The nitrogen cycle was explained later in the school year, as this topic is part of the last chapter of the biology book. As this study took place in the months April, May and June, students were already familiar with the menstrual cycle. The nitrogen cycle, however, was being taught after the study took place. Students were therefore not familiar with this process diagram at the start of the study.

Procedure and learning tasks

This study built on the work of Kragten et al. (2015). In a study conducted in the Netherlands, Kragten et al. (2015) examined which learning activities distinguished between more and less successful students when studying a process diagram, which is determined by the number of correct inferences made by students when explaining a process diagram (Kragten et el., 2015). In this study, roughly following the procedure used by Kragten et al. (2015), participating students were first be asked to perform two learning tasks. This took place in an empty classroom for at most 20 minutes. Before the session started, students were informed about the procedure and the purpose of this study. They were also made aware of privacy considerations, and they were told what would happen to the data during and after the study. When this introduction was finished, the procedure started. Students were asked to first look at a process diagram of either the menstrual cycle (figure 5) or the nitrogen cycle (figure 1) for 5 minutes in which they had to learn as much as possible. The following was said to each student:

> *You will be shown two process diagrams in random order: one of the nitrogen cycle (BINAS 93G) and one of the menstrual cycle (BINAS 86C).*
>
> *You will study the process diagram for a maximum of 5 minutes. During this time, try to understand and remember as much of the diagram as possible as if you must make a test about it right afterwards.*
>
> *After you have finished studying, try to tell everything you got from the process diagram. You may of course use the process diagram for this. Try to be as comprehensive and detailed as possible.*
>
> *The previous steps will be repeated with a second process diagram.*
>
> *Finally, you will be asked several knowledge questions about the last process diagram. Try to answer these as accurately as possible using the process diagram.*
>
> *In total, the interview will take about 20 minutes.*

After the students finished a learning task, they were asked to think-aloud and tell the researcher everything he or she noticed in the process diagram. When students were finished with the first learning task, the procedure was repeated using the second process diagram. The rationale behind this was that by using two process diagrams, it can be checked whether students use the same learning strategies for a variety of process diagrams. To prevent bias due to students telling each other about the activities of the research, the order of both process diagrams was swapped after each interview. After both learning tasks were completed, the researcher asked a set of eight knowledge questions about the last process diagram that was shown to the student. For the reason of low usability, these knowledge questions were not used in this study. Throughout the interview, audio was recorded. A camera also faced the table where the students may point at the process diagram with their hands. The student itself was not visible. Afterwards, all interviews were carefully transcribed.

Learning strategies

Different learning strategies used by the students were distinguished by using a coding scheme. An adapted version of the coding scheme established by Kragten et al. (2015) was used in this study. Kragten et al. (2015) distinguished between an orientation phase and a main phase. Every time a student told something about the process diagram in the interview of this study, this remark was coded during the data analysis. Three main categories of learning activities were defined in the coding scheme that was designed for this study: cognitive, metacognitive and diagram learning activities. The orientation phase contained all activities students performed before studying the main area of a process diagram. Learning activities included: activating prior knowledge, reading the title, reading labels, and localizing legend items in the process diagram. After the orientation phase there was the main phase. This phase included the following learning activities: giving meaning to process arrows, inferences, relating prior knowledge, formulating alternative hypothesis, comparing different elements of the process diagrams, self-questioning, rereading parts of the diagram, reading the title, reading the labels, and using the legend. For the various learning strategies that were distinguished within this study, see table 2.

Table 2 Coding scheme for the think-aloud protocol that was designed and used in this study.

Phase	Type of activity	Strategy	Short term	Example
Orientation phase	Cognitive	Activating prior knowledge	Orientate Prior	"For when an egg is fertilized. If there is no fertilization, it is broken down again and then as a woman you have the menstrual period." "This is a process without oxygen."
	Diagram reading	Reading the title	Orientate Title	"You see the hormones during the menstrual cycle." "It's about nitrogen."
		Reading the labels regarding the organizational level	Orientate Level	"Follicular phase", "Luteal phase"
		Localizing legend items in the main area	Orientate Legend	"And arrows don't end up there." "And those are N-containing organic substances that plants use. Oh no, inorganic nitrogen compounds."
Main phase	Cognitive	Giving meaning to a process arrow	Meaning Arrow	"The follicle gets bigger, after which the egg cel leaves the follicle." "And FSH goes down slightly from menstruation to about two days before ovulation."
		Making an inference	Inference	"For example, N2, which is produced by lightning, ozone and industry due to its emission, is made from N2 NOx nitrogen oxides." "And the endometrium thins out before menstruation at ovulation and rebuilds after ovulation for a new egg."
		Relating to prior knowledge	Relate Prior	"Assimilation of this therefore goes towards the consumers." "And you can also go from the NO3 nitrate to the NH4 and then there is also what you call ammonification. Bacteria do that without oxygen."
		Formulating an alternative hypothesis	Alt. Hypothesis	"Furthermore, I notice that LH is present in much greater quantities than FSH. So that's more necessary." ""You also see that the hormones FSH and LH decrease and you see that the hormone progesterone increases. This is also logical because the yellow body is broken down."
		Comparing elements across AOIs	Compare	"The trajectory of this graph is similar to that of FSH." "In this way you can eventually go through all kinds of roads you can complete the entire circle."
	Metacognitive	Self-questioning	Self-Questioning	"I don't know exactly where it all starts, but it's mainly about nitrogen, but I think also about other substances." "And with the third with estradiol and progesterone you also see that it is higher and lower, but I don't know what it all means."
		Diagram commenting	Comment	"I find this a lot less clear." "It contains all kinds of difficult names, all kinds of substances and what that reacts to and what you get."

Data analysis

Strategies were classified as ‘activating to prior knowledge’ when students said they recognized a particular concept or process from previous biology classes. They did not hereby use this prior knowledge to explain parts of the process diagram. When students noticed the subject of the process diagram or read the title, this was classified as the 'reading the title' strategy. Subsequently, when students named certain labels from the process diagram, such as 'NO3-', 'NH3' or 'nitrogen assimilation' for the nitrogen cycle or 'estrogen', 'progesterone' or 'luteal phase' for the menstrual cycle, this was seen as the strategy 'reading labels regarding the organizational level'. The final strategy within the orientation phase, localizing legend items in the main area, was when students used the legend when naming or explaining different parts of the process diagram. This was the case, for example, when they identified the role of consumers, producers, and decomposers in the nitrogen cycle, using the legend colors for these types of organisms.

When students superficially tried to explain part of a process diagram, it was classified as 'giving meaning to a process arrow'. This strategy therefore resembles 'making an inference'. The difference between these strategies, however, is that with 'giving meaning to a process arrow' students read very literally what they saw happening in a process diagram without really understanding what it was about. Whether this was really the case was interpreted by the researcher. An example of this strategy from the current study was, for example:

> *"I see that around ovulation the hormones FSH and LH increase enormously. And after ovulation it decreases again."*

In this sentence, the student clearly describes what is happening, but no deeper meaning is given as to why, for example, LH and FSH increase around ovulation and what role these hormones play in the menstrual cycle. When a student did provide this more in-depth explanation, the strategy was classified as 'making an inference'. When students hereby used prior knowledge, the strategy was also classified as 'relating to prior knowledge. Kragten et al. (2015) defined an inference as a correct statement that includes the relation between processes that are not literally displayed. In this study, an example of a correct inference when looking at the menstrual cycle could be:

> *“When the concentration of estradiol increases, so does the concentration of LH”*

> *“When the corpus luteum is formed, the concentration of progesterone increases”*

> *“The endometrium thickens when the concentration of estradiol rises.”*

When looking at the nitrogen cycle, correct inferences could be:

> *“Ammonification means that ammonium (NH_4^+) is made from nitrate (NO_3^-). This is an anaerobic process performed by ammonifying bacteria.”*

> “Nitrification must be an aerobic process because nitrite (NO_2^-) is formed from an ammonium ion (NH_4^+), which contains two oxygen atoms.”

> *“Inorganic nitrogen compounds are formed from organic nitrogen compounds by putrefactive bacteria. This process is called ammonification.”*

When students made mutual connections between different parts of a process diagram, and gave their own interpretation, this was classified as 'formulating an alternative hypothesis'. Examples of these alternative hypotheses were, among others:

> *“And then there's that which can volatilize to the atmosphere it can evaporate. Then it ends up in the ozone layer.”*

> *“And part of nitrate can go back into the ground to groundwater via leaching. This is mainly due to industry that simply pumps their waste into the water.”*

When students compared different parts of the process diagram, this was seen as the strategy 'comparing different elements across the area of interest'. Finally, there were two metacognitive strategies that students could apply when they see different process diagrams. The first was 'self-questioning'. When students asked themselves a question about the process diagram or when they noticed that they understood (part of) the process diagram or not, this was classified as 'self-questioning'. Examples of ‘self-questioning’ include:

> *“Of course, there are no questions, so I don't really know what to look for.”*

> *“There are also a lot of names in there that I don't know yet.”*

> *“I found this one a bit more difficult because I don't know those words anymore, but I do recognize those figures. I thought those are cells. Or something. And I learned that with biology.”*

Finally, when students criticized the design of the process diagrams, for example by making it clear that they did not understand something through the shape of the process diagram or the use of arrows and colors, this was seen as 'diagram commenting'. Compared to the coding scheme of Kragten et al. (2015), this is an additional strategy that has been added in this study. Examples of this strategy include, among others:

> *“You don't see a table, how do you explain that properly, a kind of step-by-step plan for how things work in the nitrogen cycle. So, a lot of information is in there.”*

> *“And because of those help lines, the graphs are nicely aligned, and the lines help you to see a connection how many hormones are in the body and what effect that has on other things.”*

> *“I found this one more difficult. I think you can get from this table in what kind of substance there is or is released and certain action-reaction in that direction.”*

> *“It's a very unclear picture. You don't see clearly where the beginning or the end is. This will be the start. I don't really see a cycle or anything.”*

To distinguish between high and low achieving students, the average biology grade in the school year 2020/2021 was used on both levels of education (vwo and havo). This study is a mixed-methods study. At first, qualitative data was collected in the form of students’ responses to the questions asked for the two learning tasks. Verbal responses were used to determine the used strategies by students when studying the process diagrams and the quality of their responses. These responses were then quantified using an adapted coding scheme based on the coding scheme by Kragten et al. (2015). Each strategy that was used by the students was coded according to the coding scheme designed for this study (table 2). It was noted when a strategy is used explicitly or implicitly. A difference between the implicit and explicit use of strategy was the naming by the students of the strategy in question. For example, if they used information from the legend without naming it, that was counted as implicitly locating items from the legend in the process diagram (orientate legend). When they mentioned that they looked at the legend it was coded as explicit. Another example was when students listed labels that can be seen in the process diagram. For example, when they named hormones (progesterone, FSH, LH, estradiol) or molecules (NH3, NH4+, NO3-), this was considered as implicitly using the 'orientate level' strategy. This was when students read labels with regard to the organizational level. Furthermore, for each strategy used by the students it was examined whether this strategy is factually correct or incorrect. When students gave meaning to a process arrow, but the information given was wrong, this was considered to be ‘incorrect’. For example, if students read the legend incorrectly, this was labeled as incorrect.

To guarantee the reliability and validity of the results, all interviews with students were transcribed and analyzed by the researcher himself. Therefore, all student interviews were interpreted and processed in the same way. Something that reduces the reliability of the results is that the responses of the students were interpreted by one person. It may therefore be the case that some responses would have been interpreted differently by other researchers if they had been involved in the study. This will be discussed further later in the discussion and conclusion. Something that increased the reliability and validity of the study was that all students participated in the study in the same way. All students were asked the same questions and they were not interrupted during their responses.

To conclude, it was noted for each strategy how often it is used, how often this was done explicitly and implicitly and how often this was correct and incorrect. The means of all values were also calculated. For example, how often each strategy was applied in total by students, how often this was done by havo and vwo students on average, how often this was done on average by high and low-performing students, how often each strategy was used explicitly and implicitly in total and how often each strategy average right or wrong.

Results

Menstrual cycle and nitrogen cycle

As can be seen in Table 3 and figure 6, a total of eleven different strategies were identified. Two of these were by far the most used: orientate level and meaning arrow. In other words, students most often tried to give meaning to process arrows and often associated labels with regard to the organizational level. These two strategies were predominantly used together. There do not seem to be any major differences between both process diagrams. However, minor differences can be observed. On average, students were more likely to use the 'orientate level' strategy when they study the process diagram of the nitrogen cycle compared to when they look at the process diagram of the menstrual cycle (figure 6). Conversely, students more often compared different parts of the process diagram of the menstrual cycle than when they looked at the nitrogen cycle. It is noticeable that all strategies other than 'orientate level' and 'meaning arrow' were used very little. Some students used a lot of strategies when studying the process diagrams and others were very succinct in their study.

Table 3 Results of the analysis. In the table it can be seen what strategies were used for both process diagrams, how many times they were used, the percentage of strategies used, how many times the strategies were implicit and explicit and how many times the strategies were correct and false.

Phase	Type of activity	Strategy	Strategy	Menstrual Cycle						Nitrogen Cycle						Total	% Relative use
				Implicit	Explicit	Correct	False	Subtotal	% Relative use	Implicit	Explicit	Correct	False	Subtotal	% Relative use		
Orientation phase	Cognitive learning activities	Activating prior knowledge	Orientate Prior	5	8	11	2	13	4,3%	2	5	5	2	7	2,1%	20	3,2%
	Diagram learning activities	Reading the title	Orientate Title	1	7	8	0	8	2,7%	2	3	5	0	5	1,5%	13	2,1%
		Reading the labels regarding the organizational level	Orientate Level	83	27	106	4	110	36,7%	103	30	122	11	133	40,7%	243	38,8%
		Localizing legend items in the main area	Orientate Legend	1	3	4	0	4	1,3%	16	9	24	1	25	7,6%	29	4,6%
Main phase	Cognitive learning activities	Giving meaning to a process arrow	Meaning Arrow	0	95	85	10	95	31,7%	0	97	81	16	97	29,7%	192	30,6%
		Inference	Inference	0	15	14	1	15	5,0%	0	14	12	2	14	4,3%	29	4,6%
		Relating prior knowledge	Relate Prior	10	3	12	1	13	4,3%	7	1	8	0	8	2,4%	21	3,3%
		Alternative hypothesis	Alt. Hypothesis	0	14	3	11	14	4,7%	0	8	3	5	8	2,4%	22	3,5%
		Comparing elements across AOIs	Compare	7	14	20	1	21	7,0%	0	10	10	0	10	3,1%	31	4,9%
	Metacognitive learning activities	Self-questioning	Self-Questioning	0	3	3	0	3	1,0%	0	7	7	0	7	2,1%	10	1,6%
		Diagram commenting	Comment	0	4	4	0	4	1,3%	0	13	13	0	13	4,0%	17	2,7%
Total				107	193	270	30	300	100%	130	197	290	37	327	100,0%	627	100,0%

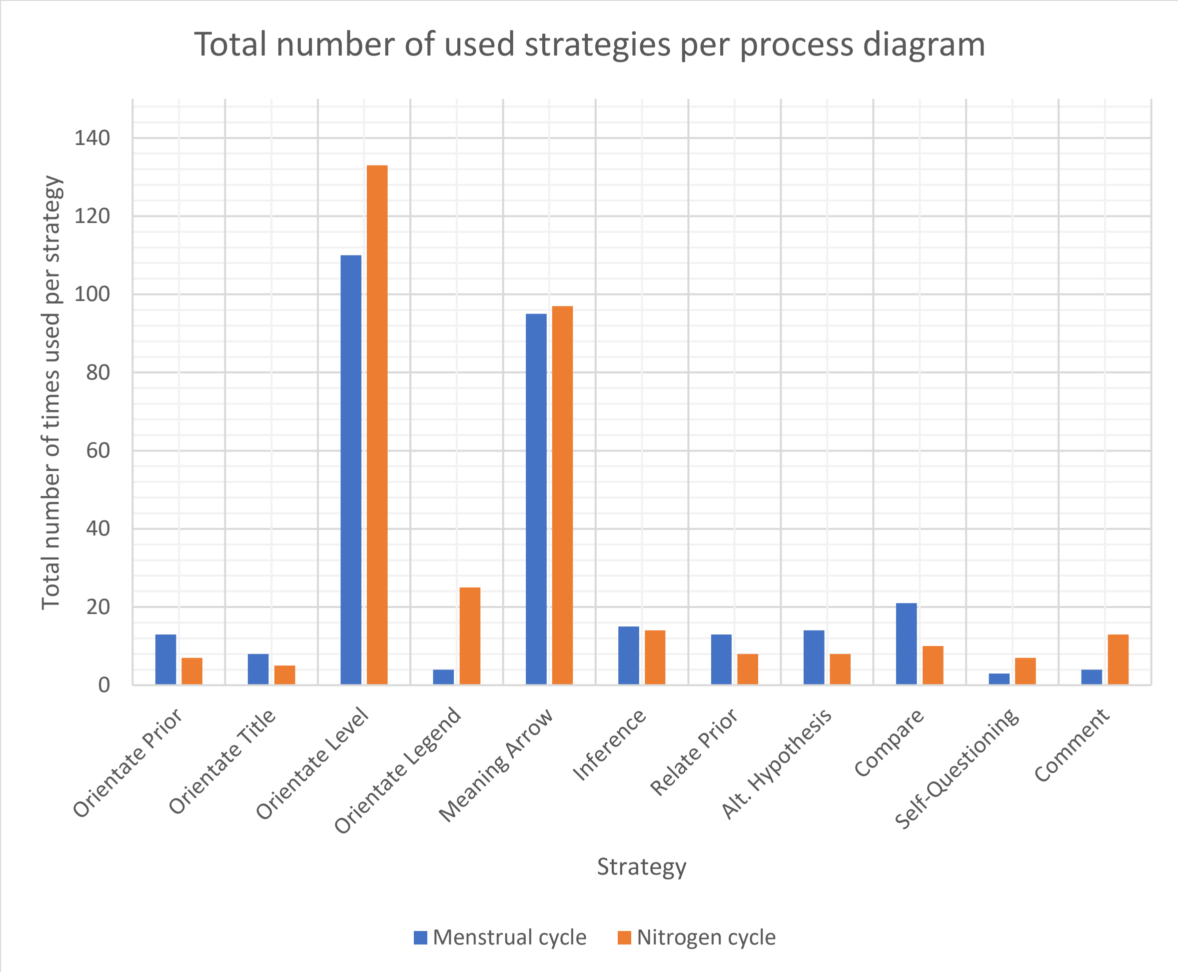

Figure 6 Total number of times used per strategy for each process diagram. In this figure it can be seen how many times each strategy was used in total when studying both process diagrams (N=20).

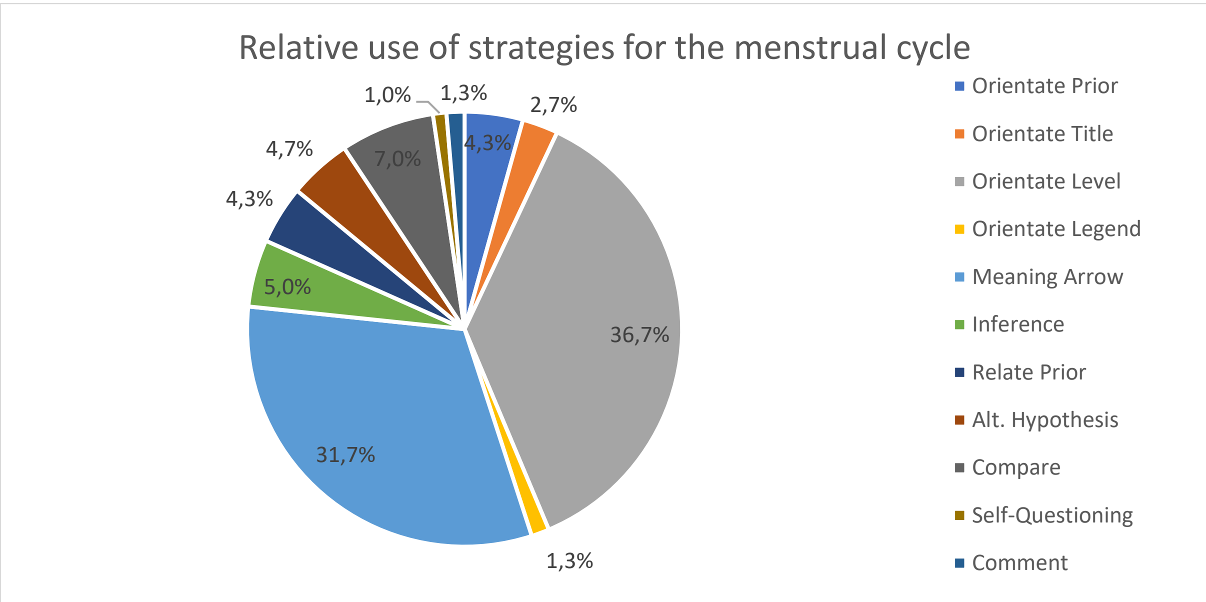

Figure 7 Relative use of each strategy for the menstrual cycle. This chart shows how often each strategy was used relative to the other strategies.

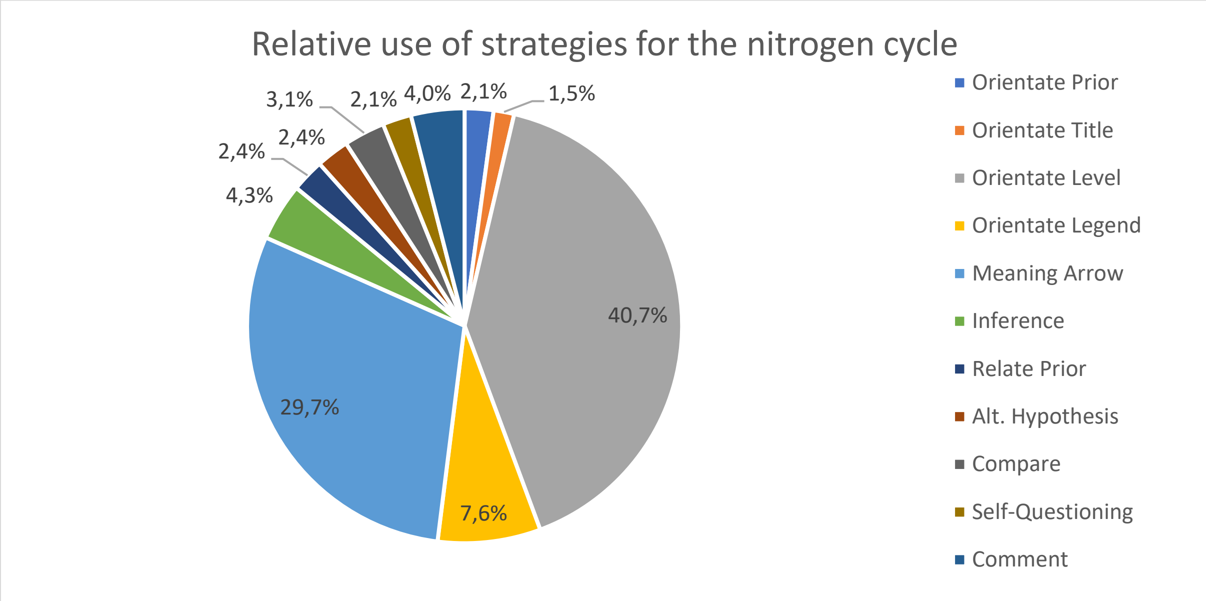

Figure 8 Relative use of each strategy for the nitrogen cycle. This chart shows how often each strategy was used relative to the other strategies.

Figures 7 and 8 show the ratio in which each strategy was applied for both process diagrams, the nitrogen cycle, and the menstrual cycle. For both strategies, reading labels with regard to the organizational level ("orientate level") and giving meaning to a process arrow ("meaning arrow") were used most often.

Observed strategies

The first strategy that was identified was activating prior knowledge in the orientation phase. As can be seen in figure 6 and table 3, this strategy wasn't used very often. Students activated prior knowledge on average once for both process diagrams. Activating prior knowledge meant that the student related to prior knowledge, without using it to explain (a part of) the process diagram. For example:

"Here you see the follicle I think [points at egg development]."

It is clear in this example that the student remembered the name of the part that grows and contains an egg, namely the follicle. Another example of this strategy that was found was:

"FSH stands for follicle stimulating hormone. LH I just don't know."

Nowhere in the figure is the meaning of the abbreviation FSH. However, if students do know the abbreviation, they can also know the function of this hormone, namely that it stimulates the growth of follicles. In this example, the student only mentions the meaning of the abbreviation, and this is therefore an example of activating prior knowledge.

Another strategy that was used very little was reading the title. Only thirteen times this strategy was used by students when reading the process diagrams. Examples include:

“It's about the menstrual cycle.”

“It's about the nitrogen cycle. You see all kinds of things happening.”

“This is the menstrual cycle.”

It is very clear that here students referred to the main topic of the process diagrams, which they could get from the title of the process diagrams.

The strategy that was most used was reading labels regarding the organizational level. This meant, for example, that students named certain labels of the process diagrams, implicitly or explicitly, and used them when, for example, giving meaning to process arrows or explaining certain parts of the process diagram. On average, students applied this strategy about 6 times for a process diagram. For example:

> “For example, N2 is produced by lightning, ozone and industry by its emission from N2 NOx nitrogen oxides are made.”

In this example it can be seen that students (implicitly) read the labels ‘N2’, ‘lightning’, ‘ozone’, ‘industry’ and ‘NOx’. These labels were then used by the student to explain what was happening in this part of the process diagram. Another example of this strategy was:

> *“Estrogen and progesterone also rise during the cycle. Only the estrogen rises just before ovulation.”*

In this example, the student read the labels ‘estrogen’ and ‘ovulation’. It is evident that students often apply this strategy, because to be able to say something about the process diagrams, it is necessary to read which labels were used in the process diagram. Students who were only moderately able to tell something about the process diagrams made very little use of this strategy. They then fell into generalities like 'something is rising here' and 'I see something happening here', so they did not name and use the labels to explain in depth what happened during a certain process.

The last strategy that was identified in the orientation phase was localizing legend items in the main area. This meant that students used the legend, implicitly or explicitly, to say something about the process diagram. Not surprisingly, this strategy was predominately applied when studying the process diagram over the nitrogen cycle. This process diagram contained an extensive legend which students could use when reading the process diagram. The menstrual cycle on the other hand, contained only a very small legend containing only the meaning of two parts of the process diagram. Examples of this strategy are:

> *“And those are N-containing organic substances that plants use. Oh no, inorganic nitrogen compounds.”*

In this example, it is clear that the student had seen which color inorganic compounds had in the process diagram.

> *"Then there is nitrogen assimilation and that goes to the producers or the plants."*

In this example it is also clear that the student had seen the color of producers in the nitrogen cycle, namely green. The arrow or nitrogen assimilation was green, and it pointed to a green bar. This student therefore used the legend to identify the type of organisms in which this process took place. Moreover, this student named plants as an example of producers, which is also in the legend.

The second most frequently used strategy was giving meaning to process arrows. This strategy was often used in combination with the strategy 'reading labels with regard to the organizational level' in the orientation phase. This strategy meant that students tried to explicitly explain what a part of the process diagram was about, without providing an in-depth explanation of the underlying biological concepts. On average, this strategy was used around five times per process diagram. Examples of this strategy when looking at the process diagram of the menstrual cycle are:

> *"And FSH goes down slightly from menstruation until about two days before ovulation and FSH eventually goes down after ovulation and on the 26th day it goes up a little bit, so it starts again and then goes down again."*

> *"Estradiol increases enormously just before ovulation. And once ovulation has taken place, it decreases again."*

When looking at the nitrogen cycle, examples of this strategy are:

> *"But if I start, for example, with NO3- (nitrate) by means of ammonification, it will become NH4+ I think. It is a kind of transition to a different substance."*

> *"Then it goes from consumers back to urea, uric acid after it has been broken down again. And then it goes indirectly back to the inorganic substances."*

In these examples, students explained literally what they saw was happening in a specific part of a process diagram. In most cases, this strategy was applied correctly (166 out of 192 times). However, when looking at the quality of the responses, it can be said that students who use this strategy often, usually don't really understand the underlying, complex biological concepts. Students, for example, explain that the concentration of FSH changes during the menstrual cycle, but they usually didn't explain why this was the case and that the function of FSH is in the menstrual cycle. And students often explained that, for example, NO3- became NH4+ by means of ammonification, but they didn't explain what the function of this chemical reaction was and why specific organisms enable this chemical reaction.

When they did, it was classified as an 'inference'. An inference is defined by Kragten et al. (2015) as a correct statement that includes the relation between processes that are not literally displayed. Students applied this strategy only 29 times in total, which is on average 1.45 times per two process diagrams. There was no difference between the different process diagrams. Vwo students, however, seemed to apply this strategy more often than havo students (figure 9). Examples of this strategy are:

“For when an egg is fertilized. If there is no fertilization, it is broken down again and then as a woman you have the menstrual period.”

It is clear that the student in this example has a good understanding of the underlying biological concept, which is that the endometrium is broken down when no egg is fertilized and a woman then menstruates, after which the menstrual cycle starts again. This concept is not literally present in the process diagram and this student explains well what is happening. Another example is:

“And you can also go from the NO3, nitrate, to the NH4 and then there is also what you call ammonification. Bacteria do that without oxygen.”

In this example, a student explains that NO3 is converted to NH4 and that this chemical reaction is carried out by bacteria under anaerobic conditions. Finally, the student states that this process is called ammonification. As with the previous example, here it is not explicitly mentioned in the process diagram of the nitrogen cycle that bacteria carry out this chemical process and that it is done without oxygen. The fact that this student combined all these loose facts into a coherent, in-depth explanation of what was going on makes this a good example of an inference.

Another strategy in the main phase was relation to prior knowledge. When students used prior knowledge to explain parts of a process diagram, this was classified as relation to prior knowledge. In total, students applied this strategy only 21 times, which was only once every two process diagrams on average. There didn’t seem to be differences between havo and vwo students, low-achieving and high-achieving students. Examples of this strategy include, among others:

“And then it goes through deammonification again, and that's another process without oxygen, and that goes back to N2.”

In this example, the student mentioned that a process is carried out without oxygen. This student implicitly arrives at this statement by reading the word 'anaerobic', which means 'without oxygen'. Students had no prior knowledge about the subject of the process diagram, the nitrogen cycle, but the concept of 'anaerobic' had already been introduced and explained in previous lessons as part of a different chapter. So, this student had memorized this concept and used its meaning in studying and explaining the nitrogen cycle. An example of this strategy when looking at the menstrual cycle is:

“And the follicle stimulating hormone then causes it to grow or something.”

In this example, the student memorized the meaning of the abbreviation ‘FSH’, which stands for ‘follicle stimulating hormone’. The meaning of the abbreviation wasn’t part of the process diagram, so this student related to prior knowledge to understand what the function of the hormone FSH was. Students often used the strategy ‘relate to prior knowledge’ implicitly, as they didn’t explicitly state that they knew something because they memorized certain concepts or words.

When students tried to explain parts of process diagrams in more depth, they often came up with alternative hypotheses to explain connections between certain parts of a process diagram. This strategy was observed a total of 22 times, 16 of which were incorrect. Examples of this strategy were:

> "Furthermore, I notice that LH is present in much greater quantities than FSH. So that's more necessary."

> *"And progesterone that peaks while the yellow body exists so that ensures that the yellow body then stays."*

> *"And when ovulation has taken place, the follicle containing the egg is broken down by the progesterone and we call that the yellow body."*

In these examples, students give meaning to process arrows and try to connect underlying relationships by formulating an alternative hypothesis. For example, a student says that progesterone is necessary to maintain the yellow body because the concentration of this hormone peaks in the second part of the menstrual cycle in which the yellow body is formed. However, the reality is the other way around: the yellow body produces the hormone progesterone.

In total, the students applied the strategy 'compare' 31 times. This strategy meant that the student tried to compare different parts of the process diagram with each other. Examples include:

> *"Above you can see the LH peak. This then causes the follicle to burst open. Below that you see the FSH peak, at the same time. So that has something to do with it too."*

> *"In the table you can read that FSH and LH, say the concentration in the blood, that remains quite neutral during the menstrual cycle. Only at ovulation, if say the blood comes out, then there is a peak."*

> *"If you then look at ovulation, you see that especially the hormone LH and estrogen rise very much in the blood level. And you can see that the endometrium is slowly becoming thicker. And during ovulation, the body temperature makes a little jump and goes to about 37.3 degrees."*

These examples illustrate that students compare different parts of the process diagram about the menstrual cycle with each other. This process diagram consisted of five different diagrams that were placed underneath each other (figure 5). This provoked comparison between the graphs as this strategy was more often applied to the menstrual cycle (21 times) than to the nitrogen cycle (10 times).

The penultimate strategy to be classified was 'self-questioning'. This strategy involved students asking themselves questions about the graph, or about their own knowledge of the subject in question. This strategy was only observed 10 times. Examples include:

> *"There are also a lot of names in there that I don't know yet."*

“I found this one a bit more difficult because I don't know those words anymore, but I do recognize those figures. I thought those are cells. Or something. And I learned that with biology.”

“That third me had no idea what that was about. Hormones I think.”

In these examples, students were explicitly aware of their own knowledge, or lack thereof. They name for themselves which words they do not know and whether they understand a certain biological concept or not.

The last strategy observed, along with self-questioning part of the metacognitive learning activities, was diagram commenting. This strategy involved students actively commenting on the process diagrams. They were no longer concerned with reading and understanding the figures in terms of content, but they were checking what they thought of the design of the figures, whether they found this understandable and what the design of the figures meant for their understanding of the underlying biological concepts. The strategy of diagram commenting was observed much more when students were looking at the nitrogen cycle (17 times) compared to the menstrual cycle (4 times). Examples of this strategy are:

“I find this a lot less clear.”

“You don't see a table, how do you explain that properly, a kind of step-by-step plan for how things work in the nitrogen cycle. So, a lot of information is in there.”

“And because of those help lines, the graphs are nicely aligned, and the lines help you to see a connection how many hormones are in the body and what effect that has on other things.”

“It's a very unclear picture. You don't see clearly where the beginning or the end is. This will be the start. I don't really see a cycle or anything.”

Most of the comments on the graphs were negative and focused on the complex design of the nitrogen cycle in particular. The core of the complexity of this process diagram from the BINAS was best described explicitly by one of the participants of the study. This student said the following:

It's a very unclear picture. You don't see clearly where the beginning or the end is. This will be the start. I don't really see a cycle or anything. Other than that, I really don't know. The arrows go everywhere. You really must look with your finger like that from there, along there, oh then it goes back again. It's very hard to understand if you don't know what it's about. If you quickly need to look up something quickly, a round of such a circle would be easier than all arrows everywhere. Because I don't think if you would just give this to someone like me, you would quickly see a cycle in it.

Havo and vwo students

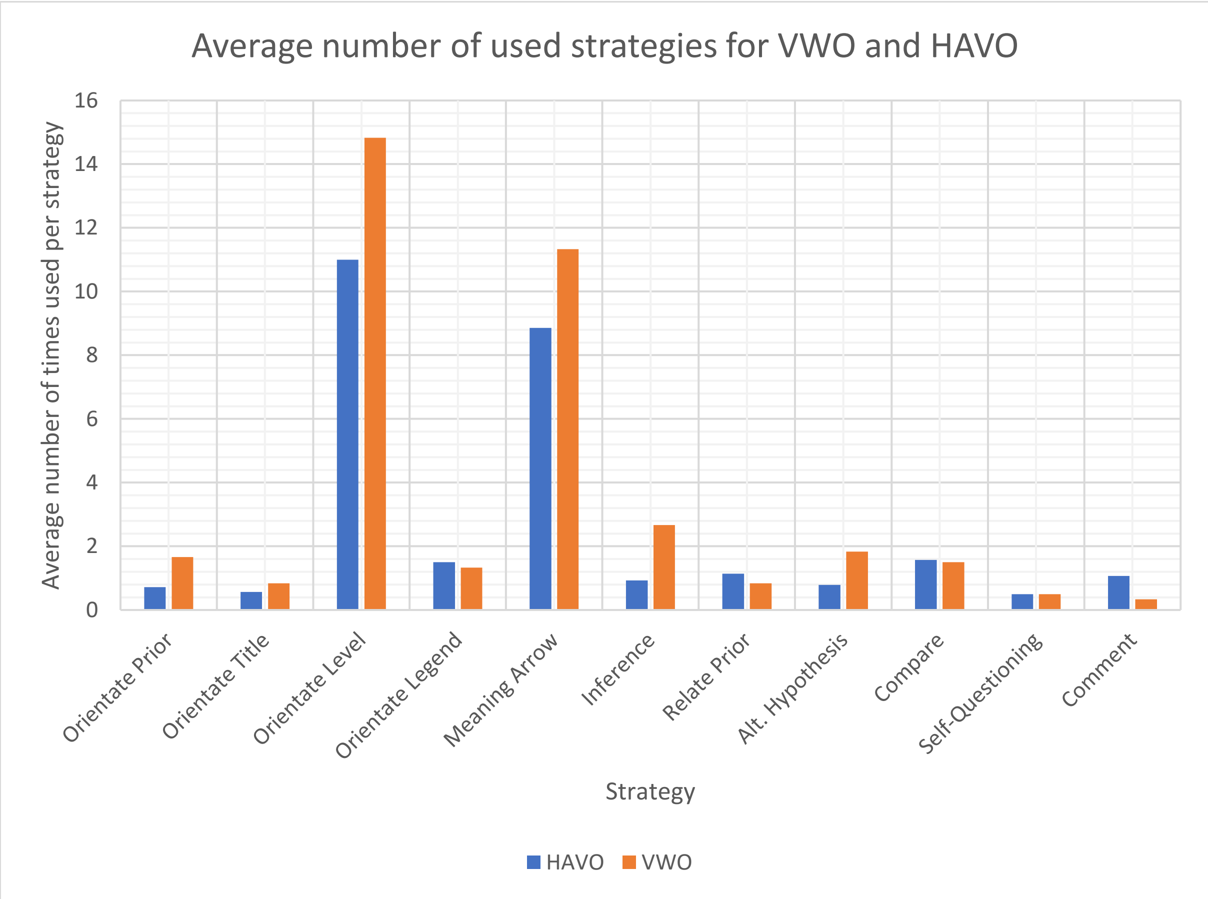

Figure 9 Average number of times used per strategy for each educational level. In this figure it can be seen how many times each strategy was used on average for vwo students (N=6) and havo students (N=14).

When we compare the vwo students (N=6) with the havo students (N=14), it is noticeable that the distribution of the number of strategies used is the same for both levels of education (figure 9). Both havo and vwo students mainly read labels regarding the organizational level and they try to give meaning to process arrows. It is notable, however, that vwo students do this on average slightly more often than havo students for both strategies. Vwo students also activate prior knowledge slightly more often than havo students. Finally, on average, vwo students produce slightly more inferences than havo students.

High achieving students and low achieving students

When we divide the students into four different groups: high and low achieving havo students and high and low achieving vwo students, it is noticeable that for both vwo and havo, the group of high achieving students apply the strategies 'orientate level' and 'meaning arrow' much less often. They therefore name labels with regard to the organizational level much less often and they give meaning to process arrows less often compared to the group of low achieving students (figure 10). The group of high achieving vwo students also look less often in the legend compared to the group of low achieving vwo students. Finally, it seems that for both levels of education, the group of high achieving students is less likely to activate and use prior knowledge when studying the process diagrams than the low achieving students (figure 10). In addition, it seems that on average havo students comment slightly more often on the process diagrams, compared to vwo students (figure 9).

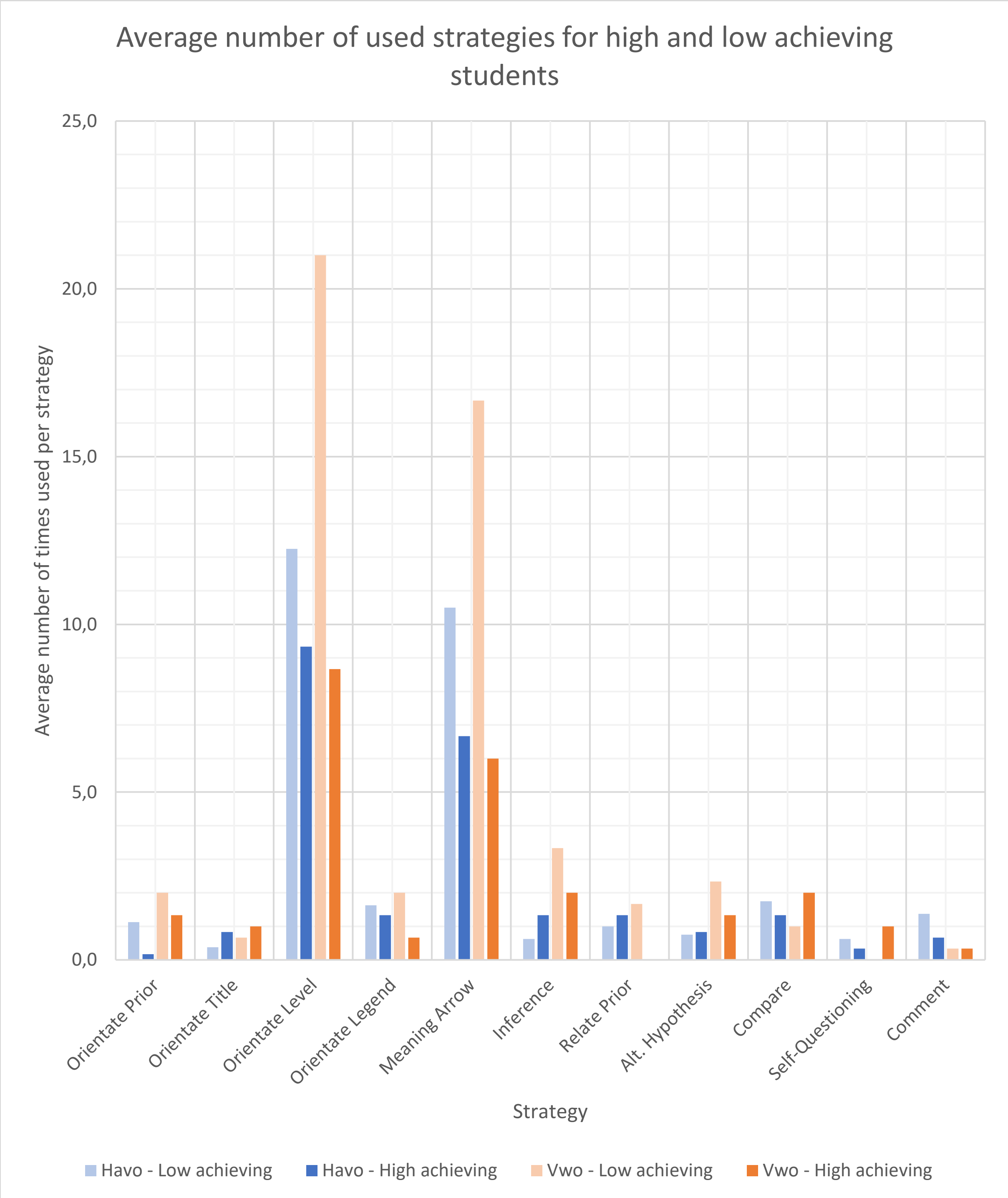

Figure 10 Average number of times used per strategy for each educational level and achievement status. In this figure it can be seen how many times each strategy was used on average by high achieving vwo students (N=3), low achieving vwo students (N=3), high achieving havo students (N=6) and low achieving havo students (N=8).

Discussion and conclusion

Problem analysis, research purpose and research question

As a biology teacher, visual representations of biological concepts are probably easy to understand. But unfortunately, students can struggle with them a lot. In empirical research, it appears that students generally understand various types of visualizations poorly (Bergey et al., 2015; Cromley et al., 2013). Students often lack prior knowledge and they do not understand different parts of figures. Therefore, they cannot draw correct conclusions from the figures (Cromley et al., 2013). Students also find it difficult to draw a connection between figures and texts. Even when there are explicit references to the text, they often pay little attention to the corresponding figure (Bergey et al., 2015; Cromley et al., 2013). Sometimes this can even lead to students skipping figures altogether (Bergey et al., 2015). Furthermore, in a study that was conducted with high school biology students, Cromley et al. (2013) found that students do not use knowledge gained from one figure for the next figure (Cromley et al., 2013).

By gaining insight into the strategies used by students when studying process diagrams, a teacher can more easily intervene in students' erroneous study of process diagrams and gain more insight into which strategies are particularly helpful when studying process diagrams. As a biology teacher myself, the problem outlined above piqued my interest to know more about the strategies used by students when studying a biological process diagram. I looked at the strategies used by high-performing students and moderate to low performing students. I therefore formulated the research question as follows:

> *"What strategies do high and low achieving students use when studying a biological process diagram?"*

Limitations

This study has several limitations. First, the sample size is relatively small (N=20). Twenty students is a reasonable number, but when these students are divided into subcategories, such as for example havo and vwo students, high-performing and low-performing students, the sample size can become a lot smaller. These groups of students are then not representative of the entire population of students. This makes it more difficult to draw generalizable conclusions that may apply to a large group of secondary school students in the Netherlands. However, it is possible to detect certain trends by looking qualitatively and extensively at the answers of some students. When interesting results are obtained, this may be an impetus for further quantitative research on a larger group of students. In addition, another limitation is that it is possible that only a specific group of students has registered as a test subject in this study. All students of the fourth year of havo and vwo were asked if they wanted to participate in this study. In total there were about 80 to 90 students. A total of 20 of these participated. It may have been the case that students with high self-confidence in biology were more likely to participate in the study than students who were less self-confident in their own abilities. The study therefore ends up with a non-representative group of students because of this. However, given the average grades of the group of participating students, this is probably not the case. The group of participating students had an average of 6.0 for biology this school year. This coincides with the average of all students in the 4th year of havo and vwo. The group of students who participated in the study was therefore probably representative (in this respect) of the entire group of students at this school.

In addition, the design of this study may not have been good for students who are more visual than verbal. Students were asked to articulate and explain a process diagram. Students who understand the figure well but may have difficulty putting their thoughts into words may have performed less well in this study. There are indications that this was indeed the case with several students. For example, there was one vwo student who performed very poorly in this study. The student produced a total of only twelve strategies for both process diagrams together. This is a lot less than the more than 30 strategies that all students produced on average. However, this student has the highest mark of all students for the subject of biology. This may indicate that this student simply had difficulty verbally explaining a process diagram. Conversely, there was also a student who produced as many as 58 strategies during the interview while studying the process diagrams. This student was very thorough in describing and explaining the diagrams and gave the impression that he had understood everything in the diagrams correctly. However, this student has a very low grade for biology. It may therefore also be the case that using the average grade for biology in this school year was not a good indication for dividing students into high and low achievers. Perhaps a standardized test specifically aimed at process diagram comprehension could have provided more valuable information.

Finally, as mentioned before, a limitation of this study is the fact that all data were processed and interpreted by only one researcher. This ensured that all data was interpreted in the same way. This increases the reliability of the results, but it also means that the results are completely dependent on one person's interpretation. It is possible that another researcher would have interpreted some of the student responses differently and this would mean that the results would have been different.

Strategies used by students when studying a process diagram

It follows from the results that students mainly assign meaning to process arrows in the process diagram. This means that students superficially try to explain and understand what is happening in a particular part of a process diagram. Combined with this, students name many labels with regard to the organizational level. This means that students name certain parts of the process diagram that they see and use to give meaning to a process arrow. However, this is a superficial strategy. It can be concluded from the quality of the answers given that students understand very superficially what the figure is about. They make hardly any connections, they activate little or no prior knowledge, they hardly look at the legends and they also show very little to no metacognitive learning activities. This is in line with the hypothesis and results of previous research on student studying and understanding of process diagrams. For example, Cromley et al. (2013) found that students often lack prior knowledge and they do not understand different parts of figures. Therefore, they cannot draw correct conclusions from the figures. The lack of prior knowledge was also described by Kapteijn et al. (2018) as a major obstacle when studying a process diagram. Another problem described earlier was that students can name the definitions of important concepts, but they don't really know what it means exactly. They are therefore unable to apply and use the concepts for biological reasoning (Kapteijn et al., 2018). It can therefore be concluded that, without prior knowledge, students will find it very difficult to comprehend such complex figures.

As described before, students' descriptions of the process diagrams remained quite superficial. Students in general didn't thoroughly explain the meaning of each part of a process diagram. The commentary was limited to naming different labels and trying to give meaning to individual parts of the process diagram. This resulted, for example, in the few times when 'compare' was used as a strategy by students. Students generally only focused on a small part of the process diagrams, losing sight of the bigger picture. This was found also by Eilam (2002) and Ummels (2014). For example, students are relatively well able to understand the individual processes in a cycle, but they have difficulty placing these processes in a larger whole and seeing the interrelationships (Ummels, 2014). Furthermore, Eilam (2002) and Ummels (2014) describe that student find it difficult to recognize and use different organizational levels. Complex cycles such as the nitrogen cycle vary from processes at the molecular level to major biological processes in ecosystems. This makes it relatively difficult for students to understand that the nitrogen cycle, for example, is the driver of all kinds of ecological processes. Or that various hormones are responsible for big changes in a human body. This lack of a so-called 'helicopter view' limits students' comprehension of complex processes that are shown in even more complex process diagrams.

Implications for biology education

The problems described in this study may seem like problems for students, but they are really a problem for the teachers that are trying to teach the students. The results show that there is work to be done for biology teachers. Teachers should teach students to actively retrieve prior knowledge from complex figures that they could potentially use in understanding these process diagrams. The diagrams used for the nitrogen cycle and the menstrual cycle contained many concepts that had been previously taught to students in other chapters, such as the concepts 'aerobic' and 'anaerobic', 'organic substances' and 'inorganic substances' and 'consumers, producers and decomposers'. Students were still moderately able to recognize these words and use their meaning in understanding the process diagrams. In general, students in this study made very little use of prior knowledge that they undoubtedly should have had. Teachers should therefore actively encourage students to recognize these concepts and to try to understand their meaning with the help of prior knowledge.

Students should also be taught to break complex process diagrams into smaller pieces so that they are easier to understand for students. As the literature shows, a complex process diagram can quickly lead to cognitive overload. Students should therefore be taught to look first at one part of a process diagram and then at the next part. Only when students understand the individual components will students be able to understand the bigger picture. What helps here is sketching a context in which the concepts can be learned. For example, literature shows that students understand process diagrams better if they can place them in a context, such as the carbon cycle in the context of climate change (Ummels, 2014). Teachers should therefore actively outline this context for students so that the concept becomes more understandable for students.

It is also important that students become familiar with the design of process diagrams. Certainly, the diagram of the nitrogen cycle is incomprehensible to students at first glance. Arrows cross and pass each other, many different molecules, processes, and bacteria are mentioned, and different colors are used everywhere to indicate consumers, decomposers, and producers. However, this complexity makes it difficult for students to see the bigger picture. The design of these figures plays a major role in this (see figures 1 and 4). For example, students do not see a clear cycle due to the jumble of arrows, something that is more comprehensible in, for example, the process diagram as shown in figure 3. However, the process diagram in figure 3 cannot be used by students on tests, while the diagrams of figures 1 and 4 can be. Students should therefore be able to understand and use these more complex diagrams. What does not help is that teachers make little use of the BINAS. The use of the BINAS by teachers is often limited to only referring to the BINAS and having students practice looking for the correct BINAS figure (Vertelman & Kunst, 2016). Teachers should therefore make much more use of the figures in the BINAS and actively involve students in these figures so that they can be better understood. Teachers should provide explicit instructions to help students understand and learn these complex figures. It is important to do this in as many different ways as possible. It follows from the literature that the greater and more varied the effort of learning complex process diagrams, the greater the learning yield (Bowen & Roth, 2002). For example, teachers could let students make such a process diagram in class themselves about, for example, a text about a nature reserve and the nitrogen cycle in the BINAS. This exercise requires many different strategies from students, such as reading a text well, recognizing and naming different molecules, types of organisms and processes and recognizing and understanding the underlying relationships. All in all, it is therefore important to let students practice a lot with such complex process diagrams. The more often students are exposed to this, the more confident they become and the better they can understand these diagrams. In doing so, they learn a fixed strategy that they can use one-on-one with any new process diagrams they have not seen before.

Future research

In the future, it is important to continue researching students' reading and understanding of complex process diagrams. This study uncovered the strategies students use when studying two process diagrams: the nitrogen cycle and the menstrual cycle. Future research could focus on other complex process diagrams such as complex food webs, energy flows, the transmission of an action potential through nerve cells, and so on. While there are similarities between various different process diagrams, it is also true that each process diagram has its own difficulties and challenges. It is important for (biology) teachers to be aware of these difficulties and to recognize and parry them early. In the future, research could also be done into students' actual understanding of process diagrams. This study only investigated which strategies students used, but not how well students understood a figure. By looking at this, it can be identified which strategies students who generally understand complex process diagrams well, use. This can then be used to help students who are less able to learn and understand such figures.

Finally, an interesting extension of this research is the tracking of eye movements made by students while studying complex process diagrams. In this study, students were asked to use the think-aloud method to explain what a figure was about and what they all looked at. This has the limitation that the students may not tell everything. If the researcher or teacher has knowledge of what a student has looked at, and for example how often, it is also clearer what a student is very focused on while studying such a process diagram. This knowledge can be used to make the strategies explicitly visible and to further develop successful strategies when studying process diagrams, so that a higher learning yield can be achieved. All in all, there is enough to do in the future to pay continued attention to this important aspect of biology education. Only when we are explicitly aware of the learning process of students, we can intervene in this learning process and allow students to achieve a higher learning outcome.

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