Fostering Students' Understanding of Complex Biological Systems

Melde G. R. Gilissen,[†‡¶*] **Marie-Christine P. J. Knippels,**[†§] **and Wouter R. van Joolingen**[†ǁ]

[†]Faculty of Science, Department of Mathematics, Freudenthal Institute, Utrecht University, 3844 CC Utrecht, The Netherlands; [‡]Bonhoeffer College Bruggertstraat, 7545 AX Enschede, The Netherlands

ABSTRACT

The main aim of this study is to teach students to take a systems perspective in understanding complex biological problems. Two lessons were designed and tested in two secondary classes (15- to 16-year-old students), using a lesson study approach. Three students from each class were observed more closely when visualizing and reasoning about two complex biological problems. The results, based on student worksheets, peer discussions, classroom observations, and interviews, indicated that students were able to visualize complex problems with the aid of a systems model based on eight system characteristics: boundary, components, interactions, input and output, feedback, hierarchy, dynamics, and emergence. Moreover, explicit scaffolds encouraged students to reason across different levels of biological organization. Based on the findings, four design guidelines were formulated: 1) Start with a central complex problem/question. 2) Let students visualize a complex biological problem using a systems model. 3) Assist students in reasoning step by step within and between the levels of biological organization. 4) Make students explicitly aware of the use of the system characteristics in various contexts. As systems thinking assists students in creating an overview of a system and reasoning about a complex problem systematically, it is also valuable outside the biology classroom.

INTRODUCTION

An ant colony, the economic system of a country, the digestive system, or a family are all examples of systems. A system is a collection of components that interact with each other; the way one of these components functions can have an effect on the system as a whole. *Systems thinking* is the ability to interpret and understand these complex systems (Evagorou *et al.*, 2009). It can be used as an approach for reasoning about complex problems involving different (sub)systems; for example: How do ants work together in a colony? What is the effect of a war on the economic system? How does a protein deficiency lead to a bloated belly?

In recent education-related literature, various articles can be found that focus on students' systems thinking in subjects ranging across geography (Mehren *et al.*, 2018; Cox *et al.*, 2019), technology (Barak, 2018), chemistry (Orgill *et al.*, 2019; Samon and Levy, 2020), and biology education (Tripto *et al.*, 2018). However, differences can be found in the definitions that are used to describe systems thinking for the different educational domains (Bergan-Roller *et al.*, 2018; Yoon *et al.*, 2018). According to Boersma *et al.* (2011), these differences are due to implicit or explicit reference to one or more systems theories. Historically, systems thinking originated from three different types of systems theories: general systems theory (GST), cybernetics, and dynamic systems theories (DST). These three systems theories offer different perspectives on systems. GST focuses on the hierarchical structure of systems in terms of the system components and their relations (Von Bertalanffy, 1968). Cybernetics focuses on the regulation of systems by feedback loops (Wiener, 1948). DST focuses more on

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[¶]ORCIDs: 0000-0002-0668-4525; [§]0000-0003-4989-1863; [ǁ]0000-0002-4271-2861.

*Address correspondence to: Melde G. R. Gilissen (m.g.r.gilissen@uu.nl).

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nonlinear processes (Prigogine and Stengers, 1984). According to Verhoeff *et al.* (2018), it is important to pay attention to the characteristics addressed in all three systems theories to develop a good understanding of systems.

In a previous study (Gilissen *et al.*, 2020b), the perspectives of current systems biology experts were studied in light of the three systems theories. This study led to a description of eight universal system characteristics that apply to biological systems: Each system is distinguished from its environment by a *boundary* and consists of several *components* that have *interactions*. In each system there is an *input and output* of energy, information, and matter, and there are *feedback loops* to maintain the system. In addition, systems are *dynamic*, because (regular) changes occur in the input or output or through (developmental) changes over time. Systems have a certain *hierarchy*: they can be divided into different levels of biological organization. These characteristics together result in *emergent behavior* of systems*:* properties that emerge on a specific level of biological organization through the interactions of the underlying components, for example, a school of fish that swims in harmony. The system characteristics can assist students in developing a more coherent understanding of biology: the characteristics can not only give more insight into the structure and functioning of living systems in general, but can also be used to get to know more about a specific biological system (Verhoeff *et al.*, 2018; Gilissen *et al.*, 2020a).

In the Netherlands, systems thinking has been part of the secondary biology curriculum since 2010 (Boersma *et al.*, 2011, p. 33). However, a recent study (Gilissen *et al.*, 2020b) indicated that Dutch biology teachers need support for incorporating systems thinking in their daily teaching practice.

Therefore, in a follow-up study, Gilissen *et al.* (2020a) made a first attempt to foster students' systems thinking in secondary biology education. In two lessons, they introduced students to the concept of systems and the corresponding system characteristics. The results showed that students developed a basic understanding of the eight system characteristics. Based on the results of the lessons, the researchers concluded that it is important to introduce the system characteristics in a well-known biological context and to pay in-depth attention to the characteristics of feedback, hierarchy, and dynamics, because these were considered difficult by students compared with the others. Because students developed a basic understanding of the concept of systems and the system characteristics in the previous study, the next step is to teach students to take a systems perspective to understand complex biological phenomena.

RECOMMENDATIONS FROM THE LITERATURE

Three major elements can be found in the literature to foster students' systems thinking: 1) *modeling activities*: visualization of the (sub)systems involved in terms of the eight system characteristics; 2) *cross-level reasoning*: reasoning within and between the different levels of biological organization; 3) *systems language*, namely, using the eight system characteristics to describe and talk about systems (Appendix 1 in the Supplemental Material).

Modeling

Systems thinking is often mentioned in combination with modeling (Verhoeff *et al.*, 2008; National Research Council, 2012; Dauer *et al.*, 2013; Bergan-Roller *et al.*, 2018). Models can act both as *representations* in which students make a visualization of the system of interest and as a *tool* to shape their own reasoning (Forbes *et al.*, 2015). According to Wilson *et al.* (2020, p. 5), models can change students' views on biological processes "from the static into the dynamic, the flat to the 3D, and siloed to integrated." Two types of models are computational and qualitative. Experts in the field, such as systems biologists, make use of computational models. Computational models can be used to simulate systems' dynamic behavior, for example, by performing a simulation in which a system component is added or removed (Yoon *et al.*, 2013, 2016; Yoon and Hmelo-Silver, 2017). An example of a qualitative model is a concept map. With concept mapping, it is possible to externalize students' systems thinking (Brandstädter *et al.*, 2012; Dauer *et al.*, 2013; Tripto *et al.*, 2013, 2018). Another example of a qualitative model is the *systems model* by Verhoeff *et al.* (2008), which presents the structure of systems (Figure 1). In summary, the literature shows that modeling activities can be used to visualize biological phenomena and to assist students' reasoning.

Cross-Level Reasoning

Systems thinking is known as an approach for examining complex problems and systems (Jacobson, 2001; Bergan-Roller *et al.*, 2018; York *et al.*, 2019). The essence of understanding a complex biological problem from a systems perspective is to understand the causality of the interactions between the components between and within different levels of biological organization (hierarchy) that result in *emergent* behavior. Students need to learn to reason across the different levels of biological organization when explaining complex biological phenomena (Knippels and Waarlo, 2018; Asshoff *et al.*, 2020), for example, students should be asked to explain a phenomenon at one level using concepts and processes from a different level (Marbach-Ad and Stavy, 2000). An approach to assisting students in reasoning between the different levels of biological organization is called the *yo-yo learning and teaching strategy* (Knippels and Waarlo, 2018; Knippels, 2002). This strategy specifically emphasizes the hierarchy of systems and the interactions between and within the different levels of biological organizations. Students should be involved in a guided-learning dialogue that starts with the introduction of a central question to foster their reasoning between these levels. Partial problems or questions can serve as a content-related motive to explore the different levels of organization. Moving down to lower levels of organization provides causal explanations and moving up provides functional explanations (Knippels and Waarlo, 2018). Afterward, it is important for students, in terms of development of metacognition, to reflect about what levels of organization were considered when reasoning about the problem (Asshoff *et al.,* 2020). In summary, the literature shows that teachers have to scaffold students in reasoning between the different levels of biological organization when explaining complex biological phenomena.

Systems Language

When reasoning about a complex biological problem, experts seem to use significantly more systems language, that is, references to system characteristics, in comparison to novices (Jacobson, 2001). Moreover, experts integrate structures,

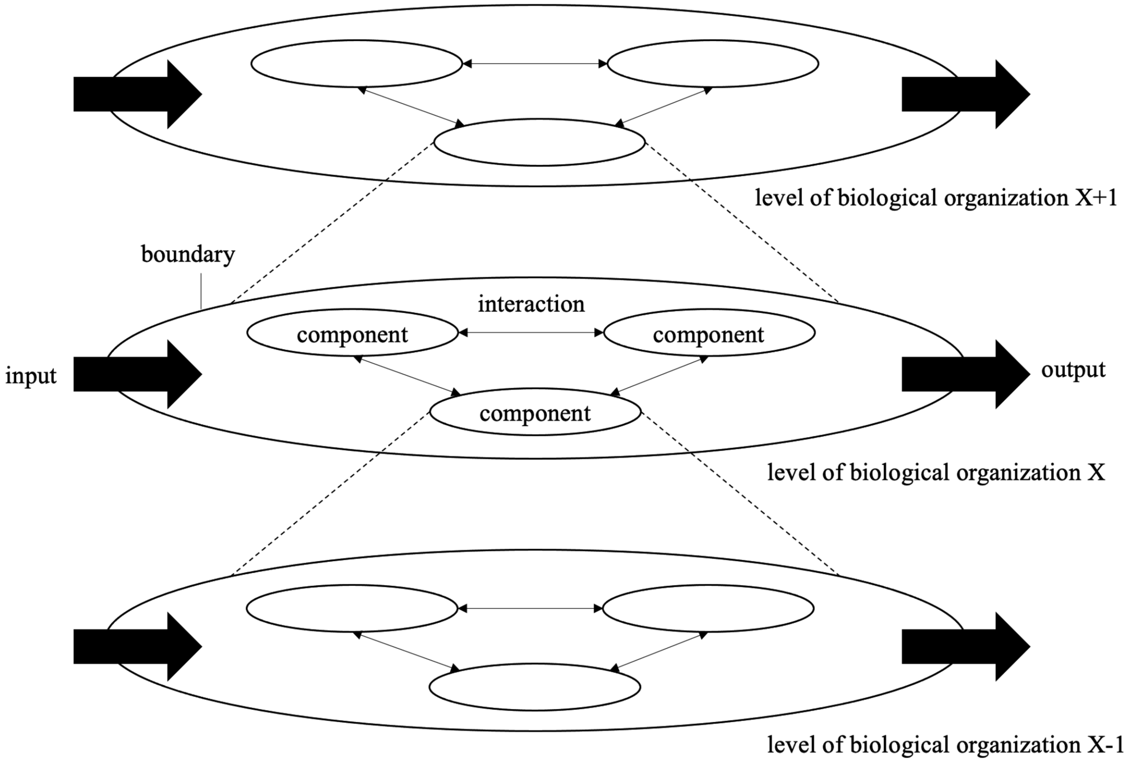

FIGURE 1. The systems model used in this study. This model presents the general structure of biological systems in terms of the following system characteristics: boundary, components, interactions, input and output, and hierarchy (different levels of biological organization). Feedback can be found in the interactions between some of the components. The dynamic features of a system are more difficult to represent, because the systems model is a static representation of a biological system, and emergence arises on a specific biological level of organization by the interaction of the underlying components. This figure is based on the systems model used by Verhoeff (2003).

behaviors, and functions in their reasoning, while novices focus more on the perceptually available, static structures of the subsystems involved (Hmelo-Silver *et al.*, 2007). Many studies have recommended stimulating the development of students' systems language, because it seems to encourage students' systems thinking (Verhoeff *et al.*, 2008, 2018; Tripto *et al.*, 2016; Gilissen *et al.*, 2020a). This can be done by explicit use of systems language by the teacher during teaching and learning activities. Our hypothesis is that explicit attention to the eight system characteristics in teaching and learning activities can be used to get students acquainted with application of the system characteristics when reasoning about biological phenomena (i.e., taking a systems perspective). In summary, the literature shows that explicit attention should be paid to the eight system characteristics in teaching and learning activities.

RESEARCH FOCUS

The main aim of this study is to teach students to take a systems perspective in understanding complex biological problems. Based on the three main recommendations from literature, two lessons were designed and evaluated in which students had to reason about two complex biological problems in terms of the eight system characteristics (Appendix 1 in the Supplemental Material). Moreover, as we aim for students to internalize systems thinking in the future, it is important to investigate to what extent students experience systems thinking as a valuable approach. The following research questions were addressed:

1. How do modeling activities, cross-level reasoning, and systems language change students' understanding of complex biological phenomena?
2. To what extent do students experience systems thinking as a valuable approach to understanding biological phenomena?

METHODS

Overall Research Design

In this study, we employed lesson study (LS) as the main research method (Murata, 2011) for designing and evaluating two lessons. In an LS cycle, a small group of teachers collaboratively set a goal, select and plan a lesson, teach the lesson with peer observation, debrief the lesson, refine and reteach the lesson, and evaluate the whole cycle (Allen *et al.*, 2004). LS is often used in the context of professional development (Lewis *et al.*, 2006), but because of its cyclic nature, LS can be seen as a form of design research and therefore can be used for research purposes as well (Cobb *et al.*, 2003; Design-Based Research Collective, 2003; Bakker, 2018). In this study, we used LS as a research method to gain insight into students' understanding of complex problems from a systems perspective. LS plays an important role in bridging the gap between research and educational practice, because of the close interplay among researchers, teachers, and students. Involvement of the teachers in the design and enactment of the lessons gives higher chances of good *fidelity of implementation* (Bakker, 2018, pp. 82–83), because the teachers are aware of the underlying principles of the lesson. The close

TABLE 1. Pseudonyms of the case students and teachers. The first letter of the case students' name represents which type of student they represent. Case student A scored high on the insight and application questions in a regular biology test, student B on the application questions, student C on the factual questions

Case student	Class 1	Class 2
A	Alec (male)	Abel (male)
B	Boaz (male)	Britt (female)
C	Caro (female)	Chris (male)
Teacher	Julia (female)	Frans (male

observation of students during the lessons and analysis of student products give insight into students' learning.

Participants

The three authors (the researchers), two teachers (Julia and Frans [pseudonyms]), and an observer formed the LS team. The first researcher (Gilissen, M.G.R.) has five years of experience as a secondary biology teacher and is a colleague of the teachers involved. She was present during the whole LS trajectory and chaired, prepared, and summarized the different meetings. The other two researchers (Knippels, M.C.P.J. & van Joolingen, W.R.) attended a couple of meetings. The researchers functioned as knowledgeable others (Takahashi, 2014) and provided the teachers with relevant literature. Julia (female) has eight years' experience as a secondary biology teacher and a background in physiotherapy. Frans (male) has 10 years' experience as a secondary biology teacher and a background in tropical forestry. The lessons were taught in a school in the eastern part of the Netherlands that offers senior general secondary education and pre-university education. During the lessons and the evaluation meetings, the LS team was accompanied by one extra observer, a colleague of the teachers. In each class, three students, the case students, were selected. Students were selected based on their scores on a regular biology test at the beginning of the school year, in terms of three cognitive levels. The test questions were categorized in terms of what they aim to assess: students' *insight*, ability to *apply* their knowledge, and *factual* knowledge. Insight is the highest level and factual the lowest. In each class, Case Student A scored especially high on the insight and application questions, Student B on the application questions, and Student C on the factual questions. Pseudonyms were used for the six case students (Table 1).

The 60-minute lessons were taught in two senior general secondary education biology classes (Julia's class: n = 26, 14 girls and 12 boys; Frans's class: n = 29, 14 girls and 15 boys) with 15- to 16-year-old students. Parental consent was obtained for all involved students. Senior general secondary education is called *havo* in Dutch. It takes five years and prepares students for higher professional education.

LS Cycles

The LS team together enacted four LS cycles within one school year (Figure 2). In the first and second cycles, students were introduced to the concept of systems and the eight system characteristics (Gilissen *et al.*, 2020a). In the third and fourth cycles, students had to visualize and reason about two complex biological systems in terms of the eight system characteristics. This study reports on the final two lessons, which from now on will be called Lessons 1 and 2.

Each of the LS cycles consisted of four preparation meetings (~2 hours each), two enacted lessons (original and revised) with a postlesson evaluation in between, and an evaluation meeting afterward (~2 hours); see Figure 2. During the preparation meetings, the team determined the learning goals and designed the lesson with input from the literature provided by the researchers and teachers' didactic and pedagogical experience. One teacher taught the designed lesson, while the other three members of the LS team each observed a specific case student and described the student's behavior for each teaching and learning activity using an observation schedule. The observation schedule included the goals of each activity, expected student behavior, and a place to write down the actual behavior of the student. The schedule was discussed with the observers to make sure that they took adequate notes. After each lesson, the observers conducted a brief individual interview (~5 minutes) with the case students and audio-recorded this. Examples of questions are: "What have you learned in this lesson?," "What did you value in this lesson?," and "How do you think this lesson can be improved?"

Based on student answers, the observers asked more in-depth questions. After each lesson, the team had an evaluation meeting (~1 hour) in which they evaluated and improved the lesson based on their observations and the input from the case students during the interviews. The other teacher then taught the improved lesson in his/her class. During the

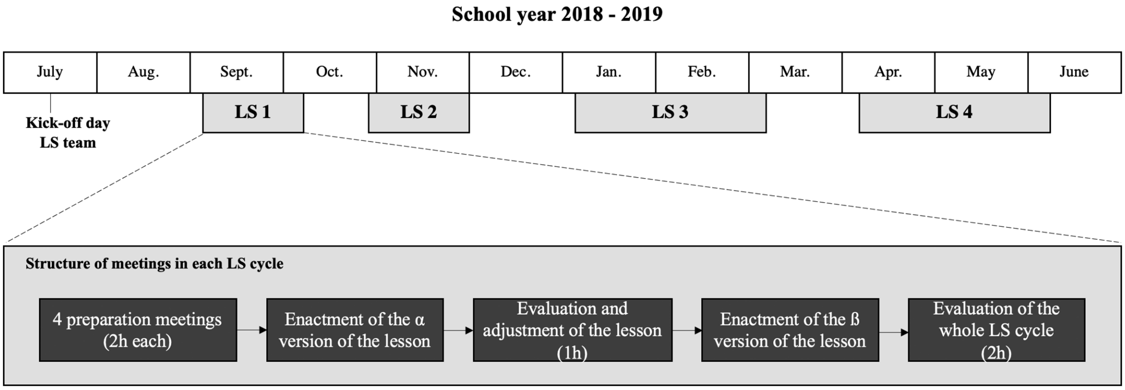

FIGURE 2. Timeline of the four LS cycles within the 2018–2019 school year.

TABLE 2. Overview of the key activities (KA) of Lesson 1 and the revisions that have been made after evaluation of the α version of the lesson

Lesson 1
Learning goals: • Students are able to visualize the complex Mount Everest Tibetan problem with the aid of the system characteristics and guiding questions. • Students are able to formulate hypotheses in terms of cause-and-effect relations to explain why Tibetan people are more capable of climbing Mount Everest than Dutch people are.
KA1. Teacher introduces the complex question: “Why are Tibetan people more capable of climbing Mount Everest than Dutch people are?” The teacher used news articles reporting about research regarding this question to motivate students. KA2. Visualization of the problem with the aid of the guiding questions related to the system characteristics (Appendix 2 in the Supplemental Material). Students first visualized the problem individually and then worked in groups of four to combine their visualizations into one visualization. At the end of this activity, the teacher showed the students his/her own visualization of the problem. KA3. Reasoning about the problem. Students, in groups of four, received a paper worksheet on which they could formulate: 1) the possible cause of the problem; 2) the effect on Dutch people; 3) their hypothesis related to the evolutionary adaptations of Tibetan people. At the end of this activity, the teacher showed the hypothesis tested by researchers and the related conclusions.
Revisions after Lesson 1α → Lesson 1β KA2: Besides visualization in terms of the system characteristics, students were asked to determine and visualize the subsystems that are involved in the problem. KA3: Students received a worksheet with questions to scaffold students’ reasoning between the different levels of biological organization more gradually and explicitly: • What factors from the environment could be a cause? • What consequence does factor X have for Dutch people? • What evolutionary adaptation(s) could Tibetan people have to explain their capability to climb Mount Everest? • At what biological organizational level does this adaptation take place? • What is the effect of this adaptation on a higher and/or lower level of organization? • Do you think this adaptation is likely? Explain your answer. As an example, the team elaborated on one hypothesis, answering the abovementioned questions in detail.

evaluation of the improved lesson, the team evaluated what the critical key activities were to achieve the student learning goal. The first version of the lesson is indicated with α, and the revised version is indicated with β. Julia enacted Lessons 1α and 2β, and Frans Lessons 1β and 2α.

Design of the Lessons

Lessons 1 and 2 both started with the introduction of a complex biological problem, after which students had to visualize the problem and reason about it. The purpose of this activity was for students to identify and visualize the system of interest and to think of possible explanations (and not per se a correct scientifically based answer) and reason about the problem from a systems perspective. Tables 2 and 3 show an overview of the key activities (the term “KA” is used when a reference is made to a specific key activity) of Lessons 1 and 2. The aim of Lesson 1 was to determine to what extent students were initially capable of visualizing the problem with the aid of the guiding questions related to the eight system characteristics (Appendix 2 in the Supplemental Material) and to determine to what extent students were initially able to reason step by step between the different levels of biological organization. Based on the results of Lesson 1 and informed by the recommendations from the literature provided by the researchers, the LS team determined how they could assist students in visualizing and reasoning about another context in Lesson 2. The aim of Lesson 2 was to determine to what extent a systems model assists students in visualizing the problem in terms of the system characteristics and to what extent partial questions scaffold students’ cross-level reasoning. Note: In Lesson 1, students worked in groups of four, and in Lesson 2, they worked in pairs.

Data Collection and Analysis

During this study, data from various sources were collected and processed with different aims (Table 4). We have translated some of the data (instructional materials, student products, observation notes) for use in this article.

- Summaries of the audio-recorded LS meetings: The first researcher highlighted the design choices that were made based on recommendations from the literature and/or from the LS-team expertise, which resulted in the different key activities. Moreover, the summaries of the audio-recorded postlesson discussions were used to highlight the choices that were made to revise the lessons.
- Video-recorded lessons: The enacted lessons were compared with the original lesson plans to determine whether the teachers implemented the lesson as intended, that is, fidelity of implementation (Bakker, 2018). If a teacher deviated from the plan, this is noted in the Results.
- Observation notes: The transcribed notes were used to illustrate what a specific student did or said during the different key activities. Moreover, the notes were coded by the first author according to the main categories: modeling activities, cross-level reasoning, and systems language. The following example shows an observation note (for KA2 of Lesson 1β; Table 2) from the categories of modeling activities and systems language:

Student 1: “What is the boundary?”

Student 2: “Human body.”

TABLE 3. Overview of the key activities (KA) of Lesson 2 and the revisions that have been made after evaluation of the α version of the lesson

Lesson 2

Learning goal:

- Students are able to visualize the biological problem: "starvation of red deer in the Oostvaardersplassen" using the systems model, and they are able to use the systems model to reason about the complex question regarding the red deer.

KA4. Introduction of the systems model as a method for visualizing biological phenomena from a systems perspective. As an example, the "Tibetan problem" of Lesson 1 was visualized in a systems model and explained to the students (Appendix 3 in the Supplemental Material).

KA5. Introduction of the complex question "What measures can be taken to prevent high starvation mortality of red deer during the winter in the Oostvaardersplassen (a Dutch enclosed landscape nature reserve)?" by the teacher with the aid of some news articles reporting about this problem.

KA6. Visualization of the problem with the aid of the guiding questions related to the system characteristics (Appendix 2 in the Supplemental Material) and the systems model. Students did this assignment in pairs. The systems model was presented to the students on paper. The ecosystem level was already filled in, and the students had to fill in the population and organism levels themselves. At the end of this activity, the teacher showed the students an example of a possible visualization of the problem.

KA7. Reasoning about the problem (in pairs). Students first had to think of possible measures to reduce red deer mortality by starvation on different levels of organization, namely, the ecosystem, population and organism levels, before reasoning about the effects of the measure "introduction of the wolf." The teacher first gave an example (according to the guidelines of the yo-yo strategy) with the measure "add input to the system: additional feeding of the red deer," in which the reasoning starts on the level of the ecosystem before descending to the population level and the organism level and then ascending back to the ecosystem level (Appendix 4 in the Supplemental Material). Afterward, students were shown a graph that was generated by a computer model and that showed the effect of the measure in terms of the number of red deer and other animals, amount of grass, and death by starvation. The students had to describe what they observed in the graph and explain to what extent the graph was in line with their own initial observations. Next, students had to predict, observe, and explain the measure "add the component wolf" by themselves. During this activity, they could make use of their completed systems model.

Revisions after Lesson 2α → Lesson 2β

The team decided that students should be able to reason about one of their own chosen measures in more detail. Also, the decision was made not to show the graphs of the computer model. The graphs showed some irregularities; for example, the amount of grass continued to decrease while the number of animals also decreased, which we could not solve easily with the computer model we used. Because our learning goal was to show students how the systems model can be used to reason about complex problems, we thought it would be better to focus on that and not on interpreting the partially incorrect computer model, because this requires other modeling/reasoning skills. Therefore, we also decided not to report on students' observations regarding the graph. In the revised Lesson (2β), the students could choose one measure, for example, the introduction of the wolf, for which they had to describe its effects on different levels of biological organization.

Abel: "By boundary they mean the whole problem, so it also includes the environment and the atmosphere."

Abel: "The respiratory system is a component."

Student 1: "But also a system."

Abel: "Yes, but here it is also a component."

Based on these notes, it seems that these students based their model (modeling activities) on two system characteristics: boundary and components. The students used these two system characteristics explicitly (systems language) in their conversation. The coded notes were combined with insights from the analysis of the student products.

- *Student products*: Most key activities (Tables 2 and 3) included a worksheet for students to write their answers down. The worksheets were analyzed in terms of students' ability to model a complex problem or reason about the problem, and their use of implicit or explicit systems language:
  - KA2 of Lesson 1: Students' models were categorized into three types: 1) students described each of the system characteristics for the context (e.g., Figure 3); 2) students visualized only some subsystems (e.g., Figure 4); and 3) combination of types 1 and 2 (e.g., Figure 5).
  - KA3 of Lesson 1 and KA7 of Lesson 2: Student worksheets were used to determine which levels of biological organization were implicitly or explicitly used by the students in their reasoning and in what order.
  - KA6 of Lesson 2: Students' visualizations using the systems model were used to determine whether the students wrote down the correct components, interactions, and input and output for the population and organism levels in their models.
  - Additionally, all worksheets were coded in terms of implicit or explicit usage of systems language. By explicit use, we mean that the students mentioned one of the system characteristics, and by implicit use, we mean that students described the system characteristics but did not use the term itself.

- *Postlesson interviews*: The transcribed interviews were used to describe what improvements to the lesson were proposed by the case students and to determine to what extent students experienced systems thinking as a valuable approach for understanding biological phenomena. In the *Results* section, we use quotes to describe students'

TABLE 4. Overview of the various data sources that were collected in this study

Data source	Processed	Aim
LS meetings	Audio-recorded and summarized	Identify design choices and conclusions of the LS team based on implications from literature, practice, and the other three data sources.
Observation notes research lessons	Transcribed	Determine learning progress of students regarding complex problem solving from a systems perspective in terms of visualization, reasoning, and use of systems language.
Student products of the research lessons	Digitized, categorized, and described	
Postlesson interviews with case students	Audio-recorded and transcribed verbatim	Determine students' learning progress and attitude toward systems thinking and identify ideas for improvement of the lesson that can be used as input for the design of the improved lesson.

attitudes and learning experiences concerning systems thinking.

RESULTS

In this section we describe to what extent modeling activities, cross-level reasoning, and use of systems language changed students' understanding of complex biological systems (RQ 1), see also Appendix 1 in the Supplemental Material. Moreover, we describe to what extent students experienced systems thinking as a valuable approach to understanding biological phenomena (RQ 2).

Modeling Activities

In Lesson 1, students were asked to visualize the Tibetan problem with the aid of the eight system characteristics (Table 2). The aim was to determine how students initially model a complex biological problem in terms of the system characteristics.

In Lesson 1α, two types of models were seen: individual descriptions of the system characteristics (type 1) and division of the problem into subsystems (type 2). Caro's group described the characteristics individually for the context of the Tibetan problem (Figure 3). Alec's and Boaz's groups visualized different subsystems of the problem; for example, Boaz's group visualized the Mount Everest on the ecosystem level, Tibetan people on the population and organism levels, and genes on the cellular level (Figure 4). The type 1 models suggest that students did not know how to visualize the system characteristics on paper other than by describing them. The type 2 models suggest that students were able to determine the system of interest and divide it into subsystems on different levels of biological organization, which can be related to the characteristic of hierarchy, an important skill in systems thinking.

In Lesson 1β, students were asked to visualize the problem in terms of the system characteristics and to identify the subsystems involved (a type 3 model). Chris's group visualized the problem in this way and identified four different subsystems: Mount Everest as an ecosystem, Tibetan people and Dutch people, and the respiratory system (Figure 5). Additionally, they zoomed in on the respiratory system and explicitly described each of the system characteristics for this system.

Based on the findings for Lesson 1 (α and β), the LS team concluded that students need more assistance in creating a coherent model of the problem: one in which the system characteristics are presented in a more meaningful way instead of

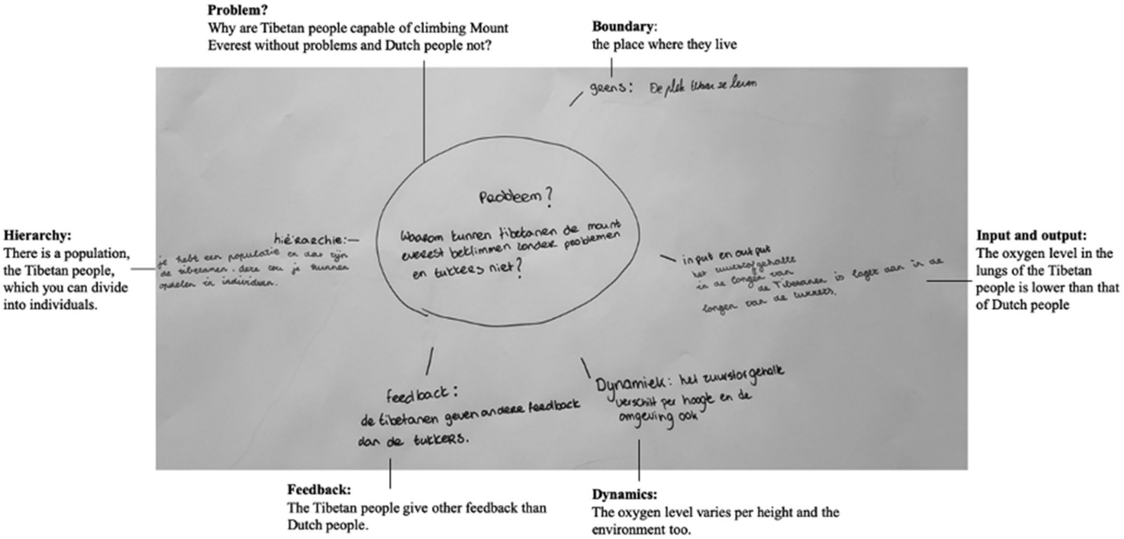

FIGURE 3. Example of students' visualizations of the Tibetan problem. Caro's group (Julia's class) visualized the Tibetan problem in terms of the different system characteristics (type 1 model).

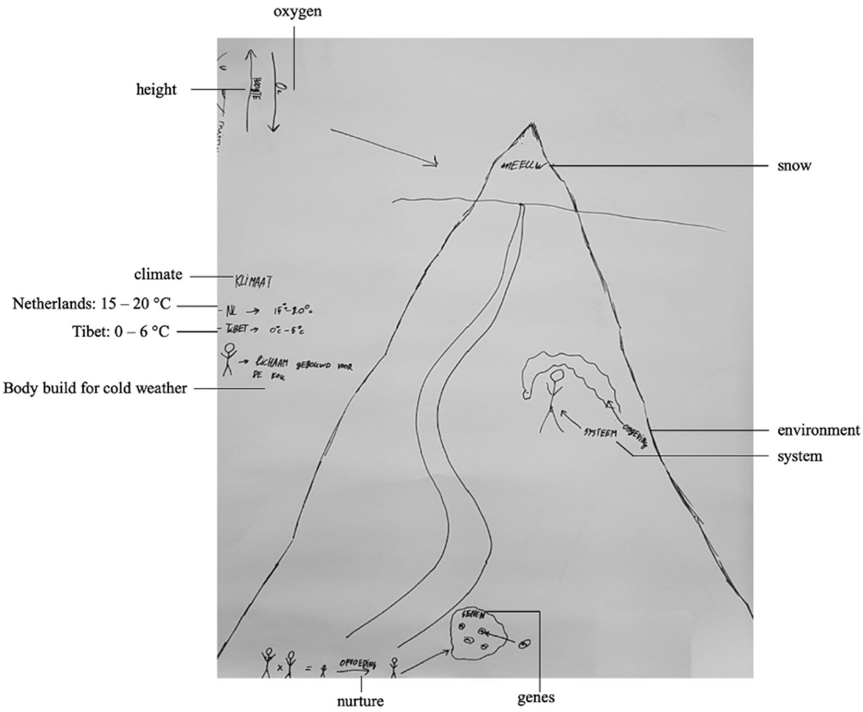

FIGURE 4. Example of students' visualizations of the Tibetan problem. Boaz's group (Julia's class) implicitly visualized four subsystems on different levels of biological organization (type 2 model).

describing them and in which it becomes clear how different subsystems are related. Therefore, in Lesson 2 (α and β; Table 3), students were introduced to the systems model of Verhoeff *et al.* (2008), which presents the structure of biological systems in terms of the eight system characteristics (Figure 1). This choice was based on the study by Forbes *et al.* (2015), who concluded that models can assist students in visualizing and reasoning about biological phenomena, and on the study by Verhoeff *et al.* (2008), who found positive results for using the systems model to visualize the system's structure. The aim of this lesson was to determine to what extent the systems model assists students in modeling a complex biological problem from a systems perspective. Based on students' systems models (e.g., Figure 6) of KA6 (Table 3), it seems that the students were able to visualize most aspects of the red deer problem in the systems model. The students indicated the main system components and the underlying interactions and the input and output of the subsystems on the population and organism levels. Some students used upward- and downward-pointing arrows to illustrate an increase or decrease in input or output (e.g., Figure 6, arrows next to birth, mortality, O_2 and food, and waste products), which is an implicit example of dynamics, because it reflects a change in the input and output (see definition in Appendix 2 in the Supplemental Material).

Although most students represented input and output in the systems model, the observation notes showed that students experienced some difficulties with it:

- Abel: "I do not quite understand what the input and output does." Abel also pointed this out during the postlesson interview: "Frankly, it makes it less clear rather than more, because, say, birth is also input, that was explained, but I think birth is a change within the boundaries and not just something that comes from outside. I think it is output

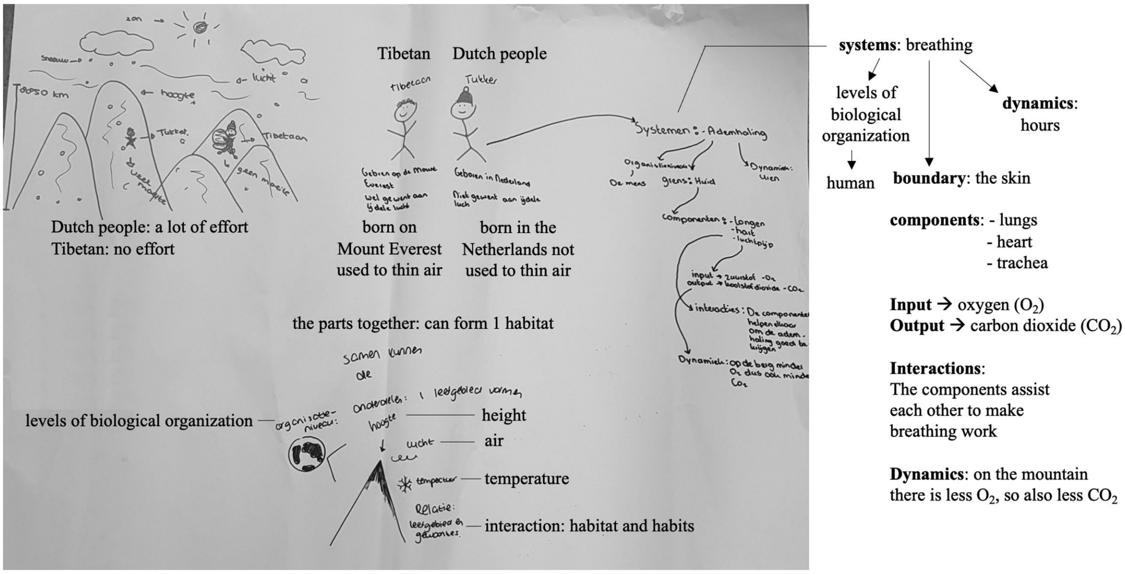

FIGURE 5. Example of students' visualizations of the Tibetan problem. Chris's group (Frans's class) visualized the problem in subsystems (type 1 model) and in terms of systems characteristics (type 2 model).

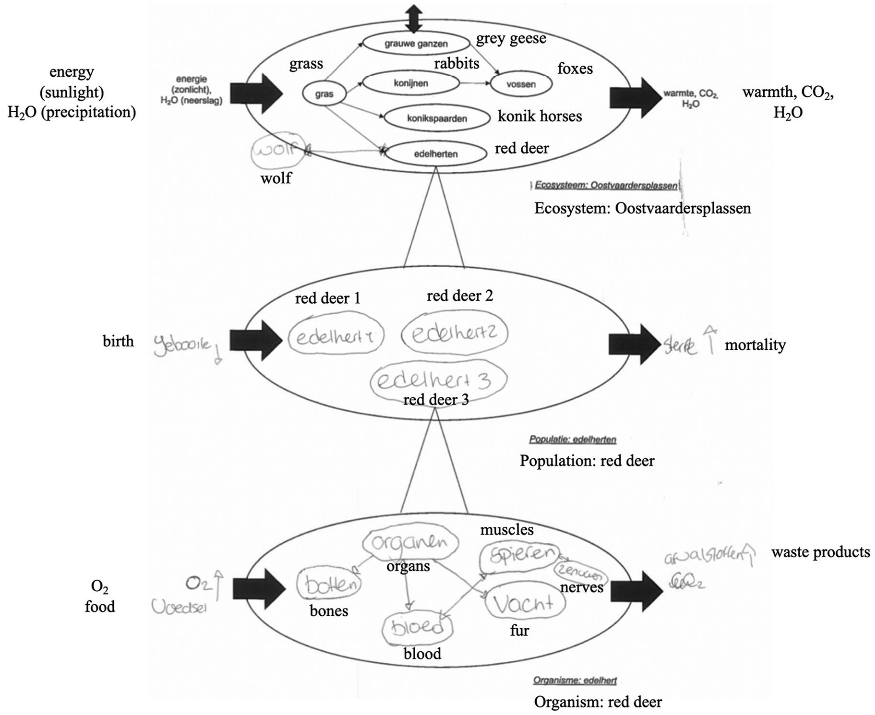

FIGURE 6. An example of students' systems models, completed by Caro's group (Julia's class).

rather than input, because there is food coming, water comes in, oxygen comes in, and that is used by the deer, and for my idea birth would be output rather than input."

- Britt indicated food as input and emission as output. When her neighbor asked for an explanation, she said: "Because I just saw food and emission 'things' on the image [the systems model example of the teacher]." This indicates that Britt did not know what input and output mean, because she just copied the teacher's answers.

Cross-Level Reasoning

In Lesson 1, students were asked to formulate a hypothesis to explain why Tibetan people are naturally more capable than Dutch people of climbing Mount Everest (Table 2). The aim was to determine to what extent students are initially able to reason between the different levels of biological organization.

In Lesson 1α, it seems that all case students were able to formulate the main cause of the problem: the low oxygen level at Mount Everest and the effect on Dutch people: suffering from low blood oxygen. The worksheets for KA3 (Table 2) showed that their reasoning stayed on a very general descriptive level, for example:

- Alec: "Tibetan people make more EPO [erythropoietin], which leads to more red blood cells and more uptake of oxygen." Alec described one cause (more production of EPO) and its effects (more red blood cells and thus more uptake of oxygen), but some steps are missing in his reasoning process, because he did not switch systematically between the different levels of biological organization.
- Caro thought that it had to do with "habituation": "It is in the genes of the Tibetan people." She described only an adaptation on the subcellular level (genes) but did not describe the effect on the other levels of organization.

The observers described in their observation notes that it seemed that the students already had some solutions in mind and did not approach the problem systematically by descending or ascending the different levels of organization.

For the revised Lesson (1β), the LS team formulated scaffolding questions (which were provided in a worksheet) to assist students' cross-level reasoning (Table 2). This is in accordance with Knippels (2002) and Knippels and Waarlo (2018), who concluded that partial questions can motivate students to explore the different levels of biological organization. Based on student answers on the worksheets for KA3 and the observers' notes for Lesson 1β, it seems that the addition of scaffolding questions influenced students' reasoning. An illustration of this can be found in a discussion within Abel's group. The first researcher made almost verbatim observation notes on this discussion in her observation scheme. The students followed the format of the scaffolds carefully (see underlined words):

> Abel: "Less O_2 the higher you get [which is an example of a <u>factor</u>]. <u>Consequences</u> of O_2 deficiency is that there is less O_2 in your muscles, which can cause your heart to stop. <u>An adjustment</u> could be that you have more/larger lung vesicles or that you have more red blood cells so that you can transport more O_2."
>
> Student 2: "Larger lung capacity? Could that be possible? <u>At which organizational level does this adjustment take place?</u>"
>
> Abel: "Cellular and organ level. The effect on a <u>higher level</u> is that all parts of the body get more O_2. Larger lungs lead to more O_2 uptake at a higher level. Extra red blood cells have an effect on a <u>lower level</u>."
>
> Student 3: "But then you also need more blood vessels."
>
> Abel: "Maybe they have a completely different physique. [Students view a picture of a Tibetan.] So thin and light, so maybe less energy is needed."

Based on this discussion, it looks like the scaffolding questions (Table 2) assisted the students in reasoning about the problem across different levels of organization. Britt's group described on their worksheet (KA3) that they thought the cause is the lower oxygen level in the ecosystem, and according to them, the organs and cells of Tibetan people can function with a smaller amount of oxygen, for example, "mitochondria are getting more out of the oxygen." While the students stayed on the organism level in their visualization (worksheet KA2), they did descend to lower levels of organization during their reasoning (worksheet KA3 and the observer's notes). Perhaps the scaffolding questions assisted students in doing this. Chris's group thought that Tibetan people have greater muscular endurance. They thought that this is caused by larger uptake of air by the lungs, but unfortunately, they did not gradually descend further to lower levels of organization. In summary, it seems that the scaffolding questions helped some of the students to reason more systematically between the different levels of organization.

In Lesson 2 (Table 3), students had to think of possible measures to reduce red deer mortality due to starvation and reason about the effects of one of the measures on the system. In Lesson 2α, all case students could think of different types of measures to prevent starvation-related mortality of red deer, namely, additional feeding of the red deer, expansion of the nature reserve, introducing a red deer predator (the wolf), birth control, shooting of red deer, moving some red deer to other ecosystems. The observers noted that students already started reasoning during the visualization of the problem in the systems model. For example, Britt and her neighbor started to reason during completion of the systems model: "Drying out of grasses leads to more excess water and to a lower amount of food for red deer, which leads to a smaller population of red deer." These reasoning steps are not directly related to the initial problem—mortality of red deer due to starvation—but apparently the visualization of the ecosystem encouraged the students to think of factors that influence the red deer habitat. The students explained on their worksheets how they think the introduction of the wolf will have an impact:

> Abel: "More deer will die and other herbivores → less deer → more grass."
>
> Britt: "Fewer red deer, but more food for those who remain. Wolves also reproduce, so it remains balanced. More grass available means more food for the red deer."
>
> Chris: "An increase in the number of wolves and a decrease in the number of red deer."

These quotes show that students' reasoning was quite brief and stayed primarily on the ecosystem level.

In the revised Lesson (2β), the students received more time to reason about the effects of a specific measure on the system and were asked more specifically to determine the effect of the measure on the different levels of biological organization (Table 3). Just as in Lesson 2α, the results showed that the students used the systems model as a tool to reason about the question; for example, students drew upward- and downward-pointing arrows to indicate an increase or decrease in components, input or output in the systems model. Different examples can be found in the observation notes that show students' cross-level reasoning skills:

- Alec elaborated in his worksheet from KA7 on the measure, "add more foxes": "Increase in the number of foxes leads to a decrease in geese and rabbits and an increase in the amount of grass for Konik horses and red deer [effects on ecosystem level]. This means that the individual red deer have more food [effect on organism level], which leads to more births and lower mortality of red deer [effect on population level]." He also indicated that birth and mortality are interrelated with each other: "They always go in a circle."
- Boaz focused on the isolation of weaker red deer. He described the effect on three levels of organization and visualized this in the systems model with arrows: "Ecosystem: number of red deer decreases and the amount of grass increases. Population: components 'weaker red deer' are removed, so the population number is decreased while the input (amount of grass) is increased, so this leads to the following output: less starvation. Organism level: the input (birth rate) increases, which leads to less starvation within the organism, so this leads to a lower output: mortality." Boaz and his partner did not recognize that their measure had a positive effect in the short term, but not in the long term, perhaps because they did not reason back from the organism level to the population level and then to the ecosystem level. The students also mixed up the input and output for the population and organism levels.
- Caro described the effect of the introduction of the wolf on her worksheet for KA7 (Table 3): "There is an additional component in the ecosystem. The wolves hunt the red deer, which leads to fewer red deer. The birth rate decreases, and the death rate increases. This reduces the surplus in the number of red deer. This is done in a natural way. The population is getting smaller."

These examples of students' reasoning show that the systems model encouraged students to reason within and between the different levels of biological organization (hierarchy) and to discuss interactions and processes over time (dynamics).

Systems Language

In both lessons, explicit attention was paid to the eight system characteristics, because several studies have indicated that this encourages students to take a systems perspective (Tripto *et al.*, 2016; Verhoeff *et al.*, 2008, 2018; Gilissen *et al.*, 2020a). For instance, students were asked to visualize the biological problem in terms of the system characteristics.

In Lesson 1 (α and β), case students Caro, Abel, and Chris described the individual system characteristics explicitly in their visualizations for the context of the Tibetan problem (type 1 model). The remaining case students visualized different subsystems (type 2 model), which implicitly referred to the characteristic of hierarchy. Based on students' reasoning processes in Lesson 1 (reflected in students' worksheets and described in the observation notes), it seems that students did not often mention the system characteristics explicitly. The following is an example in which students made explicit use of systems language (Lesson 1β, KA2):

> Student 1: "What is the <u>boundary</u>?"
>
> Student 2: "Human body."
>
> Abel: "By <u>boundary</u> they mean the whole problem, so it also includes the environment and the atmosphere."

> [Continuing explicit discussion about the system characteristic of boundary, before they start discussing the system characteristic of components.]
>
> Abel: "The respiratory system is a <u>component</u>."
>
> Student 1: "But also a system."
>
> Abel: "Yes, but here it is also a <u>component</u>."

In Lesson 2 (α and β), none of the students explicitly mentioned the eight system characteristics on their systems model worksheet, but, as already mentioned, this systems model implicitly visualizes the system characteristics. Based on students' reasoning processes for Lesson 2 (reflected in students' worksheets and described in the observation notes), it seems that students often implicitly made use of the system characteristics, for example:

- In Lesson 2α, Britt addressed some of the characteristics implicitly on her worksheet for KA7: "After a certain time, a repeating line appears. Adding the wolf is the first cause of death and not the food shortage." In her reasoning, she talked implicitly about the interactions and balance (feedback) between the components of grass, red deer, and wolves.
- In Lesson 2β, Alec gave an implicit example of a feedback loop (feedback): "The circle between birth and starvation."
- Some of the possible measures that were mentioned in Lesson 2 (α and β) by the case students also implicitly refer to the system characteristics. The expansion of the nature reserve implicitly refers to the movement of the boundary of the system. Introduction of the wolf implicitly refers to the addition of a component to the ecosystem. Additional feeding refers implicitly to the input to the system: people have to put some extra food into the system. Birth control implicitly refers to feedback that can control the number of births and deaths within the system.

Analysis of student worksheets and student observations showed examples of implicit or explicit use of six out of the eight system characteristics. The characteristic of dynamics was less used by students, and emergence was not used by students.

Do Students Experience Systems Thinking As A Valuable Approach?

In the postlesson interviews for Lessons 1 and 2, we asked the case students what they learned and to what extent they see the use of the system characteristics and the systems model as adding value. Two out of six case students indicated that they would not directly use systems thinking themselves.

- Abel: "I know better how to apply systems thinking in a certain situation and not only within a system itself." Abel about his own use of systems thinking: "If I had to learn for a test, I would not use it [systems model]. I think it would make everything even more vague. Usually, for example, if I get a question on a test or something, I do not consciously think about it [the system characteristics]. Sometimes unconsciously, but then I am not going to write it out completely, because only more things will be added that will only make it more difficult."
- Alec: "It [the systems model] makes it easier to visualize, how do you say that, a problem like this, that you have a bit of an overview. That is cool about a systems model. That you can divide those boxes. For example, like this up and down pointing arrow, so that you get a bit of an idea of what it will ultimately do. That helps with this systems model." However, he also indicated that he would not use it himself, and when we asked him why, he said: "I have not really had moments when I really needed this."

The remaining four case students were very positive about the use of the system characteristics and the systems model and explained why.

- Britt indicated that she learned to apply the system characteristics more quickly in order to find solutions: "If you look at the system characteristics, you immediately see what you need to look at, so that's why it is useful." She also indicated that she could be more creative, because "it made you think." She learned: "That by removing or adding a component you can notice very small differences or very large differences that you do not expect immediately." She said also that the systems model was useful because it gives a good overview of everything that plays a part: "And it is easy because you already have something to think about. I guess it would be harder if you did not write anything down."
- Boaz said that he experienced that he unknowingly used the system characteristics more than he thought, and he found it useful to apply them in an actual daily life context. He indicated that the system characteristics ensure that you "delve deeper into the problem." He said: "It gives a different picture of how you can use the system characteristics and how you can learn and how you can work with it. […] I now notice that I understand it better than when I only have to state the system characteristics one by one. I think this will help me a lot more. […] It just really gives a better view, not because you only mention things, but you see it, you also get a real picture with all the arrows that are there. […] It provides an overview."
- Chris explained: "I think it is more useful than just reading from the book and then trying to solve the questions for such a system. This will make you understand more." He indicated that the system characteristics helped him to tackle the problem: "If you look at the system characteristics, you immediately see what you need to look at, so that's why it is useful. […] You see more quickly where to look at, therefore you know where to search faster." He also learned: "That something, if you change it, leads to more changes. One change can have a major influence on an entire system." He indicated why the systems model can be valuable: "It all affects each other, and has to do with each other and you can easily see that. [You can use it] for more difficult assignments, if you no longer know what to do, it gives you a little more overview." However, he also had a more critical comment: "It is sometimes easier, because it gives more overview, but on the other hand you sometimes already have the answer on your own without the systems model. And then you have to think again about how you will put that in this [the systems model]."

Caro concluded that she now better understands the system characteristics and their usefulness: “Because you look better at other perspectives or at other things. I would not look at it that way by myself.” According to her, this helped her to understand the problems: “That you might be able to see solutions faster or make connections, if you know all this [system characteristics].” In Lesson 2, she learned how you can fill in the systems model: “It looks like a mind map, which I use a lot, but this [the systems model] is clearer.”

CONCLUSION AND DISCUSSION

RQ 1: How Do Modeling Activities, Cross-Level Reasoning, and Systems Language Change Students’ Understanding of Complex Biological Phenomena?

In this study, we investigated how modeling activities, cross-level reasoning, and use of systems language changed students’ understanding of complex biological systems (Appendix 1 in the Supplemental Material). Therefore, in Lesson 1, we first investigated students’ initial capability for modeling and reasoning. The results for Lesson 1 (α and β) suggested that the eight system characteristics did not provide enough support for students to visualize a biological problem from a systems perspective and to reason between and within the different levels of biological organization. Students visualized (modeling activity) the Tibetan problem as different subsystems or described the system characteristics without interrelating them. Moreover, students did not descend or ascend the different levels of organization systematically; for example, they switched between the ecosystem level and the cellular level, and then back to the population level. Therefore, in Lesson 2, the systems model (Figure 1) was introduced to students as a tool to visualize the problem in terms of the system characteristics. Moreover, the students received scaffolding questions to assist their cross-level reasoning.

The results for Lesson 2 (α and β) and the student interviews suggested that the systems model assisted students in making a more meaningful overview of the problem in terms of the system characteristics. Moreover, it also seems that visualization of the problems in the systems model encouraged students’ reasoning from a systems perspective. The systems model (Figure 1) used in this study is a static representation of the structure of a system (Verhoeff *et al.*, 2008), but completion of the systems model seems to encourage students to reason about the system in a more dynamic way. For instance, by using arrows next to the components (input or output) an increase or decrease can be visualized in the model. Moreover, in the systems model, different components and their interactions are visualized on different levels of organization (hierarchy), which enables students to realize that a change in one of the components has an effect on the system as a whole (e.g., Chris: “It all affects each other, and has to do with each other and you can easily see that.”). So, for most students, the systems model gains meaning by reasoning about it. This is in line with Forbes *et al.* (2015), who claimed that models can act both as *representations* of biological systems and as *tools* to shape students’ reasoning. Moreover, these results connect with work by Wilson *et al.* (2020), who suggested that modeling prompts students to build connections within and across biological systems and to reason about system dynamics, causality, and emergence.

The scaffolding questions (Table 2) assisted students in reasoning back and forth between the different levels of biological organization, as represented in the systems model, more systematically. Scaffolding questions include partial questions that remind students of the biological level of organization they are thinking about and what consequence a change on this level has on the higher and lower biological levels of organization. During the two lessons enacted in this study, the students did not often make use of systems language, that is, explicit mentioning of one or more of the eight system characteristics. Although students did not explicitly use the characteristics themselves very often, many examples could be found of implicit use of the system characteristics (describing the system characteristic while not using the term itself), which indicates that students know what they mean. Perhaps it is more important that students are aware of the system characteristics and can use them when reasoning about biological systems than that they mention them explicitly. As shown by the example of the misunderstanding of input and output by some of the students given in the *Results* section, it remains important to pay attention to the understanding of the individual system characteristics in classroom practice. Moreover, the characteristics of dynamics and emergence seem to need more specific attention, because the results indicate that these were less used by students.

RQ 2: To What Extent Do Students Experience Systems Thinking as a Valuable Approach to Understanding Biological Phenomena?

In our previous study (Gilissen *et al.*, 2020a), students were introduced to the concept of systems and the eight system characteristics. Most of the students involved indicated that they did not experience the value of applying the system characteristics to a specific biological system. In the current study, students made use of the system characteristics to visualize and reason about a complex biological problem. This study investigated to what extent students experienced systems thinking as a valuable approach to understanding biological phenomena. Based on the individual interviews ($n = 6$) after Lesson 2, the case students indicated that the systems model and the related system characteristics assisted them in making a clear overview of the problem and in reasoning in more detail about the problem, which was also in line with our observations (see answer to RQ 1). Interestingly, the two A type case students (who scored especially high on the insight and application test questions) indicated that they did not directly see the value of systems thinking. Alec indicated that he personally has not needed the systems model so far, while Abel indicated that the systems model confused him, especially the input and output for the different levels of biological organization. A possible explanation for this is that these students already are capable of thinking systematically about a complex problem. In that case, students can experience the explicit application of the system characteristics and the visualization in the systems model as unnecessary, perhaps because they already take these steps implicitly. For example, Abel said: “Usually, for example if I get a question on a test or something, I do not consciously think about this [system characteristics]. Sometimes unknowingly, but then I will not write it out completely, because then only more things will be added that will only make it more difficult.”

Nevertheless, it is interesting to see that the two type B case students (who scored especially well on the application questions) and the two type C students (who scored especially well on the factual questions) indicated that they did see the value of systems thinking. They stated that the systems model in combination with the system characteristics gives them more guidance to visualize a problem and to think in depth about the corresponding subsystems. According to Boaz and Britt, the system characteristics helped them to delve deeper into the problem. Caro indicated that systems thinking invites you to take different perspectives on the problem (i.e., focusing on the different system characteristics), allowing you to see more connections, while Chris noticed that the systems model is particularly valuable for difficult problems and not for simple questions: "[You can use it] for more difficult assignments, if you no longer know what to do, it gives you a little more overview." Systems thinking is often mentioned as a metacognitive skill. So, recognizing what situations systems thinking can be applied to, which Chris seemed be capable of, is an important element of systems thinking ability. Although these are results for only a small group of students (*n* = 6), it seems that the average and low student achievers especially experienced the value of systems modeling. Other studies, interestingly, have also found positive relations between the learning of lower-performing students and the use of modeling activities. For example, Bennett *et al.* (2020) found that modeling activities led to greater learning for all types of students, but especially for the students who might be considered lower achieving. Dauer *et al.* (2013) observed that students who entered the modeling course with a lower grade achieved greater learning in comparison to the highest-performing students. Our study seems to confirm this trend, although further research is necessary.

Design Guidelines

Based on the results of Lessons 1 and 2, design guidelines have been formulated for teachers to support students in visualizing and reasoning about complex biological problems from a systems thinking perspective:

1. Start with a central complex problem/question that covers different levels of organization.
2. Let students visualize a complex biological problem in a systems model. The value and applicability of the system characteristics become clear to students when applying them to a complex biological problem that covers different levels of biological organization. A systems model format seems to assist students in visualizing a problem in terms of the system characteristics in a coherent way and encourages them to reason about it.
3. Assist students in reasoning step by step within and between the levels of biological organization. Visualizing the system in the systems model makes the structure of the system (hierarchy) become visible for students. Students also need some scaffolds to reason systematically between the different levels of biological organization. According to Knippels (2002) and Knippels and Waarlo (2018), partial questions (problems) can guide students to answer the central question by descending and ascending the different levels of biological organization (yo-yo strategy). This can be done by asking students explicitly what levels of organization should be included in their answers and on what level of organization they are starting their reasoning. Furthermore, they have to determine what effect a change in the system has on the different levels of biological organization. Students have to learn that causal explanations can be found by moving down to lower levels and functional explanations by moving up to higher levels of biological organization.
4. Make students explicitly aware of the use of the system characteristics in various contexts. The main aim of developing students' systems thinking is that students become aware of the eight universal system characteristics and that they are able to approach complex biological phenomena from a systems perspective. Explicit attention is needed to foster students' understanding of the individual system characteristics. Ways that seem effective to make students aware of the system characteristics include making explicit connections with the system characteristics in the teaching and learning activities and the teacher's regular use of systems language.

Putting the Guidelines in Context

The students in this study had already been introduced to the concept of systems and system characteristics in a well-known biological context in previous lessons (Gilissen *et al.*, 2020a). With a new group of students, it is important to keep in mind that students must first be introduced to the term "system" and the corresponding system characteristics. In-depth attention is needed to foster students' understanding of each of the system characteristics. Moreover, the students were introduced to the systems model for the first time in this study, and they only saw two elaborated versions of the systems model. The results showed that some students still found it difficult to complete the systems model by themselves. For example, during Lesson 2, the observers noted that Britt and her peers copied information from the example that was given by their teacher in another context. Therefore, it seems important that students need to practice more with the systems model in other biology contexts as well. Moreover, it would be interesting to determine whether students will use the systems model themselves when they are introduced to a new complex problem.

Externalization of Systems Thinking

In this study, we fostered and externalized students' systems thinking by having them make schematic drawings. Completion of the systems models in combination with the discussion between peers gave the teachers and observers insight into students' systems thinking in terms of the eight system characteristics: boundary, components, interactions, input and output, feedback, dynamics, hierarchy, and emergence. This allowed teachers to identify the difficulties that students encountered and let the instructors provide scaffolds or extra instruction to students to overcome these difficulties. This can be of added value with regard to prior research that has reported difficulties in fostering students' reasoning about biological processes, such as the ability to trace matter in dynamic systems (Wilson *et al.*, 2006). The systems model represents the structure of systems in terms of the system characteristics and guides students to visualize biological phenomena from a systems perspective in a wide variety of contexts. Therefore, we think it is easier to use the systems model to identify the extent to which students can visualize a biological phenomenon from a systems perspective. For example, Van Geelen (2019) analyzed student drawings in terms of system characteristics to determine students' systems thinking perspective with regard to the phenomena of respiration, photosynthesis, and digestion. In the discussion, she mentioned the difficulty of coding the different system characteristics in the drawings, because it was not clear which elements of the drawings could be linked to the different system characteristics. A possible solution is to introduce the systems model to students and then hand out the systems model and give the assignment to illustrate a biological problem or phenomenon in the systems model. In this way, it will be easier to code the extent to which the different system characteristics are represented correctly, because you already know where to look in the model to find the different system characteristics. For example, the circles illustrate the components of the system, the arrows between the circles represent the interactions, and so on (Figure 1).

Future

This study has shown that it is possible to encourage students' reasoning about dynamic features in a static representation such as the systems model, but computational models seem to be more suitable to represent systems' dynamic interactions, changes over time, and scales. With computational models, it is also possible to simulate experiments in which the effects of changed variables can be more easily shown (Yoon *et al.*, 2013, 2016; Yoon and Hmelo-Silver, 2017). The qualitative modeling approach we introduced can serve as a first step toward quantitative modeling by schematically visualizing biological phenomena and identifying the components (the agents) and their interactions (actions). To narrow the gap between school biology and research biology, it would be good to start at the high school level with the introduction of these types of models (Wilensky and Reisman, 2006). In a follow-up study, a way to add a quantitative aspect to the current qualitative systems model could be an interesting route to explore.

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