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Teachers' and educators' perspectives on systems thinking and its implementation in Dutch biology education

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ABSTRACT

Systems thinking, the ability to reason about systems in abstract terms, fosters students' coherent understanding of biology. This study aimed to determine to what extent the integration of systems thinking in Dutch biology education is in line with perspectives from systems theories and experts. We related the perspective on systems thinking of systems biologists (n = 7) to those of biology teachers (n = 8) and educators (n = 9). The resulting perspectives were interpreted in terms of three systems theories, General Systems Theories (GST), Cybernetics and Dynamical Systems Theories (DST). Thirdly, we determined to what extent and how teachers and educators pay attention to systems thinking in their teaching practice. This was all done by the use of open-ended interviews and online questionnaires. The results show that the systems biologists and teacher educators involved implicitly refer to three systems theories, whereas the teachers refer to the GST and cybernetics only. Despite this, the results suggest that the implementation of systems thinking in Dutch pre-service teacher training and secondary biology education falls short of expectations. These outcomes underline the importance of teacher (educator) professional development on teaching systems thinking to bridge the gap between research and teaching practice.

KEYWORDS
Systems thinking; biology education; coherent understanding; secondary education; professional development

Introduction

Biologists study living organisms varying from cells, plants, and human behaviour to ecosystems. To understand how these organisms function biologists switch constantly between different levels of biological organization, i.e. from the molecular to the ecosystem level and back (Knippels and Waarlo 2018). Biologists are used to think within and between these levels of organization, are able to identify patterns, and to transfer their insights to other contexts, but for non-biologists, like students in secondary school, this is very challenging (Knippels and Waarlo 2018; Ummels et al. 2015; Verhoeff, Waarlo, and Boersma 2008).

For biology teachers, it is essential to realize that biology comprises a specific way of thinking, and uses specific terminology to talk about biological phenomena and processes. These different biological topics are often taught as separate topics with limited integration, such as plant biology, respiration, endocrine regulation and ecology, which may lead to compartmentalized learning by students (Tripto, Ben-Zvi Assaraf, and Amit 2013; Verhoeff, Boerwinkel, and Waarlo 2009).

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Teachers have an important role in promoting and assisting students in developing a coherent conceptual understanding of biology and helping them to overcome this problem.

One approach that is suggested in the literature to achieve a more coherent understanding of biology is called 'systems thinking'. This way of thinking can be described as the ability to reason about systems in abstract terms. The Research Council (NRC, 2012, 84) identifies 'systems and system models' as a crosscutting concept, which focuses on '*defining the system under study, specifying its boundaries and making explicit a model of that system*'. Crosscutting concepts '*help provide students with an organizational framework for connecting knowledge from the various disciplines into a coherent and scientifically based view of the world*' (National Research Council 2012, 83). Systems thinking as a crosscutting concept can be widely applied in education, e.g. in geography (Cox, Steegen, and Elen 2018; Rempfler and Uphues 2012), sustainable development (Schuler et al. 2018), chemistry (Hrin et al. 2017), and biology (Tripto, Ben-Zvi Assaraf, and Amit 2013).

Systems thinking is especially important in biology education because it reflects biological reasoning: '*being able to apply fundamental principles and rules to complex dynamic systems*' (Wilson et al. 2006, 323). Focusing on systems thinking as one of the fundamental principles of biology may lead to an improvement of students' coherent understanding (Verhoeff, Waarlo, and Boersma 2008). Systems thinking can be used as a guiding principle within the various topics of the secondary biology curriculum in which the universal principles of biological systems play a central role: biological systems have a concrete or more abstract boundary, consist of components that interrelate with each other, have input and output, have self-regulating closed networks, are dynamic, are nested and have emergent properties (Boersma, Waarlo, and Klaassen 2011; Verhoeff et al. 2018).

The importance of systems thinking in biology education is also reflected by the amount of studies that report on learning and teaching approaches to foster or assess students' systems thinking. For instance, Tripto, Ben-Zvi Assaraf, and Amit (2013) concluded that concept maps are an effective tool to provide a detailed picture of students' systems thinking development. Hmelo-Silver, Jordan, Ederbach & Sinha (2017) showed that the use of a Components-Mechanisms-Phenomena (CMP) conceptual representation in combination with modelling practices in the context of ecosystems increases students' understanding of natural systems. The CMP representation supports students to think about the components (C) of a particular phenomenon (P) and how they interact to result in a specific mechanism (M) of the phenomenon. Riess and Mischo (2010) showed that students' systems thinking can be effectively promoted by dynamic computer simulations in combination with lessons which explicitly cover aspects of systems theory. Verhoeff, Waarlo, and Boersma (2008) developed and tested a system modelling teaching and learning strategy in the context of a cell as a system. The results support their assumption that modelling activities enable students to acquire a coherent understanding of biology. However, they also noticed that fostering students' systems thinking requires more effort than one series of lessons focused on one topic: modelling activities should be used more frequently and within different biological topics (Verhoeff, Boerwinkel, and Waarlo 2009). The results of the aforementioned studies show that systems thinking should have a prominent place throughout the curriculum and raise the question of how an explicit teaching and learning pedagogy can be shaped.

However, the literature on systems thinking research is yet to show consensus on what systems thinking entails. Many researchers who report about systems thinking use their own model, including sub-skills, to describe systems thinking. Ben-Zvi Assaraf and Orion (2005) developed the Systems Thinking Hierarchical (STH) model. Hmelo-Silver et al. (2017) developed the Components-Mechanisms-Phenomenon (CMP) model, and Verhoef, Waarlo, and Boersma (2008) used a model derived from the General Systems Theory to describe systems thinking. Although all these models share some similarities, the differences can be attributed to references, explicit or implicit, to the key concepts of different systems theories, i.e. General Systems Theory

Table 1. Three systems theories, their focus and key concepts. The original figure is with permission copied from Verhoeff et al. (2018).

Systems theory	Focus is on:	Key concepts
General Systems Theory (GST)	Hierarchical (nested) open systems	Identity, system boundary, level of organization, components, in- and output.
Cybernetics	Self-regulating closed networks	Feedback, self-regulation, equilibrium.
Dynamical Systems Theories (DST)	Complex self-organizing systems	Self-organization, emergence, nonlinearity, equilibrium states.

(GST), Cybernetics, and Dynamical Systems Theories (DST) (Boersma, Waarlo, and Klaassen 2011). Each systems theory has its own focus and related systems concepts (see Table 1). GST focuses on the hierarchical structure perspective (Von Bertalanffy 1968), Cybernetics focuses on the regulatory perspective (Wiener 1948), and DST focuses on the dynamical perspective of biological systems (Prigogine and Stengers 1984; Thelen and Smith 1994).

According to Boersma, Waarlo, and Klaassen (2011) and Verhoeff et al. (2018) systems thinking should focus on the systems concepts of all three systems theories. Application of the systems concepts can be the basis for exploring and analysing complex biological phenomena as biological systems.

Overall, the importance of systems thinking is clear. However, there are many perspectives on what systems thinking implies, and there is no pedagogy that describes explicitly how systems thinking can be fostered by teachers within biology education. Nevertheless, in the Netherlands systems thinking has been included since 2010 as a domain-specific skill in the examination requirements for secondary biology education (Boersma et al. 2010, 33). The present study is a current state analysis of the perspectives of systems biologists, biology teacher educators and secondary biology teachers on systems thinking in biology education and how these can be related to the three systems theories, as well as the implementation of systems thinking in teaching practice.

So, the first aim of this study is, therefore, to determine the perspective of current systems biology experts on systems thinking in relation to biology education and to what extent the systems biologists' perspective matches the perspectives of biology teachers and educators and the three systems theories. The second aim is to determine to what extent systems thinking has found its way into teaching practice, i.e. pre-service teacher training and secondary biology education.

The main research question is: *To what extent is the implementation of systems thinking in Dutch biology education in line with experts' perspectives on systems thinking, and with three systems theories?*

The following four sub-questions were addressed:

(1) What should be the focus of systems thinking in relation to biology education according to systems biologists?
(2) What does systems thinking in relation to biology education imply according to biology teacher educators and teachers?
(3) To what extent are the perspectives of systems biologists, biology teacher educators and secondary biology teachers related to the three systems theories?
(4) To what extent do biology teacher educators and secondary biology teachers pay attention to systems thinking in teaching practice?

Methods

Participants

Three groups of participants were involved in this study: systems biologists, teacher educators and biology teachers.

Systems biologists (n = 7; 2 female and 5 male) were selected from four Dutch universities. They are professor or PhD in the field of systems biology, and all have their own research specialism varying from synthetic biology, bioinformatics, computational developmental biology, medical systems biology to molecular systems biology. They all teach a course on systems biology at the university level but do not have a specific teacher educational background. They were involved as systems thinking experts to determine their perspective on systems thinking in relation to biology education.

Biology teacher educators and biology teachers were involved in this study to determine what they think systems thinking implies in biology education, and to investigate to what extent they pay attention to systems thinking in their teaching practice, respectively, in pre-service teacher training and upper-secondary education. In the Dutch teacher education system, teachers qualify through attending a teacher track in higher professional education or at university. In this study, we involved biology teacher educators (n = 9; 4 female and 5 male) from all six university pre-service teacher training institutes in the Netherlands. Attending the university teacher track results in a grade one teacher qualification; teachers are qualified to teach at all levels of secondary education. After lower-secondary education (13–15 years) students in the Netherlands have to choose whether they want biology as an examination subject or not in upper-secondary education (16–18 years). Biology teachers (n = 8; 2 female and 6 male) were selected from six Dutch schools, with the criterion that they have more than five years' experience in teaching upper-secondary biology education.

Data collection and analysis

Data were gathered by the use of interviews and an online questionnaire. To answer sub-question 1 and 2 open-ended face-to-face structured interviews were conducted with all participants. The main purpose of the interviews was to investigate what the participants understand by with systems thinking in relation to biology education. Based on the interviews, aspects of systems thinking were selected and these were used as input for the first part of an online questionnaire (Q-part 1) that was presented to all participants approximately three months after the interviews (see Appendix 1). The purpose of Q-part 1 was to determine whether the systems biologists, teachers and educators confirmed the aspects that were selected from the interviews as important aspects of systems thinking (sub-question 1 and 2). To answer sub-question 3, the systems thinking aspects that had been taken from the interviews were compared and linked to the key concepts of the three systems theories (see Table 1) to determine to which systems theories the participants implicitly or explicitly referred in their perspective on systems thinking in the questionnaire (sub-question 3). To answer sub-question 4 the teacher educators and teachers were asked in the second part of the online questionnaire (Q-part 2) to indicate to what extent and how they pay attention to these aspects of systems thinking in their own teaching practice.

Open-ended interviews

The main question of the interview was: '*What is your perspective on systems thinking in relation to biology education?*' The participants were asked to elaborate on this question. If a teacher educator or teacher did not know what was meant by systems thinking the definition that is included in the biology examination requirements was shown (Boersma et al. 2010, 33): '*Within different contexts a student is able to make a distinction between different levels of organization, elaborate on relationships within and between levels of organization and explain how biological units at different levels of organization can maintain and develop themselves.*' The participants were asked to elaborate on this description. In the interviews with teacher educators and teachers, the following question was asked: '*Can you provide some concrete examples from your own teaching practice where you pay attention to (aspects of) systems thinking?*'. The interviews were conducted in Dutch (except one with a non-native systems biologist), audio recorded, and lasted between 30 and 75 min. Audio recordings were transcribed verbatim; the text fragments used in this article were translated into English by the first author and were revised with the help of a native speaker. Data-analysis started by selecting the text fragments in which participants articulated their view on systems thinking. The text fragments were categorised bottom-up using an inductive coding approach (Denscombe 2014, p. 106–121). Coding of the interview transcripts resulted in a coding scheme, which illustrates aspects of systems thinking. This coding scheme was used to code all transcripts. An external coder was provided with a codebook, which included the coding scheme and an example of a text fragment that was categorised using this code, and coded three of the 24 transcripts to determine the inter-rater reliability. Cohen's kappa was .83, indicating that the coding procedure was reliable.

Online questionnaire

After analysing the transcripts of the interviews online questionnaires were administered. The questionnaire consisted of a part for all participants (Q-part 1), and a part for teacher educators and teachers only (Q-part 2) (see Appendix 1). In Q-part 1, a description was given of the different aspects of systems thinking that had been extracted from the interviews. The participants had to indicate whether they considered each of these as an important aspect of systems thinking, and whether they missed any aspects. In Q-part 2, the teacher educators and teachers had to indicate on a five-point Likert scale to what extent they paid attention to the listed aspects in their own teaching practice. Additionally, they were asked to give concrete examples of teaching and learning activities in which they already pay attention to one or more aspects of systems thinking. One systems biologist and one teacher did not respond to the questionnaire. Their answers were not included in the data analysis of the questionnaire.

Results

The first section below presents an overview of the systems biologists' perspective on systems thinking in relation to biology education (sub-question 1) and to the systems theories (sub-question 3). The second section presents the teacher educators' and teachers' perspective on systems thinking in biology education (sub-question 2) in relation to the three systems theories (sub-question 3). The third section presents to what extent teacher educators and teachers pay attention to systems thinking in their own teaching practice (sub-question 4). The original names of the participants have been replaced with letters and a number, i.e. systems biologists SB1-7, teacher educators TE1-9, and teachers T1-8.

Experts' perspectives on systems thinking in relation to the three systems theories

Five different aspects of systems thinking were identified from the interviews: identify the system, input and output, emergence, development and modelling (see Table 2). All systems biologists (6 out of 6) indicated each of the aspects as an important aspect of systems thinking in the questionnaire. The different aspects of systems thinking show overlap with key concepts of one or more systems theories (see Table 2). GST focuses on the structure of a system, which includes drawing a systems boundary around the systems' components ('identify the system'). GST also includes that systems are open and exchange matter, energy and information with the environment ('input and output'), and relates to the hierarchy of a system ('emergence'). Cybernetics focuses on the regulatory perspective, which is included in 'input and output', i.e. the output has an effect/feedback on the input. DST focuses on the dynamics of systems, which includes the 'development' of biological systems and 'emergence'. The dynamic interactions between the systems' components result in emergent properties, which emerge at the system level and cannot be observed in the underlying levels. 'Modelling' can be categorised to all three systems theories, because each systems theory has its own theoretical systems model. In summary, the systems biologists involved in this study emphasize systems thinking aspects that can be found in all three systems theories.

Table 2. Five important aspects of systems thinking according to the systems biologists involved in this study. Column 1 presents the five aspects that had been extracted from the bottom-up coding approach. Column 2 gives a description of each of the codes. Column 3 gives an example of a quote that was categorised to this aspect. Column 4 'systems theories' represents the linkage of an aspect with one or more systems theories. The C stands for cybernetics.

Systems thinking aspects	Description	Example of a quote	Systems theories		
			GST	C	DST
Identify the system	Biological phenomena can be seen as systems: they can be distinguished from their environment with a boundary and they consist of different interacting components.	SB5*: 'When you investigate a system you have to be able to identify the most important players. [. . .] What are the most important players and what are the interactions between these players? So actually being able to define a system and the players involved in the system is an important point.'*	x		
Input and output	Biological systems are open systems; they interact with their environment. Matter, energy and/or information enter the system (input), then the system itself can be seen as a black box where all sorts of processes take place and after that, matter, energy and/or information comes out (output). Open systems are also self-regulating and dynamic. Most systems balance around a set point. With the aid of feedback mechanisms/control circuits, the system ensures that a deviating value is brought back to the set point. At the level of the cell and the organism, this process is called homeostasis.	SB3: *'[. . .] and there is exchange across that boundary, because a sheep, for example, perceives things, there is heat exchange, it takes up nutrients, it excretes things, etcetera.'*	x	x	
Emergence	The components of a system work together to achieve a certain goal or function at a higher organizational level. This is called emergence. To be able to explain this phenomenon, you have to descend to the underlying levels or ascend from the parts to the top. This is also called yo-yo strategy or vertical coherence.	SB2: *'[. . .] trying to understand the system based on the components and their interactions. Thus the properties of the components and their interactions. Therefore, it has a lot to do with emergent properties that cannot be seen in the individual components. It is when they start interacting that you suddenly see [a new] behaviour.'*	x		x
Development	A system has a certain development, e.g. in terms of developmental biology (how does an individual develop during his life) or in terms of evolution.	SB4: 'For example, *the state of a system may depend on the history. You may takeo a certain route on the way there, but that you should do something different on the way back. It is not all the same.'*			x
Modelling	A quantitative computational model or qualitative model in which a biological system is visualized or where predictions about the system can be made.	SB6: *'The entire network is branched and it becomes too complex and therefore you need mathematical techniques, or at least modelling [. . .]. You need a systematic method to write everything down and to indicate the interactions, because that is too complex for the human mind. So they [students] need mathematics in order to be able to model.'*	x	x	x

Teacher educators' and teachers' perspectives on systems thinking in relation to the three systems theories

Interesting to note is that six out of eight teachers did not know what was meant with systems thinking in biology education or only could give a brief definition, so they had to be introduced to the definition that is included in the biology examination requirements. One teacher educator mentioned that he finds it very difficult to describe what systems thinking exactly implies in terms

Table 3. Overview of the results from the questionnaires, displaying the number of participants that indicated a specific aspect as important in the questionnaire as well as whether they apply the specific aspect regularly or more often in their teaching practice.

	Indicated as important		Indicated as applied in teaching	
Systems thinking aspects	Teacher Educators	Teachers	Teacher Educators	Teachers
Identify the system	5/9	7/7	2/9	5/7
Input and output	8/9	7/7	3/9	6/7
Emergence	9/9	6/7	5/9	4/7
Development	8/9	4/7	4/9	3/7
Modelling	8/9	5/7	5/9	3/7

of learning goals. TE1: *'That is what I find difficult when you are going to work with that skill [systems thinking]; what should students be able to do in terms of systems thinking?'* Table 3 presents the number of teachers and educators who indicate a specific aspect as an important aspect of systems thinking in the questionnaire.

Teacher educators

The teacher educators indicated that they thought most of the aspects that are included in the three systems theories were important. There was only a small difference in opinion concerning the aspect 'identify the system' of the GST. A possible explanation for this is that some teacher educators do not think it important to use the word 'system' or 'boundary' explicitly in teaching practice and therefore did not indicate 'identify the system' as important TE6, for example explains systems thinking in terms of identification of the system, emergence, and input and output, but he not directly would use the word system in practice: *'I see systems thinking as a specific form of thinking in biology in which you can view the parts of an organism as a system. A cell, or an organism or an organ or an ecosystem. [...] In other words, where you try to teach students to find all kinds of relationships within the system. You also try to place the system in relation to the environment and of course between systems on different organizational levels. Then you use the yo-yo strategy to make connections between different systems. From a disease [organismal level] you often, for example, go to the genes [molecular level] and along the way you pass the organs [organ level] and cells [cellular level] and switch back to the disease [organismal level] again. So you could say it [systems thinking] is thinking from big to small or going back and forth from big to small and from small to big. And also that a system is not closed: something goes in and something goes out. That is also something that is characteristic to a system,* ***while I would not directly use the word system in the classroom****.'* Most of the teacher educators saw modelling as an important aspect of systems thinking. They identified modelling as a tool to visualize biological systems, which can be done quantitatively or qualitatively. TE7: '*I think that models are very important. So to be able to model. [...] It does not necessarily have to be a computer model, but the visualisation of the processes is important. BINAS [textbook with science images that is used by students in secondary education] is of course full of all kinds of diagrams and images of processes that are invisible to the naked eye, but it is difficult for students to comprehend these diagrams and images. I think it is very important that they physically construct and understand these visualizations in a broad perspective, from diagrams and graphs, but also making stop-motion videos of meiosis or something else.*'

Biology teachers

The biology teachers mostly emphasized the systems concepts of the GST and Cybernetics focusing on the structure and regulation of biological systems. Interestingly, in the interviews, none of the teachers explicitly mentioned finding it important that students should be able to identify the system of interest. T3 addresses this: '*What I find important for students to know is* *that everything influences each other. If they see it as a system or not, that does not really interest me. They probably do not see it as a system. However, I think it is important that they realize that it all reacts to each other and interacts with each other and has an influence on each other and that this happens on all levels.'* No examples of quotes about 'input and output' can be found in the interviews with teachers, while all teachers indicate this as an important aspect in the questionnaire. Four teachers indicated 'development' as an important aspect in the questionnaire, but during the interviews, none of the teachers mentioned the development of biological systems. Almost all teachers indicated modelling, qualitative or quantitative, as an important aspect of systems thinking to visualize biological systems. T4 explains that thinking in models can be used to understand systems: '*That students get to know that through thinking in models, as I call it, you try to give the best possible explanation for what happens in an ecosystem. That system, that model that you have formed or the way you now think about it could be better, but that requires more research, more measurements and more time. So it is the best explanation for now.'*

Additionally, we asked the participants whether they missed an aspect of systems thinking in our interpretation of the interviews into five different aspects of systems thinking (see question 2 in Appendix 1). The participants did not come up with new aspects, only with suggestions for small adjustments. For example, TE7 and TE8 both recommended to split 'input and output' into two aspects. TE8: '*I think that you could split up the first category ["input and output"], especially because thinking in feedback loops is such an important part of the biology curriculum*'. In retrospect, this might have been better, especially because it would have been easier to determine how many participants relate systems thinking to Cybernetics. We now also think it would have been better to rename the aspect 'development' as 'dynamics', because that fits the description of the aspect and the DST better.

Implementation of systems thinking in teaching practice

Table 3 shows the number of teacher educators and teachers who indicated paying attention to systems thinking aspects regularly or often.

Pre-service teacher training

During the interviews, seven of the nine teacher educators mentioned that they briefly introduce systems thinking in pre-service teacher training as an educational approach. TE3 and TE9 mentioned they do not use the term 'systems thinking' explicitly. TE9: '*Definitely. I now notice that I do not always refer to it as systems thinking. I am paying attention to the different levels of organization, emergent properties and make the importance of this clear for students. However, I find the term or concept "systems thinking" confusing because it is not always used in the same way in literature. In my opinion, this term does not add something to student understanding.*' According to the teacher educators, there is not enough time to extensively elaborate on systems thinking. TE2: '*We do not have time for something complex like concept-context education, let alone for systems thinking. [. . .] Systems thinking is not a skill that you can teach within a month. It is something that should get attention through the whole year and it should be done gradually.'* Therefore, while most teacher educators only inform the pre-service teachers about systems thinking, they do not aspire to enable them to implement it in practice directly. TE4: '*I see this [pedagogical] part of the pre-service teacher training also partly as planting seeds that I hope will grow over the coming years.'* The seven teacher educators who introduce systems thinking give their students an assignment to design a set of lessons that foster students' systems thinking. It is remarkable that the teacher educators themselves conclude themselves that the products of students, who have chosen for the elaboration on systems thinking, mostly focus on switching between different levels of organization ('yo-yo strategy'), and not on other aspects of systems thinking. The results from the questionnaire show that five of the nine teacher educators regularly or often pay attention to 'emergence', so this may explain the focus on the levels of organization by students. The results also show that four of the nine teacher educators regularly or often pay attention to modelling, but from the examples that are given it seems that they do not pay attention to 'modelling' in the context of systems thinking specifically. TE7: '*I am not using models explicitly in the context of system thinking, but I do pay a lot of attention to the use of models. System thinking is actually so implicit in many aspects of biology, and thus in modelling, therefore it [modelling] is a form of systems thinking.*'

Upper-secondary biology education

Most teachers, five of the seven, indicate they pay attention regularly or often to 'identify the system' (see Table 3). T6 gives an example of how he pays attention to this aspect: '*As an introduction to ecosystems. I use various slides with examples of "typical" ecosystems. What are characteristic (a)biotic factors? Where do they differ from other ecosystems*?' Several teachers provide examples of topics where they pay attention to the aspect 'input and output'. T7: '*For example the nitrogen cycle where we will follow the route of nitrogen into the human body.*' T4: '*Blood pressure control, respiratory rate, blood sugar level, [and] body temperature, are good examples of systems where the input is interpreted by the different sensors in the control system, compared to set values and [then] an output is caused by effectors*.' T6: '*Dissimilation. What goes into the cell, and what goes out of it to make (an)aerobic dissimilation possible?*' Four teachers regularly or more often address the aspect 'emergence', and provide examples of topics where they pay attention to this aspect. T1: '*Cooperation between the vascular system and the respiratory system for better sport performances.*' T6: '*Immune response (specific). White blood cells (cellular level) work together to keep of an individual healthy (organismal level).*' T7: '*For example, when we talk about form and function, how the [form of the] beak of a bird originates from DNA, via cells and tissues.*' The aspect 'development' receives less attention from the teachers in this study (see Table 3). It is striking that only one teacher, T4, tries to teach several biological concepts throughout the year from an evolutionary perspective, and refers to Dobzhansky (1973) '*Nothing in biology makes sense, except in the light of evolution*'. Two teachers indicate that they pay attention to 'development', but only mention examples that are directly linked to the topics embryonic development or evolution and do not introduce this aspect in other biological topics. Three of the seven teachers indicate that they regularly or often pay attention to the aspect 'modelling' (see Table 3). T4 mentions that he would like to make more use of modelling in his teaching practice, especially the use of dynamic models and that students should be able to design or adjust a model of a biological phenomenon, but that they do not have such programs and/or facilities at their school. T7 uses IP-Coach, a computer modelling program, when he is teaching ecology. All teachers point out that they teach students to visualise biological phenomena and interpret existing pictures, diagrams, and figures.

Conclusion and discussion

This article started by articulating the importance of systems thinking for biology education, but also raised questions about what systems thinking exactly implies and how it has been integrated in biology education since 2010. The main research question was: *To what extent is the implementation of systems thinking in Dutch biology education in line with experts' perspective on systems thinking, and three systems theories?*

According to the systems biologists in this study, current secondary biology education should address the investigation of the universal characteristics of biological systems by students: identification of the system, input and output, emergent properties and the development of systems over time. Moreover, attention should be paid to modelling, such as visualizing biological phenomena into system models, but also predicting of systems behaviour through the use of models. In this expert perspective on systems thinking, we identified implicit links to the three systems theories (see Table 2). The systems biologists' perspective is in line with Boersma, Waarlo, and Klaassen (2011) and Verhoeff et al.

(2018) who argued that the systems concepts of the three systems theories should be the focus of students' conceptual development. In comparison, we identified the same implicit links to the three systems theories in the perspective of the teacher educators of six different pre-service teacher-training programs, whereas we identified only implicit links to the GST and Cybernetics in the perspective of the teachers who were involved in this study. Although the involved teacher educators refer implicitly to all three systems theories, it seems that they pay limited attention to systems thinking in their practice because they '*do not have time for something complex*'. The results show that teachers rarely include systems thinking in their teaching practice, and when they do this it is mostly done implicitly.

In conclusion, the perspectives of teachers and educators are mostly in line with those of the systems biologists and with the three systems theories. However, the corresponding systems thinking aspects appear to be not fully implemented in the teaching practice of these teachers and educators. Though the present study is a qualitative approach with a limited number of participants the results indicate that systems thinking in Dutch (pre-service and secondary) biology education does still need more attention. This is regrettable because systems thinking can promote an integrated view on biology as a science, which is important as biology covers living system at many different levels and from many perspectives (e.g. Knippels and Waarlo 2018).

For a more fruitful and sustainable future implementation of systems thinking in biology education, we suspect that both teacher educators and teachers should be involved in training activities to learn more about systems thinking and its implementation in biology education to eventually foster students' systems thinking as a crosscutting concept. The outcomes of this study underline the importance of current and future studies on professional development for teachers in relation to teaching systems thinking (e.g. Rosenkränzer et al. 2016a, 2017; Schuler et al. 2018; Yoon et al. 2017). For example, Yoon et al. (2017) studied what type of professional development support teachers need to teach about complex systems in education. Moreover, the results emphasize the need for more research on bridging the gap between research, curriculum development, pre-service teacher training and educational practice. A next step in our research will be to involve teachers and educators in the process of developing and testing teaching and learning material to create insight into how to shape an explicit teaching and learning pedagogy to foster students' systems thinking within biology education.

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References

Ben-Zvi Assaraf, O., and N. Orion. 2005. “Development of System Thinking Skills in the Context of Earth System Education.” *Journal of Research in Science Teaching* 42: 518–560. doi:10.1002/tea.20061.

Boersma, K., A. J. Waarlo, and K. Klaassen. 2011. “The Feasibility of Systems Thinking in Biology Education.” *Journal of Biological Education* 45: 190–197. doi:10.1080/00219266.2011.627139.

Boersma, K. T., M. J. A. Kamp, L. Van Den Oever, and H. H. Schalk (2010). *Naar actueel, relevant en samenhangend biologieonderwijs*. Eindrapportage van de commissie vernieuwing biologie onderwijs, met nieuwe examenprogramma’s voor havo en vwo. [Towards actual, relevant and coherent biology education. Final report of the board for the innovation of biology education, with new examinations programs for general upper secondary and pre-university education]. Utrecht: CVBO.

Boersma, K. T., A. J. Waarlo, and K. Klaassen. 2011. “The Feasibility of Systems Thinking in Biology Education.” *Journal of Biological Education* 45: 190–197. doi:10.1080/00219266.2011.627139.

Cox, M., A. Steegen, and J. Elen. 2018. “Using Causal Diagrams to Foster Systems Thinking in Geography Education.” *International Journal of Designs for Learning* 9: 34–48. doi:10.14434/ijdl.v9i1.22756.

Denscombe, M. 2014. *The Good Research Guide for Small-Scale Social Research Projects*. New York, NY: McGraw-Hill.

Dobzhansky, T. 1973. “Nothing in Biology Makes Sense except in the Light of Evolution.” *The American Biology Teacher* 75: 87–91. doi:10.2307/4444260.

Hmelo-Silver, C. E., R. Jordan, C. Eberbach, and S. Sinha. 2017. “Systems Learning with a Conceptual Representation: A Quasi-Experimental Study.” *Instructional Science* 45. doi:10.1007/s11251-016-9392-y.

Hrin, T. N., D. D. Milenković, M. D. Segedinac, and S. Horvat. 2017. “Systems Thinking in Chemistry Classroom: The Influence of Systemic Synthesis Questions on Its Development and Assessment.” *Thinking Skills and Creativity* 23: 175–187. doi:10.1016/j.tsc.2017.01.003.

Knippels, M. C., and A. J. Waarlo. 2018. “Development, Uptake, and Wider Applicability of the Yo-Yo Strategy in Biology Education Research: A Reappraisal.” *Education Sciences* 8: 129. doi:10.3390/educsci8030129.

National Research Council. 2012. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. Committee on a Conceptual Framework for New K-12 Science Education Standards. Board on Science Education, Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press. https://www.nap.edu/catalog/18290/next-generation-science-standards-for-states-by-states.

Prigogine, I., and I. Stengers. 1984. *Order Out of Chaos: Man’s New Dialogue with Nature*. New York: Bantam Books.

Rempfler, A., and R. Uphues. 2012. “System Competence in Geography Education. Development of Competence Models, Diagnosing Pupils‘ Achievement.” *European Journal of Geography* 3: 6–22. http://www.eurogeographyjournal.eu/articles/EJG_Vol3_No1.pdf#page=7

Riess, W., and C. Mischo. 2010. “Promoting Systems Thinking through Biology Lessons.” *International Journal of Science Education* 32: 705–725. doi:10.1080/09500690902769946.

Rosenkränzer, F., C. Hörsch, S. Schuler, and W. Riess. 2017. “Student Teachers’ Pedagogical Content Knowledge for Teaching Systems Thinking: Effects of Different Interventions.” *International Journal of Science Education* 39: 1932–1951. doi:10.1080/09500693.2017.1362603.

Rosenkränzer, F., T. Kramer, C. HöRsch, S. Schuler, and W. Riess. 2016a. “Promoting Student Teachers’ Content Related Knowledge in Teaching Systems Thinking: Measuring Effects of an Intervention through Evaluation a Videotaped Lesson.” *Higher Education Studies* 6: 156–169. doi:10.5539/hes.v6n4p156.

Schuler, S., D. Fanta, F. Rosenkränzer, and W. Riess. 2018. “Systems Thinking within the Scope of Education for Sustainable Development (Esd)–A Heuristic Competence Model as a Basis for (Science) Teacher Education.” *Journal of Geography in Higher Education* 42: 192–204. doi:10.1080/03098265.2017.1339264.

Thelen, E., and L. B. Smith. 1994. *A Dynamic Systems Approach to the Development of Cognition and Action*. Cambridge, MA: MIT Press.

Tripto, J., O. Ben-Zvi Assaraf, and M. Amit. 2013. “Mapping What They Know: Concept Maps as an Effective Tool for Assessing Students’ Systems Thinking.” *American Journal of Operations Research* 3: 245–258. doi:10.4236/ajor.2013.31A022.

Ummels, M. H., M. J. Kamp, H. Kroon, and K. T. Boersma. 2015. “Promoting Conceptual Coherence within Context-Based Biology Education.” *Science Education* 99: 958–985. doi:10.1002/sce.21179.

Verhoeff, R. P., A. J. Waarlo, and K. T. Boersma. 2008. “Systems Modelling and the Development of Coherent Understanding of Cell Biology.” *International Journal of Science Education* 30: 543–568. doi:10.1080/09500690701237780.

Verhoeff, R. P., M. C. P. J. Knippels, M. G. R. Gilissen, and K. T. Boersma. 2018. “The Theoretical Nature of Systems Thinking. Perspectives on Systems Thinking in Biology Education.” *Frontiers in Education* 3: 1–11. doi:10.3389/feduc.2018.00040.

Verhoeff, R. P., D. J. Boerwinkel, and A. J. Waarlo. 2009. “Genomics in School. Science & Society Series on Convergence Research.” *Embo Reports* 10: 120–124. doi:10.1038/embor.2008.254.

Von Bertalanffy, L. 1968. *General Systems Theory: Foundations, Development, Application*. New York: George Braziller.

Wiener, N. 1948. *Cybernetics*. New York: Wiley.

Wilson, C. D., C. W. Anderson, M. Heidemann, J. E. Merrill, B. W. Merritt, G. Richmond, and J. M. Parker. 2006. "Assessing Students' Ability to Trace Matter in Dynamic Systems in Cell Biology." *CBE Life Sciences Education* 5: 323–331. doi:10.0.4.163/cbe.06-02-0142.

Yoon, S. A., E. Anderson, J. Koehler-Yom, C. Evans, M. Park, J. Sheldon, I. Schoenfeld, D. Wendel, H. Scheintaub, and E. Klopfer. 2017. "Teaching about Complex Systems is No Simple Matter: Building Effective Professional Development for Computer-Supported Complex Systems Instruction." *Instructional Science* 45: 99–121. doi:10.1007/s11251-016-9388-7.