Chapter 6
Systems Thinking in Ecological and Physiological Systems and the Role of Representations

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6.1 Introduction

The analysis of complex systems plays an important role in many areas of biology as well as in other scientific fields and in addressing global challenges. The consideration of systems represents a holistic perspective and is thus opposed to earlier reductionist approaches. Common to all complex systems is, at a minimum, the presence of various elements and multiple interactions between them. Today, systemic approaches are applied in many areas of biology, such as physiology (Noble, 2002), microbiology (Westerhoff & Palsson, 2004), ecology and evolution (Proulx et al., 2005). For example, microbiology has evolved into systems biology under the influence of the genomic revolution (Westerhoff & Palsson, 2004). Understanding complex systems can be difficult for a variety of reasons: structural and dynamical complexity as well as connection and node diversity are particularly challenging for learners (Strogatz, 2001). Another significant factor in understanding complex systems is the representation that depict the respective system (Eilam & Poyas, 2010). There are content-specific conventions for representing complex systems, which means that particular system properties sometimes remain unpictured. In this chapter, we aim to examine how these unmapped system properties may influence students' understanding of complex systems. We merge findings from three studies and discuss them from the perspective of representations. Our intention is to deduce further insights into the overarching factors influencing systems thinking.

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6.2 Similarities and Differences of Complex Systems

Despite the diversity of fields and systems, several properties can be identified that underlie many or all complex (biological) systems. Biological systems demonstrate strong hierarchical organisation (Dobzhansky, 1964; Pavé, 2006). The interaction of individual elements at one level creates emergent structures and behaviours at higher levels of organisation. One example of emergence is self-organisation in biological systems, which is observable in the schooling practices of fish, the method through which ants form trails, or the formation of honeycombs (Camazine et al., 2003). While these and other properties are ubiquitous, there are also properties that are unique to some classes of systems. To demonstrate the idea of unique properties, we examined ecological and physiological systems. In both systems, unilateral and bilateral and direct and indirect (non-linear) relations occur that can form feedback loops. Many physiological systems, such as the blood glucose regulatory system, seek to maintain a stable state called homoeostasis: that is, the physiological variable, in this case the blood glucose level, is regulated by homoeostatic processes not to exceed defined limits. If the blood glucose level exceeds the normal range, the release of insulin is stimulated as part of a negative feedback mechanism, which leads, inter alia, to an increased absorption of glucose by muscle and fat cells and the stimulation of glycogen metabolism. This mechanism lowers blood glucose levels. When the blood glucose level falls below normal, glucagon secretion is stimulated as part of another negative feedback mechanism, which leads to the breakdown of glycogen and, thus, the release of glucose into the blood. This increases the blood glucose level. As a result, the interplay between these negative feedback mechanisms maintains the balance of the blood glucose level and ensures homoeostasis. Disturbances in this control system have serious medical consequences (Cannon, 1929). In contrast, there is no such balance in ecological systems. Ecological systems have a certain resilience to perturbations, but there is no such thing as a balance of nature (Ampatzidis & Ergazaki, 2018). However, there are many alternative stable states between which ecological systems can switch back and forth when tipping points are exceeded (Scheffer et al., 2001). Generally, food webs (a type of ecological network) consist of a relatively small number of elements that demonstrate rather higher interconnectivity than other real-world systems (Kitano, 2002a). Although both homoeostatic physiological systems and ecosystems are biological systems, they are fundamentally different. Simply put, biological systems and systems in general are diverse.

6.3 Systems Thinking

Although systems from different areas can be very diverse, certain basic principles hold beyond the context of individual systems. Understanding complex systems requires systems thinking skills. Systems thinking is defined as the ability to recognise and describe systems in their full complexity, and to analyse and predict system behaviours based on constructed mental models (Rieß & Mischo, 2010). Given the variety of systems, it is not surprising that the cognitive skills of systems thinking comprise various facets and different theoretical foundations, such as general or dynamical systems theory (Verhoeff et al., 2018). However, an overarching conceptualisation both within the field of biology and across fields is still missing (Mambrey et al., 2020). Of course, the concept of systems thinking is not limited to biology, but is also prevalent in other scientific fields. Research has been conducted on systems thinking in the areas of social systems (Booth Sweeney & Sterman, 2007; Mehren et al., 2018), technological systems (Frank, 2000) and natural systems (Batzri et al., 2015; Booth Sweeney & Sterman, 2007; Mehren et al., 2018). In biology, various fields have been examined from a systems perspective, including physiology (Snapir et al., 2017; Tripto et al., 2017; Wellmanns & Schmiemann, 2020), cell biology (Verhoeff et al., 2008) and ecology (Hokayem & Gotwals, 2016; Mambrey et al., 2020, 2022).

Although there is no unified framework, there seems to be a common ground across conceptualisations that systems thinking includes three essential skills: systems thinking requires (a) identifying and describing the elements and their relations (identifying system organisation; Ben Zvi Assaraf & Orion, 2005; Booth Sweeney & Sterman, 2007; Mambrey et al., 2020; Mehren et al., 2018; Tripto et al., 2017). In biological systems, these structures and their elements vary in size and organisation (Hmelo-Silver et al., 2007). The second skill relevant to systems thinking is (b) analysing mechanisms, functions and dynamics that result from the interaction of elements in order to recognise how a system behaves to fulfil its function (analysing system behaviour; Hmelo-Silver et al., 2007; Hokayem & Gotwals, 2016; Mambrey et al., 2020; Mehren et al., 2018). Finally, systems thinking requires (c) modelling prospective target states (system modelling; Mambrey et al., 2020; Snapir et al., 2017; Tripto et al., 2017). Regarding these conceptual skills, there is no consensus on how students should gain a deeper understanding of complex systems. Although systems thinking is defined as a skill that enables the understanding of complex systems across fields, a study by Mambrey et al. (2020) showed that system specifics have a significant impact on students' systems thinking skills. Similar results were found in the work of Ben Zvi Assaraf and Orion (2005; see also Orion & Libarkin, 2014; Tripto et al., 2017), who found qualitative differences in students' performance across geography and biology. These studies showed that in human body systems, students tend to focus on the system structure, whereas in geography, they are more likely to perceive the dynamic interactions within systems. Further, the results of a study by Sommer and Lücken (2010) suggest that a content-based intervention could improve students' systems thinking skills. The question arises as to why systems thinking, which is supposed to be a superordinate skill, seems to be context-specific. It is possible that the respective immanent system properties increase the context specificity.

6.4 Representations of Complex Systems

Representations are tools used to model complex systems. They can support students in exploring various complex system features and can thus be used to foster students' systems thinking skills. External representations are an essential part of scientific communication (Tsui & Treagust, 2013). The life sciences in particular 'depend on the use of external representations and symbolic language' (Anderson et al., 2013, p. 19). External representations are collections of information that are 'printed on paper or displayed on a computer monitor, that can be perceived by an individual' (Hegarty, 2014, p. 697). The representations of system models can take a variety of different forms, including visual-spatial displays (for example, diagrams and animations) and verbal materials (Hegarty, 2014). Representations support science learning by illustrating complex biological processes or phenomena (Tsui & Treagust, 2013). In addition, representations can provide information about the assumed mechanisms underlying emergent behaviours (Constantinou et al., 2019). The comprehension of representations requires an active cognitive procedure (Schnotz, 2014) through which the learner constructs a model by memorising representational features and applying them to content knowledge. This process leads to the construction of an elaborate mental model that facilitates coherent reasoning.

Booth Sweeney and Sterman (2007) investigated students' and teachers' systems thinking skills qualitatively in a variety of contexts, finding differences in systems thinking between novices and experts regardless of system content: 'without systems-specific content knowledge, individuals appear to default to descriptive, surface features' (Booth Sweeney & Sterman, 2007, p. 305) when explaining complex systems. Consequently, the type of representation is not a sufficient explanation for the variety in students' systems thinking skills across contexts. Rather, it appears that experts integrate system properties in their reasoning beyond contexts, in contrast to novices. These structures appear imperceptible to students, but because they can be identified by experts, they are implicitly integrated into the system representation. As a result, implicit system properties in representations may greatly reduce the ease of understanding complex systems by hindering a deeper understanding of representational characteristics.

6.5 Purpose and Methodology

In this chapter, we address the role of implicit system properties in systems thinking. By implicit system properties we mean those properties that may affect the system but are not directly represented in representations of the system. As these system properties are relevant to the actual system, we assume that consideration of these implicit system properties is also relevant for systems thinking. Accordingly, we address the overarching research question: what influence do system properties which are only implicitly represented in system representations have on systems thinking?

To answer this question, we examine the results of three different studies on systems thinking in the context of ecology and physiology in the light of representations (Mambrey et al. 2020, 2022; Wellmanns & Schmiemann, 2020). First, we present the roles of the representations identified in these studies. We then illustrate the results using exemplary student statements to provide deeper insights into the challenges posed by implicitly represented system properties. In the following section, we briefly describe the potential contribution of each study. The studies investigated students' systems thinking in two different contexts, two studies in the context of ecosystems and one in physiological systems. In both contexts, representations play an important role in visualising the particular systems.

In the studies of systems thinking in ecology, two differing research approaches – a quantitative and a qualitative approach – were applied to examine students' systems thinking. The first, quantitative approach in the ecological context addressed the structure of systems thinking. In this study, about 200 lower secondary students answered items on (a) identifying system organisation, (b) analysing system behaviour and (c) performing system modelling of a food web in a given representation, showing that system-specific properties significantly impacted the students' systems thinking. Thus, identifying unmapped indirect relations was significantly more difficult than identifying direct predator–prey relationships. We discuss how relations that are only implicitly integrated into ecosystem representations can impact students' systems thinking skills. The second, qualitative study provides in-depth results of students' cognitive patterns while undertaking systems thinking in ecology. The thinking-aloud protocols of about 20 lower secondary students regarding a given food web (Fig. 6.1) were analysed to determine the impact of students' conceptions, knowledge and system representations. The understanding of representations emerged as a cognitive pattern which was particularly relevant for the identification of system organisation. To address our overarching research question, we identified the particular impact that the misinterpretation of representational features has on students' systems thinking. The results confirm the strong influence of implicit system properties on systems thinking in ecology. To gain further insight into the overarching validity of this result for systems thinking in general, we further investigated the impact of implicit system properties in physiological systems on students' systems thinking.

High school students' systems thinking skills in the study of physiological systems were also examined using a thinking-aloud approach. Thirty students were asked to analyse system behaviours and regulative measures based on a representation of blood glucose regulation (Fig. 6.2). The reasoning patterns that emerged through qualitative content analysis reveal that – inter alia – students struggled to consider both direct and indirect cause-effect relationships. In the corresponding section, we discuss students' relevant statements to identify obstacles they faced when reasoning with such a representation so as to identify challenges that result from the necessity to extract implicit system properties from a given flowchart. In sum, through the application of these approaches in different contexts, we seek to

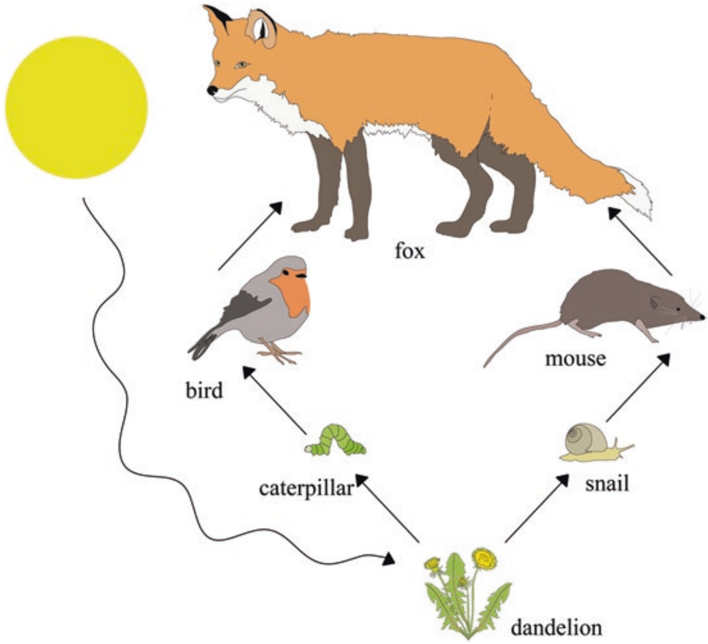

Fig. 6.1 Food web presented to the students in the qualitative thinking-aloud study. (Adapted from Mambrey et al., 2022; CC BY 4.0.)

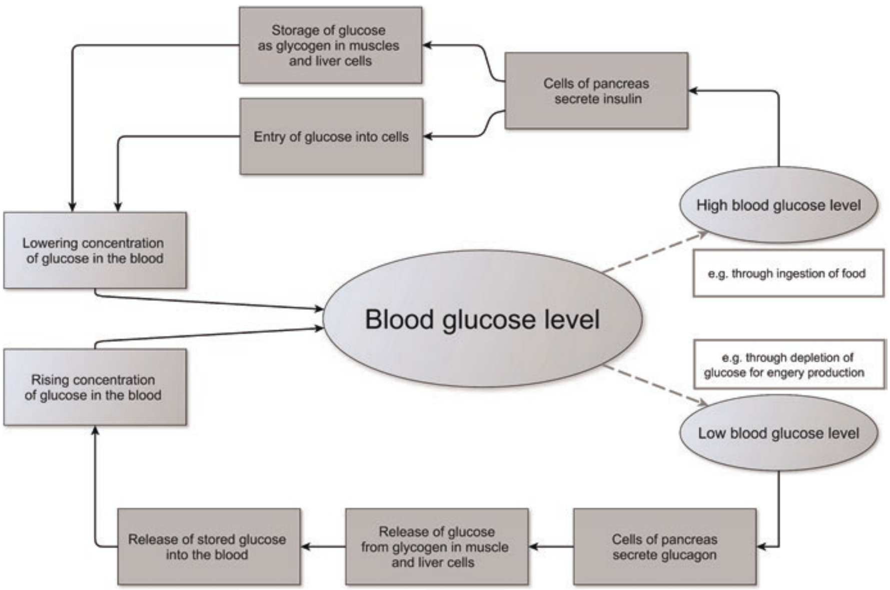

Fig. 6.2 Flowchart used to represent mechanisms of blood glucose regulation in the qualitative study. (Wellmanns & Schmiemann, 2020; CC BY 4.0.)

emphasise the importance of taking implicit system properties into account when building more sophisticated systems thinking skills.

6.6 Systems Thinking in Ecological Contexts

To visualise feeding relations in complex ecosystems, food chains and food webs are used as scientific models to depict the interconnectedness and relations between different species in an ecosystem. A food web is a model of a certain group of elements within an ecosystem (Begon et al., 2006) used to analyse and understand processes such as predator–prey relationships. Thus, the complexity of a given food web depends on the number of elements and the number of interrelations. Scientific conventions are used to express the relevant system properties within the food web. For instance, the smallest unit of a food web or food chain is the predator–prey relationship, depicted by an arrow pointing from an element at a lower trophic level to one at a higher trophic level to represent the flow of energy within an ecosystem. Feedback loop relations and their dynamic effects on the interactions of elements are thereby implicitly integrated into the model of food webs but are not explicitly presented.

Mambrey et al. (2020) quantitatively examined the impact of system specifics and system complexity on the understanding of food webs in 196 grade-five and grade-six students by systematically varying the system complexity and the qualitative type of relationship within the ecosystems. Applying an item response theory approach, they found that direct cause-and-effect relationships were significantly easier for students than indirect effects regardless of the systems thinking skill performed. Beyond that, the complexity had no further influence. These results emphasise the importance of investigating the influence of system properties on students' understanding of complex systems.

To gain further insight into students' understanding of ecosystems, Mambrey et al. (2022) focused on students' reasoning processes when dealing with complex systems so as to identify further influences on students' systems thinking abilities. Therefore, an in-depth analysis of the underlying conceptual understanding was conducted. In their study, 20 students aged 9–12 years conducted thinking-aloud protocols, which are considered a valid tool for accessing cognitive activities in educational and psychological research (Ericsson, 2006; Ericsson & Simon, 1998), while reviewing an ecosystem (Fig. 6.1).

The thinking-aloud protocols not only offered information on students' systems thinking skills, but also revealed their reasoning profiles and potential learning difficulties while verbalising their proceedings when seeking to understand food web ecosystems. Analysis of the reasoning profiles made it clear that difficulties in understanding the indirect effects in ecosystems can arise from the depiction of ecosystems. In particular, the conventionalised use of a food web does not represent the indirect effects of relationships in ecosystems, such as trophic cascades. The only effects integrated are A acts on B (the snail is eaten by the mouse) and B acts on C (the mouse is eaten by the fox). The causal consequence that the fox population indirectly influences the snail population is not depicted. Furthermore, in a food web, the population of an animal is depicted by either a picture of a single animal or by the name of a single element (for example snail or fox). If one assumes that it is not a population but rather a single animal that is depicted, complex indirect relations could not exist in the system. If the only existing snail is eaten by the only existing mouse and the mouse in turn by the only fox, a feedback effect cannot be represented. This effect is possible only under the assumption that populations interact. When students were challenged to construct these relations, it quickly became apparent that their understanding of the qualitative type of relationship was mediated by the representation of the ecosystem. For example, students negated indirect relationships in the ecosystems because "there is no connection between the animals [caterpillar, mouse] in the food web" (Student E1) or "I would assume this connection, but there is no arrow between the animals [caterpillar, mouse] in the food web" (Student E2). Thus, information that is missing through conventions – and only implicitly mapped – constitute a learning obstacle in students' statements regarding representations. These implicit system properties turn out to be a significant learning barrier for students' understanding of ecosystems. Furthermore, they offer a plausible explanation as to why the understanding of indirect relations is a significant learning barrier in all core systems thinking skills in ecology, regardless of the complexity of the ecosystem (Mambrey et al., 2020). Both of these studies (Mambrey et al., 2020, 2022) identify these implicit system properties as having a relevant impact on students' understanding of ecosystems (Mambrey et al., 2020, 2022). The question arises of whether implicit system properties are an ecosystem-specific factor that induces difficulties depending on the type of representation used to model complex systems, such as food webs in ecology.

6.7 Systems Thinking in Physiological Contexts

In contrast to ecological systems, physiological systems are characterised by self-regulation to maintain homoeostasis (Mayr, 1997). Maintaining this balance requires complex and interacting regulatory processes (Bich et al., 2016). The homoeostasis of blood glucose levels is an example of such a complex physiological system. Understanding blood glucose regulation requires integration of the effects of two negative feedback mechanisms. The first feedback mechanism represents a homoeostatic process that counteracts increased blood glucose levels and ultimately decreases blood glucose levels. The second feedback mechanism, active at the same time, acts as a homoeostatic process that counteracts decreased blood glucose levels by increasing blood glucose levels. Both feedback loops are based on processes at the molecular level in various spatial areas (for example, pancreas, muscle, liver and fat cells). To grasp the processes at the molecular level, it is necessary to understand that a multitude of processes and enzymes is involved (van Mil et al., 2016). For instance, insulin binding to cell receptors does not directly trigger the fusion of GLUT4 proteins to the cell surface to facilitate increased glucose uptake, but affects the cell indirectly through a series of molecular events (Jones et al., 2014). In most representations, however, the complex blood glucose regulation system is reduced to the most relevant processes for the sake of simplicity (for example the release of insulin and storage of glucose as glycogen).

Unlike in ecology, the depiction of complex physiological systems, such as blood glucose regulation, is less conventionalised (compare for example the following textbooks: Audesirk et al., 2017; Biggs et al., 2009; Brooker et al., 2018; Freeman et al., 2017; Hoefnagels, 2016; McGlade et al., 2016; Simon, 2017). Flowcharts as qualitative representations provide an overview of the system's structure by depicting, in a more or less conventionalised manner, the relevant system's elements and mechanisms. Elements in such flowcharts are diverse, as they can represent both regulated quantities (for example blood glucose level) and processes (for example release of insulin). Thus, explanations of the representational features may be added. Using the example of blood glucose regulation, a sequence of processes is depicted as a result of either an increased or a decreased value (Fig. 6.2). Compared to ecological food webs, negative feedback loop mechanisms are explicitly represented as characteristic features. While these processes are depicted in detail, other system properties such as the continuity of processes, self-regulation and knowledge about mechanisms as well as time delays remain implicit and must be integrated by the learners.

Wellmanns and Schmiemann (2020) used this flowchart with implicit system properties to examine how students explained blood glucose regulation as a complex biological system. Thirty students aged 14–16 participated in the thinking-aloud study. While solving the reasoning tasks, the students were asked to refer to the associated flowchart (Fig. 6.2), which models the underlying negative feedback mechanisms. Although the flowchart explicitly depicts a sequence of processes triggered by a deviation from the set point, students struggled to consider both direct and indirect cause-effect relationships to explain the consequences of external perturbation. When asked what happens when glucose is taken up with food, several students stated that the blood glucose level rises and then needs to be regulated, without mentioning explicitly represented feedback processes such as the release of insulin (Wellmanns & Schmiemann, 2020). The question arises as to why the students failed to interpret the flowchart and to what extent content knowledge about system properties is necessary for a comprehensive understanding of physiological systems. Based on the thinking-aloud protocols, we identified the challenge of integrating explicitly represented elements as well as relational properties and content knowledge. Process continuity, self-regulation and causal-mechanistic relations are implicit system properties in homoeostatic systems that seem to be challenging for students.

6.7.1 Process Continuity

To grasp complex system dynamics, students need to understand that many processes run continuously. For instance, glucose is constantly broken down at the molecular level, which is necessary for energy supply and thus the maintenance of elementary body functions. This property is shown implicitly in the associated flowchart. The diagram explicitly shows that depletion of glucose in the energy supply triggers a decrease in blood glucose levels. The necessary implication (that is, glucose is continuously broken down) has to be actively constructed by the students through their content knowledge that the body consumes energy even at rest. The lack of integration of content knowledge appears to have hindered students from gaining a deeper understanding of process continuity in homoeostatic systems; for example, student P1 stated:

> If you do not eat any food […], your blood glucose level cannot rise. As a result, the blood sugar level remains constant. The blood sugar level cannot be lowered because you probably do not do any sports during that time. (Student P1)

It is clear that the student did not realise that glucose is continuously broken down for energy supply, even if one does not exercise for a while. The implicit property that processes are continuously running appears to be a learning barrier to further insights.

6.7.2 Self-Regulation

Students' lack of awareness regarding the continuity of processes, such as basal metabolic rate, also influenced their understanding of self-regulatory processes, as they did not recognise that negative feedback processes are always active. Taking the example of the blood glucose level, it can only be maintained between meals through a continuous release of stored glucose triggered by the signalling molecule glucagon. Again, the system property of self-regulation is only implicitly integrated into the representation of the system. The flow chart explicitly shows negative feedback processes as being triggered by a decreased level of glucose; hence, there is a noticeable deviation from the set point. This lower feedback mechanism, however, runs continuously, except in situations where glucose is taken up with food. This implication is an inference of the element property that glucose is continuously broken down. Students failed to integrate these dynamic self-regulation processes into their explanations.

> If you do not eat any food, you will not consume any glucose, so your blood sugar level will not get any higher. When you rest, only a very little amount of glucose degrades, so the blood sugar level remains almost constant. (Student P2)

In this example, the student explained an observed steady state through the non-occurrence of external regulatory interventions (that is, no food intake/less glucose degradation), and thus did not recognise that homoeostasis, as the overall system behaviour, can only be maintained through the continuous effect of negative feedback mechanisms. To summarise, the students failed to transfer the explicit information, that the negative feedback mechanism becomes active after a disturbance, to the implicit extension – negative feedback mechanisms must always be active. A lack of understanding of self-regulation is a possible learning barrier, since students do not fully understand the meaning of regulative processes.

6.7.3 Causal-Mechanistic Relations

Furthermore, several students were unable to generate mechanistic explanations based on causal relations. The arrows in a flowchart explicitly represent causal relations, as linked processes symbolise a cause and subsequent effect. Beyond that, causal relations represent the starting point for the examination of the underlying mechanism. Mechanistic relations refer to implicit structures and processes that explain a causal relationship (Russ et al., 2008). In other words, mechanisms are often implicit but offer the possibility of explaining the linkage between a cause and its effect. Many students did not make any statements about mechanistic relations. For example, the following student identified causal relations but did not explain any further transport or effect mechanisms.

> Eating something results in a high blood sugar level and then causes insulin to be released into the blood. This condition causes glucose to be absorbed into the cells or stored in the liver and muscle cells in the form of glycogen, which leads to a lowering of the blood sugar level. (Student P3)

By describing causal relations, the student referred to the relations explicitly represented in the flowchart. Student P3 did not integrate any implicit relation property, such as that cause and effect are linked via numerous mechanisms, and that the effects occur with time delays. In contrast, Student P4 seemed to decode individual mechanistic relations.

> Insulin may lead to… That is, insulin ensures that glucose is taken up from blood into cells and that glucose is stored in liver and muscle cells. If there is no insulin released or if there is any disorder, glucose will not be stored. Consequently, a high blood glucose level could not be controlled. If you take up more [glucose, food], the level will increase even higher, which is not good. The person would have to do something about the disorder or see a doctor. The person would have to try to use a lot of energy – a lot of energy is necessary. (Student P4)

The student recognised that insulin controls the entry and storage of glucose into the cells. However, the student did not name the exact mechanism (that is, insulin is transported via the bloodstream and binds to receptors in the membrane, initiating protein activation cascades that lead to the insertion of the GLUT transporter). This result is not surprising, since this information was not explicitly presented to the students. Nonetheless, the student recognised that there is such a mechanistic relation, as they pointed out that somehow insulin controls entry and storage. Thus, student P4 identified an implicit relational property and inferred that if there is no release of insulin, the blood glucose level will increase permanently and further increase with each subsequent food intake, since glucose is not taken up into the cells. P3 suspected that external intervention is inevitable, concluding that it would be difficult to decrease the blood glucose level, as doing so would require great energy expenditure. Thus, the student made an assumption about the magnitude of the effect of insulin and activity in decreasing blood glucose levels. However, this information, which is not explicitly depicted in the flowchart, represents the necessary integration of content knowledge.

Overall, we can see that students failed to integrate implicit system properties in their analysis of the blood glucose regulation system. If students do not integrate their content knowledge about the basal metabolic rate, they will not conclude that the negative feedback mechanisms are continuously active. Furthermore, if students do not integrate content knowledge about molecular structures and processes, they will not be able to provide causal-mechanistic relations. Consequently, implicit system properties in physiological representations seem to represent a significant learning barrier, offering a plausible explanation for why the students failed to explain the maintenance of homoeostasis with the effect of negative feedback mechanisms.

6.8 Discussion

We have discussed some examples in which students failed to identify implicit system properties and considered the reasons for such failure. Some implicit system properties are identifiable through logic. Indirect relations in food webs, for example, are reasonably evident on the basis of logical considerations. If population A acts on population B and population B acts on population C, then it can be logically deduced that population A should also have an effect on population C. To be able to classify this inference correctly, however, learners have to integrate the implicit property of the species drawn in the food web into their mental model of the system. Each species represents a population rather than an individual. Consequently, students need representation- and system-specific content knowledge to understand system dynamics.

Flowcharts of the blood glucose regulation system usually explicitly depict negative feedback loops as central mechanisms, but other system properties remain implicit. Due to the basal metabolic rate, maintaining a more-or-less constant blood glucose level is only possible through the continuous release of glucose. However, this information is only implicitly integrated into most qualitative representations of the blood glucose regulation system (Wellmanns & Schmiemann, 2020). We demonstrated that students have difficulties in grasping the implied continuity of processes when working with this type of representation, assuming that both negative feedback mechanisms become active only after a disturbance. This demonstrates that content knowledge is required to fully understand the meaning of the processes and the negative feedback mechanisms involved in blood glucose regulation. In addition, these findings apply to causal-mechanistic relations with time delays. Students did not achieve a deeper understanding of the underlying causal-mechanistic relations due to the hindrance posed by implicit system properties. More precisely, they failed to adduce particular processes that can explain the mechanisms of causal relations. Our results reveal that this discrepancy led to difficulties in students' understanding and hampered the content-specific performance of students' systems thinking.

For a comprehensive understanding of complex systems, both explicit and implicit system properties need to be integrated. These implicit system properties include, at a minimum, implicit element properties, implicit relations and implicit relation properties. We claim that there are three reasons why system properties are not explicitly represented: simplification, convention and emergence. 1) Simplification: The modelling of complex systems for educational purposes usually involves simplifications so as to focus on specific system properties. 2) Convention: How a system is represented graphically depends largely on technical conventions and traditions. In food webs, for example, predator–prey relationships are represented by unidirectional arrows, although the Lotka–Volterra model, which is frequently used to describe individual predator–prey relationships, assumes that predator and prey populations interact. 3) Emergence: Emergent phenomena cannot be represented but arise only through the interactions of system elements.

Our results align with Schnotz's model (Schnotz, 2014) positing that prior knowledge is important for understanding representations. We consider prior content knowledge to be necessary to identify only implicitly represented system properties and integrate them into the mental model of the system, suggesting in turn that systems thinking, at least when examined in relation to representations, is significantly influenced by content knowledge, corroborating Sommer and Lücken's (2010) finding that systems thinking is related to content knowledge. Regardless of the type of influence on students' learning process, it can be perceived that there is a qualitative difference in the systems thinking of novice and experienced learners. Novices are more likely to refer to the surface features of systems, while experts consider the underlying system properties and dynamics as relevant in their reasoning process (Hmelo-Silver et al., 2007; Lee et al., 2019; Tripto et al., 2018).

Because implicit system properties can significantly influence system dynamics, content knowledge is necessary to fully understand a complex system based on system representations. Generally, tasks that require reasoning based on (multiple) system representations are suitable for promoting systems thinking skills. However, static representations of system elements and relations may not be sufficient for grasping, exploring and describing complex system dynamics, underlying mechanisms and emergent system properties (Kitano, 2002b).

There are several ways to overcome the limitations of conventional and static representations: prompts, sequencing and simulations. (1) Prompts are a way of making students aware of implicit properties (Bannert, 2009). For example, insulin is synthesised by the pancreas and affects muscle and liver cells. Therefore, a prompt could encourage students to consider which process the arrow connecting these two processes must implicitly represent. A correct answer would entail that it represents a transport mechanism for insulin, indicating that insulin is passively transported by the bloodstream. (2) Animations can help visualise systems' behaviour and dynamics over time (Lowe & Schnotz, 2014). (3) Simulations are well-suited for examining complex system behaviour under different conditions and the consequences of planned interventions. For example, simulations work well for investigating the consequences of a forgotten dose of insulin or an overdose of insulin in a diabetic patient.

We assume that the aforementioned methods can help improve students' abilities in systems thinking. However, this does not mean that students' skills would automatically increase regardless of the context, for implicit system properties limit the generalisability of systems thinking. The implicit properties vary from system to system, and specific content knowledge is usually required to decode them. Thus, the effective promotion of systems thinking requires an extensive process of analysing the system of interest and the requirements for learners, whereupon learning materials and representations must be designed in such a way that the relevant implicit properties become apparent – for example, through the use of prompting, sequencing or simulations – and to ensure that learners have the tools to successfully identify them.

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