Instr Sci (2017) 45:73–98
DOI 10.1007/s11251-016-9390-0

How is the body's systemic nature manifested amongst high school biology students?

Jaklin Tripto[1] · **Orit Ben Zvi Assaraf**[1] · **Zohar Snapir**[1] ·
Miriam Amit[1]

Received: 28 March 2015 / Accepted: 31 August 2016 / Published online: 10 September 2016

Abstract This study follows two groups of students (67 in all) through the 3 years of their high school biology education and examines the development of their systems thinking - specifically their models of the human body as a system. Both groups were composed of biology majors, but the students in one group also participated in a PBLbased extension program called "Medical Systems". Data was gathered by means of concept maps, which the students completed at four strategic stages of the learning process: beginning of 10th grade, end of 10th grade, end of 11th grade and end of 12th grade. At the end of the 3 year learning process, the students' showed more complex system models. They included a wider range of concepts in their maps, spanning hierarchy levels ranging from the molecular and cellular to the system level. We also found an increase in references to dynamic interactions, but this did not encourage the students to use cellular level processes when explaining phenomena that occur at the systems level. The impact of the PBL teaching method was strongly evident in the complexity of the Medical Systems program students' concept maps, which heavily emphasized "hierarchy" and "diseases" as system characteristics.

Keywords Biology education · Systems thinking · Complex systems · Problem based learning (PBL) · Concept maps

---

✉ Orit Ben Zvi Assaraf
ntorit@bgu.ac.il

Jaklin Tripto
triptoj@gmail.com

Zohar Snapir
zohar.snapir@gmail.com

Miriam Amit
amit@bgu.ac.il

[1] Department of Science and Technology Education, Ben Gurion University of the Negev, Beer Sheva, Israel

Introduction: complex systems and their importance in biology education

In recent years, science education research has become increasingly focused on the study of complex systems, based on the assumption that understanding complex systems is a necessary part of being a scientifically literate citizen of the world. Our understanding of what complex systems are and how they operate also comes from a variety of disciplines ranging in scope and diversity from physics and chemistry to biology, sociology, and economics (Yoon 2008). The complex systems research community, though diverse, nevertheless shares the following common assumptions about what constitutes a complex system: (a) it operates at multiple distinct levels of organization; (b) it involves nonlinear interactions among the system's elements, including positive and negative feedback loops; (c) even when the only interactions that exist in a system are among its individual elements, important macroscopic descriptions can still be applied to the system as a whole and are critical for understanding its patterns; (d) system-level patterns can emerge without any force explicitly striving for the pattern, through the self-organized activity of many interacting elements; and (e) the same system pattern can often be found in diverse domains, and it is useful to describe systems in sufficiently general terms such that these commonalities can be revealed (Goldstone and Wilensky 2008, p. 467).

Complex systems are prevalent in many scientific fields, and even more so in the field of biology. They are found within individual organisms at the level of physiology, and interactions between organisms form additional complex systems at the level of biological societies and ecology (Greenwald et al. 2015; Ben Zvi-Assaraf and Orion 2005). Natural systems are typically dynamic and changing over time; they are often held in states of equilibrium with other interdependent systems, and the interactions within and between them can be unpredictable. Disturbing this web of interconnections can have major implications as effects cascade across associated networks (Stewart 2012). Understanding the complexity of natural system is therefore crucial to a proper understanding of what they are and how they work.

Since principles of complexity repeat in many situations, understanding complex systems is an important part of scientific literacy (Sabelli 2006). Understanding these principles can promote knowledge transfer and enable cross-fertilization between disciplines (Goldstone and Wilensky 2008). Negative feedback, for example, is a basic principle that is fundamental to maintaining homeostasis in systems like the human body, helping it control a variety of elements, including respiration, circulation, nutrition, metabolism, excretion and behavior (Evans et al. 2005). It refers to the system's response to an imbalance caused by excess, and to its correction of that excess by a decrease in function that serves to restore balance. The principle of negative feedback applies to activity variety of processes that take place in the body, like the maintenance of regular body temperature or blood sugar. It is also necessary to our understanding of artificial systems, like a thermostat triggering air-conditioner activity when the room temperature rises. Thus, learning about negative feedback in one system can promote an understanding of other complex systems that utilize the same basic principle. This is also true for other common principles in complex systems, so learning about complexity exposes students to new frameworks of explanations, and to methodologies that are important and relevant in a variety of possible environments (Jacobson and Wilensky 2006).

This focus on students' understanding of complex systems has led to an increase in research about complex systems education, and about students' ability to manage natural, social and technological systems (Hmelo-Silver and Azevedo 2006; Jacobson 2001;

Stewart 2012). Recent research in science education has demonstrated the challenges students face in their attempt to understand how complex natural systems work (Eilam 2012; Jordan et al. 2014; Hmelo-Silver et al. 2015; Keynan et al. 2014). Complex systems are challenging because they consist of multiple organizational levels, within which myriad components interact in reciprocal, non-linear, dynamic ways that are not always intuitive or visible to the naked eye (Duncan and Reiser 2005; Hmelo-Silver and Azevedo, 2006). To understand the respiratory system, for example, you must address a process that takes place on two organizational levels: respiration at the macro level (i.e., the expansion and deflation of the lungs) as well as micro-level cellular respiration (Hmelo-Silver et al. 2007). Moreover, you must understand that the macro-level respiration provides oxygen for the cellular level respiration process, which in turn produces energy and expels the carbon dioxide generated in the cells from the body through the circulatory system.

To overcome students' difficulties in understanding the systemic nature of the human body, a biology curriculum called "Human Biology: Emphasizing the Role of Homeostasis" was introduced into the Israeli high school system in 2006. It was thought that unifying human biology around homeostasis, which refers to the phenomena and processes that allow living creatures to maintain a stable inner environment, would provide students with a more complete picture of the human body, allowing them to integrate its multiple components and understand how those components function as a whole.

The primary goal of this study was to understand the characteristics that make up students' "mental models" of the human body as a system, and to see how these models develop over their 3 years learning this biology curriculum. We therefore followed 67 students through the 3 years of their high school biology education, using concept maps collected from four points along the learning process to learn about the development of their systems thinking. The concept maps are a means of illustrating and externalizing the students' mental models of the human body system. Such mental models, according to McDermott (2015), represent our basic understanding of systems—the image of the systems around us that we carry in our head. All of these students studied the biology curriculum noted above, but 21 of them also participated in an extension program called "Medical Systems," which uses problem-based learning to introduce high school students to basic science in a clinical medical context. The Medical Systems program was not designed by us for the purposes of this research, but its availability provided us with an opportunity to see if and how this alternative approach to teaching students about the human body affected their perception of it as a system. Therefore, in addition to examining the evolution of the mental models of the system developed by *all* the students, the study also compares the models of the students who did participate in the extension program with the models of those who did not, to see whether (and in what ways) the manner in which the human body is presented to the students affects their personal system model. In other words, did the added experiences of the group that engaged in the PBL-based extension enrich their system models in any discernable way?

Challenges to students' system thinking in the context of the human body

System thinking, i.e., the ability to understand and interpret complex systems, is receiving increasing attention not only in education but also in everyday life (Jacobson and Wilensky 2006; Maani and Maharaj 2004; Penner 2000; Wilensky and Reisman 2006). Systems thinking can be generally referred to as a set of disciplines that promote "seeing the whole," (McDermott, 2015) and the adoption of a "systems level" perspective in which understanding how a part of a system behaves depends upon understanding the system's other parts, and that the system as a whole has properties and organization that cannot be deduced from a consideration of the parts in isolation (Booth Sweeney and Sterman 2007; Holland 1995). System thinking focuses on recognizing the interconnections between the different parts of a system and synthesizing them into a unified view of the whole. Moreover, it deals with recognizing patterns and interrelationships and learning how to structure those interrelationships in more effective, efficient ways (Ben Zvi-Assaraf and Orion 2005). The importance of system thinking was stressed in the 2013 Next Generation Science Standards (NGSS) report, which includes a list of seven "cross-cutting concepts that bridge disciplinary boundaries, uniting core ideas throughout the fields of science and engineering." All seven of these concepts reflect elements of systems and system thinking: [(1) patterns; (2) cause and effect; (3) scale, proportion and quantity; (4) systems and system models; (5) flows, cycles and conservation; (6) structure and function; (7) stability and change).

Many studies have investigated the difficulties students have with the topic of complex systems. They describe a variety of obstacles to understanding the different aspects of the system, among them difficulties drawing connections between the systems' different levels and understanding the function of the system as a whole (Hmelo-Silver et al. 2007). It is therefore very important that the development of system thinking be an integral part of the learning process.

Studies of complex systems have shown that students' understanding of the human body tends to focus on the system's structures and to favor the macro level over the micro. Hmelo-Silver, Holton and Kolodner (2000) noted this phenomenon in 6th graders. Ben-Zvi Assaraf, Dodick and Triptos' study of high school students' system thinking about the human body also reported that they had difficulty representing the body's cellular level (2013), and Verhoeff's study of secondary school students (2003) showed that they had difficulty making connections between the cellular (micro) level and other (macro) ones when explaining biological phenomena.

To understand systems we must also understand the *interactions* between a system's various components, and between one system and another (Hmelo-Silver et al. 2000). Studies of junior-high and high school students have shown that this is particularly challenging them (Ben-Zvi Assaraf et al. 2013; Hmelo-Silver and Pfeffer 2004), especially when it comes to recognizing the role of the system's micro level components (i.e., genes, cells and molecules) in the human body system's interactions (Duncan and Reiser 2007; Liu and Hmelo-Silver 2009).

Another key aspect of the human body as a complex system which students often find challenging is its dynamism and self-organization. Hmelo-Silver et al. (2000) defined the dynamic system as a coherent whole composed of multiple components working cooperatively both on a single level and between levels. Because of the dynamic nature of the connection between the system's different levels of hierarchy, complex systems are difficult to understand, even for experts (Hmelo-Silver and Azevedo 2006). A nonlinear complex dynamic system is made up numerous individual agents (or elements) whose independent interactions result in emergent and complex behavior not exhibited at the level of the individual elements (Chi 2005). Natural science literature refers to this kind of phenomena as self-organization, in which macroscopic order emerges spontaneously without plan, algorithm, or control structure. The manner in which complex systems communicate, respond to perturbations, and self-organize is understood by studying the dynamic processes through which they evolve over time, but studies have shown that students still lack basic understanding of central complex systems ideas like self-organization and evolution by natural selection (Yoon 2008). Dynamism and self-organization are also basic, crucial characteristics of another central aspect of complex systems—homeostasis (Verhoeff et al. 2008). Studies have noted students' difficulties with this concept as well (Westbrook and Marek 1992), especially when it comes to understanding the micro-level aspects of maintaining a system's dynamic balance (Chang and Chiu 2004).

Representing complex systems in the school curriculum

A standard high school biology curriculum (based on guidelines like those published in AAAS 2009; NRC 2011) incorporates several topics, among them genetics, ecology, evolution, the cell, and human body systems. Each of these includes a large number of concepts, different levels of organization, and structures and processes that change from one organizational level to another. But though a curriculum may stress the importance of system thinking in biology education, its potential is not always fully realized in practice (Verhoeff et al. 2008). Complex system education often does not address the function of the system as a whole, and students merely memorize the names of system components (Hmelo-Silver and Azevedo 2006). It can also tend to focus on isolated facts about systems, rather than on interactions and system-wide processes.

Several researchers have noted problems with how systems are represented in school textbooks, suggesting that the way the books organize their information may not be conducive to students' understanding of their complexity (Duncan and Reiser 2007; Horwitz 1996). Knipples (2002), for instance, noted that the topics in textbooks on human biology are designed as separate units that do not connect or explicitly refer to one another. Similarly, Verhoeff (2003) found that these books represent the cell as separate from the human body system.

Other researchers have noted that the biology curriculum tends to stress the structural aspect of systems over their processes (Chi et al. 1994; Songer and Mintzes 1994). Wilensky and Reisman (2006) claim that learning scientific facts without placing them in a wider context "misses the point." They recommend using a "model-based approach" that encourages students to use their knowledge of individual elements in the body to build a model of the human body system as a whole.

High school biology education in Israel and how it addresses the human body as a system

In Israel, students can choose to major in at least one scientific or nonscientific topic during the 11th and 12th grades, which is then evaluated in a national matriculation examination. Biology education is mandatory until the 10th grade, after which anyone wishing to continue in the subject must choose it as a major. In addition to three compulsory core topics (Systems in the human body, Ecology, and Cell biology), it also covers a range of advanced topics designed to reflect the dynamics of biological research and discovery, of which the students must choose three. Each of the advanced topics, including the curriculum in developmental biology, is designed to span 30–45 h of teaching.

The 2006 curriculum revolves around a series of “central ideas” in biology, which are meant to help organize the teaching and learning and increase the students’ ability to cope with and process the large amount of information. The core of the biology curriculum defines these central ideas; they are then used throughout the rest of the curriculum to help teach specific topics. Thus the curriculum shows how the central ideas are manifested in the various organizational levels of living things—at the **cellular level**, at the **organism level**, and at the **society and ecosystem level**. One of the central biological ideas that is introduced in the core and then runs through the entire curriculum is **homeostasis**.

Homeostasis is expressed by the phenomena and processes that make it possible for living creatures to maintain a stable internal environment, even when their external environment is changing. These phenomena and processes are connected to the system’s control, to its feedback mechanisms, to the mutual interdependence of the different systems in the body and to the interaction between them.

The topic “Introduction to Human Biology (Emphasizing Homeostasis),” as presented in the curriculum, addresses the human body as a system, portraying the entire organism as a complex, functioning entity. This topic introduces the circulatory system as a mediating system, which is connected to the function of the other systems in the body and involved in processes that make homeostasis possible. The human body, like that of all living creatures, functions as a complete entity. It is composed of many parts, but when working as a single unit it is far more than the sum of those parts. This curriculum uses the human body to **represent** the principles of structure and function that characterize multi-cellular, multi-system organisms as a whole. It includes instructions for addressing the systems aspects of the human body, like, “the interactions between the human body and its environment include: ingesting matter and energy, receiving information, secreting materials and expelling heat, with an emphasis on the principle of surface area to volume ratio”. It also emphasizes expressions of the existence of homeostasis in the human body, and its reliance on the control and feedback mechanisms that allow coordinated and integrated interaction between different systems: “principles of regulation and control through feedback mechanisms should be expressed through examples that emphasize how the various systems connect to the circulatory system, to the senses, to the nervous system and the hormonal system” (p. 31). Thus, for instance, when teaching about body temperature regulation, teachers should note physiological and behavioral mechanisms like sweating, shivering and changes in the diameter of the blood vessels in the skin.

The Medical Systems program and its contribution to systems thinking

The “Medical Systems” program is an elective addition to the standard school curriculum, which is available only in certain schools (based on their proximity to hospitals). The program is intended for tenth to twelfth grade high school students, and the rationale for its existence is the recognition that it is important to expose adolescents to the world of advanced medicine. In addition to the acquisition of medical knowledge as a virtue in itself, the idea underlying the course was to use an applied scientific discipline like medicine as a tool, a way of indirectly bolstering high-school students’ interest in the basic science on which medicine is based. The medicine is in this sense meant to function at least partly as a means to an end, as a way of showing students the most advanced applications of knowledge in basic science. To qualify for the program, students must major in biology, physics or chemistry. All of the students in our study majored in biology, to which the program added two extra hours per week.

The course curriculum for the "Medical Systems" program takes a completely different approach to the presentation of knowledge about the human body than the approach employed by the standard national biology curriculum. It was designed with the aid of the same people charged with designing the learning program in the country's medical schools, and it therefore reflects the innovative learning method customary in advanced medical studies—problem based learning (PBL), in which scientific knowledge is presented in the context of clinical cases. According to this method, the theoretical studies in the program are based on a holistic approach, where the student is exposed in one unit to all the basic medical science contents of each system in the human body (anatomy, physiology, patient care and preventative medicine). In this it contrasts with the old system, in which each of the basic medical sciences is studied separately. Furthermore, the scientific knowledge is presented in a clinical context that is accompanied by case studies, contributing to the understanding of the important value of the scientific knowledge to the medical profession, and to the perception of medicine as a field where basic science is put to practical use. The program also includes a practical component, in which the students volunteer in medical organizations (like Magen David Adom, Israel's equivalent to the Red Cross) and visit hospitals, witnessing actual, authentic cases in which the analysis of clinical phenomena requires system thinking and writing a final paper about a medical case that they have witnessed.

One of the goals of the Medical Systems program was to use problem-based learning and case studies to engage students' active interest and develop their systems thinking. The idea was that the case inquiry method employed by the program would help the students better understand the complex phenomena and processes that characterize the human body by engaging their motivation and curiosity, which are a necessary condition for meaningful learning (Ben-Zvi Assaraf and Even-Israel 2011).

The Medical Systems program combines a variety of basic sciences (biology, chemistry, technology) into a single program, using the context of a specific medical problem to convey facts based in a number of different fields. Students tend to find this form of learning very interesting, and it stresses the clinical-practical aspect of basic science, emphasizing its relevance (Kaufman and Mann 1997; Walton and Mathews 1989). Arndt (2006) claims that learning environments should include complex, authentic, contextually relevant activities that allow students to identify with their task, since such an environment encourages knowledge construction and helps students' broaden their views and develop their systems thinking. Similarly, Chang (2007) recommends teaching homeostasis in the context of blood sugar and connecting it to the authentic and relevant topic of the fight against diabetes. With these goals in mind, the Medical Systems program confronts students with a series of specific medical problems. These do not necessarily have just one solution, and solving them requires the students engage in inquiry and make use of higher order thinking.

Methodology

Goals and research questions

The goal of this study was gain an in-depth understanding of the systems thinking models developed over 3 years by two groups of high school biology majors. Both groups studied the same national biology curriculum, but the students in one group also participated in the "Medical Systems" extension program. Our first goal was to discover the detailed contents of the system models developed by *all* the students, asking:

What are the characteristics of the students' system models, and how have these changed over the 3 years of their high school education?

Our second goal was to compare the models of the students in the first group with those of the second group and ask:

How does the manner in which the human body is presented to the students affect the personal system model created by the students? In other words, how do the models of the students in one group differ from those of the other?

The research approach

This study employs a mixed methods approach, gathering qualitative data from multiple participants and quantifying it in order to reveal recurring themes and patterns in the development of their systems thinking. The data from the concept maps and interviews of each individual participant was also analyzed qualitatively to provide a comprehensive view of the students' mental model of the human body system as it emerges from their many individual concept maps. The results of this individual, in-depth analysis, however, are not presented here, and will be published in a separate paper. The analysis of each student's maps provided a detailed portrayal of the system model developed by that student throughout the 3 year learning process. At the same time, the quantitative analysis of the population as a whole allowed us to identify recurring patterns in the students' system thinking, so patterns and characteristics identified at the individual level were translated into changes in the entire population, providing us with a more general idea of how high school students develop a system understanding of the human body.

Research population

The research population consisted of 67 high school biology majors (25 boys and 42 girls). All of the students studied the same curriculum, since Israel has a centralized education system. The population was divided into two groups. The first (n = 46) consisted of biology students who did not also participate in in the "Medical Systems" program, and the second (n = 21) consisted of students who did. The students were gathered from two schools in two different school districts, which were chosen for their willingness to cooperate with the researchers. All of the students came from similar (mid-to-high) socioeconomic backgrounds.

Research setting

The study followed the students over the 3 years of their high school biology studies, collecting data at four stages of the learning process: beginning of 10th grade (stage 1), end of 10th grade (stage 2), end of 11th grade (stage 3) and end of 12th grade (stage 4). All of the students studied the standard national curriculum for biology majors. This curriculum includes three mandatory chapters that represent three levels of organization: the cellular level, the organism level and the society and ecosystem level.

In 10th grade the curriculum includes 3 weekly hours of biology and covers an introduction to the human body with an emphasis on homeostasis, designed to portray humans as an example of an organism that functions as a single, complete entity through the relations of interdependence that exist between all of its systems. Throughout this year the students learn about seven human body systems: (vascular, nervous, immune, endocrine, respiratory, digestive and urinary).

In 11th grade the students study 6 weekly hours of biology, in which they cover two subjects. First is the cellular level, which focusses on the structure and function of cells as a unit of life shared by all living things. The second subject introduces students to the society and ecosystem level, addressing the interaction between organisms and their environment. The final third of the 11th grade school year is devoted to going back over the material on all the human body systems, emphasizing homeostasis, from the cellular level to the organism level, in preparation for the matriculation exams.

In 12th grade the students take 6 weekly hours of biology, and topics vary between schools, with teachers choosing two elective subjects from a list provided by the national curriculum. The students in our biology group studied nutrition and evolution, while the students in our Medical Systems group studied nutrition and microorganisms (note: these differences reflect the choices of these students' different biology teachers; the topics were studied as part of the regular biology curriculum and are not connected to the Medical Systems program).

As noted above, the Medical Systems program added another 2 hours of study to the weekly schedules of the students who participated in it. In 10th grade, the Medical Systems students learned about the respiratory system, the vascular system, cardiology and holistic health. In 11th grade they learned about nephrology, neurology and endocrinology, and in 12th grade they learned about reproduction, the digestive system and orthopedics. These theoretical studies were supplemented by clinical experience gained while volunteering at clinics, ambulance services etc., where the students learn firsthand about real-life dilemmas and decision-making in medical situations. The students also visited hospitals (no less than three times per year) for tours connected to the particular topic they were studying at the time, emphasizing the practical aspects of the topic in an actual medical setting. Finally, the students were required to produce PBL-based final project, in which they describe a medical case they have followed, describing the full scope of managing a medical problem—including prevention, diagnosis and care.

Overall, the Medical Systems students are taught to approach a clinical problem in the following order:

(1) Defining the illness.
(2) Causes: (a) causes of risk (biological and environmental) and their prevention; (b) causes of illness.
(3) Signs of illness (objective and subjective).
(4) Methods of diagnosis.
(5) Medical care (goals and methods).

This sequence emphasizes the program's strong orientation towards the PBL approach, in which different topics are learned together in the context of solving a problem. The case studies expose students to a range of basic medical science contents touching on all of the human body's systems, in the "real life" context of a medical case. Thus, for instance, the students are taught about the respiratory system in the context of a case study on the hazards of smoking, about nephrology in the context of a case of kidney failure, and about the digestive system in the context of a case of Celiac.

Research tools and their analysis

Concept maps (CM) and their analysis using the STH model

Concept maps have several applications in biology education as aids to teaching, learning and assessment (Bramwell-Lalor and Rainford 2014; Henige 2012). We discussed their assessment potential at length in a previous study, where we used maps to assess and characterize high school students' system thinking in relation to the human body (Tripto et al. 2013). Chang and Chiu (2004) used concept maps to assess students' understanding of blood sugar, in which context Chang (2007) found that concept maps can be used to represent students' mental models of complex and abstract concepts like the homeostasis of blood. Raved and Yarden (2014) used concept maps to evaluate system thinking competence amongst junior high school students in the context of the circulatory system. Adopting Ben-Zvi Assaraf, Dodick and Tripto's (2013) approach, we evaluated the CMs according to the number of concepts, their linkages, and their organization within the map. It is important to note that our analysis did not discard concepts or links that were used inaccurately by the students, since scoring only 'valid' links risks missing the contribution 'invalid' links can make by supporting other, valid links in the students' mental models (sometimes temporarily), and thus contributing to the overall knowledge structure that serves those students as a basis for further learning process (Kinchin et al. 2000).

The information we gathered from the students' concept maps was analyzed by means of the Systems Thinking Hierarchy (STH) model for assessing systems thinking (Ben-Zvi Assaraf and Orion 2005). This model proposes that the way students think about and understand a system can be categorized according to eight hierarchical characteristics or abilities, which can be arranged in ascending order of advancement into three sequential levels: (A) analyzing the system components; (B) synthesizing system components; and (C) implementation. The eight characteristics are:

(1) Identifying the components and processes of a system (level A).
(2) Identifying simple relationships among a system's components (level B).
(3) Identifying dynamic relationships within the system (level B).
(4) Organizing the systems' components, processes and their interactions within a framework of relationships (level B).
(5) Identifying matter and energy cycles within the system (level B).
(6) Recognizing hidden dimensions of the system (level C).
(7) Making generalizations about a system and identifying patterns (level C).
(8) Thinking temporally (level C).

Based on the parameters of the STH model, we used the analysis of the students' concept maps to look for the following system thinking components. First, we looked for their ability to identify the system's components and processes at both micro and macro levels (level A). This was reflected by the number of concepts in their map and the presence of the different human body systems among these concepts. Secondly, we looked for attributes related to the synthesis level of systems thinking (level B). The students' ability to identify dynamic relationships within the system was reflected in the number of linkages in their maps. In this context, "dynamism" was classified within two categories: "matter transportation" (statements that describe the dynamic nature of matter transportation in the system), and "dynamic concepts" (concepts connected by a node that described a process). The students' ability to organize components and place them within a framework of relationships was reflected in the number of junctions (i.e., concepts related to three or more other concepts). Analyzing the map's junctions in this way provides us with a more holistic view of the system as the students perceive it.

The implementation level (level C) was reflected in the concept maps in two ways. The first was students' representation of patterns—namely hierarchy, homeostasis and dynamism. "Hierarchy" includes statements referring to scale in nature, while emphasizing one scale in relation to another (e.g., "the circulatory system includes capillaries"). "Homeostasis" includes statements that directly and exclusively describe the body's internal stability, as well as additional, associated terms. "Dynamism" here refers to statements that describe the dynamic nature of matter transportation that involves at least two or three systems in the human body. Finally, level C was also indicated by students' references to the time dimension, more specifically, statements describing interactions that will take place in the future (prediction) or have taken place in the past (retrospection). For a full, step by step description of concept map analysis and its translation into the STH model of system thinking, see Tripto, Ben-Zvi Assaraf and Amit (2013).

Internal validity was established at the mapping stage of the analysis. The primary and sub-categorization was debated and agreed upon by the researcher and two additional science education researchers. To ensure the trustworthiness of our results, we drafted a comprehensive final report, including contextual information, proper quotations from informants and an explicit conceptual discussion, so other researchers could review the database evidence. The analysis process was also fully documented and preserved, and the final report offered and maintained a chain of evidence. Finally, the analysis of the different STH categories was carried out by the researcher and her advisor separately and simultaneously. The advisor was consulted after each stage to further strengthen the reliability of the results.

Statistical comparisons were conducted between the concept maps of all 67 students, comparing the maps of individual students as they progressed through the four data collection points in the learning process and noting the differences between the two research groups. These comparisons were made using the Repeated Measure ANOVA and the (Independent) *t* test (see Tables 1 and 2).

Results

In this section we use the students' concept maps to provide a detailed picture of their systems thinking and its development over time, comparing the systems thinking of the students in the biology program group (BP) to that of the students who participated in the Medical Systems program (MSP). The results are organized according to the STH model of system thinking. They show how each of the model's three levels was expressed by both groups and how this expression changed over the students' 3 years of high school.

Level A: analysis of system components

The analysis level of the STH model refers to students' ability to identify components and processes in systems. This ability is expressed, first and foremost, by the number of concepts in the student's map (since these reflect the number of components and processes they have identified). Our results show that the Medical Systems students began the learning process with a larger number of concepts in their maps, averaging 34 concepts to

Table 1 Comparison between the concept maps from 4 points in the learning process and the differences between the two research groups—concept identification (n = 67)

	Concepts	Repeated measure ANOVA				(Independent) t-test			
		Biology program students-comparison 4 stages (F value)		Medical Systems students-comparison 4 stages (F value)		Medical Systems students vs Biology program students (t value)			
						Stage 1	Stage 2	Stage 3	Stage 4
a	General number of concepts	8.02***	(11,12) > (10b,10a)	34.51***	12 > 11 > (10b, 10a)	−4.17***	−3.78**	−6.60***	−8.48***
b	Junctions	3.54*	(10b,12,11) > 10a	6.74***	(12,11) > (11, 10b) > (10b, 10a)	−2.46*	−1.67	−3.44***	−4.86***
c	General number of connections	5.47**	(12,11,10b) > 10a	9.81***	12 > (11, 10b, 10a)	−3.26**	−3.80***	−5.64***	−7.32***
d	Process at human body-level	6.83***	10a > (10b,11) > (11,12)	0.81		−0.18	−2.17*	−2.69*	−3.07**
e	Process at cell-level	11.66***	(11,12) > (10b,10a)	6.75***	(12,11) > (10b, 10a)	0.23	0.44	−0.21	−0.85
f	Molecule	9.96***	(11,12) > (10b,10a)	13.69***	12 > (11, 10a, 10b)	−1.25	0.33	−0.70	−3.18**
g	Micro cell level	2.91*	(11,12,10b) > (12,10b,10a)	19.88***	11 > 12 > (10a, 10b)	−3.35**	−2.26*	−5.82***	−4.86***
h	Macro organs	0.16		22.06***	12 > 11 > (10b, 10a)	−1.80	−2.84**	−4.55***	−7.91***
i	System	10.76***	(11,10b,12) > 10a	8.35***	(12,11) > (10b, 10a)	−1.33	0.77	−2.31*	−4.09***
j	Diseases	0.66		6.75***	12 > (10b, 11, 10a)	−4.90***	−5.00***	−5.50***	−4.67***
k	Concept expresses homeostasis	6.00***	(12,11,10b) > 10a	5.49**	(12,11) > (10a,10b)	2.53*	5.08***	−0.08	0.64
l	Concept related to homeostasis	3.17*	(11,12,10a) > (10a,10b)	4.68**	(12,11) > (11,10b,10a)	0.74	−1.14	−0.27	−1.82

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

(−) Medical Systems students' performance was better

Table 2 Comparison between the concept maps from 4 points in the learning process and the differences between the two research groups—process identification ($n = 67$)

	Statements	Repeated measure ANOVA				(Independent) t-test			
		Biology program students-comparison 4 stages (F value)		Medical Systems students-comparison 4 stages (F value)		Medical Systems students vs Biology program students (t value)			
						Stage1	Stage 2	Stage 3	Stage 4
a	Simple interaction	15.50***	(10a, 10b) > (12, 11)	1.18		0.70	−0.91	−3.37**	−4.83***
b	Interaction between systems	2.14		0.90		−0.44	2.13*	−0.64	−1.29
c	Interaction between humans and environment	2.27		1.45		−2.68*	−2.37*	−1.19	−2.50*
d	Dynamic interaction	4.73**	(10b, 11, 12) > (12, 10a)	3.05*	(10a, 10b, 12) > (10b, 12, 11)	−0.21	3.27**	6.30***	2.36*
e	Descriptive connections	2.50		1.86		−1.78	−1.97	−2.60*	−3.90***
f	Pattern Homeostasis	6.38***	(12, 10b, 11) > 10a	10.52***	12 > 11 > (10a, 10b)	−0.03	3.31**	−0.40	−1.14
g	Pattern Dynamism	1.76		2.99*	(12, 11) > (11, 10a ,10b)	−0.72	1.85	−1.58	−2.57*
h	Pattern Hierarchy	0.89		12.11***	(11, 12) > (10b, 10a)	−0.53	−2.15*	−5.86***	−3.00**
i	Temporal thinking	1.00		0.88		−2.58*	−2.76*	−2.86**	−4.45***
j	Hidden dimensions	13.18***	(12, 11) > (10b, 10a)	20.18***	12 > (10b, 11, 10a)	0.48	−1.34	3.52***	−2.17*

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

(−) Medical Systems students' performance was better the other group’s 21 in their maps from the start of 10th grade. It is important to note that the first concept maps were created in December, nearly 3 months into the beginning of the school year (and the Medical Systems program), at which point the students had already been introduced to 3 body systems. This means that the first concept maps do not reflect the students’ knowledge before they had learned any part of the curriculum at all, but are rather an indication of the early stages of a lengthy 3 year learning process.

Figure 1 compares the two groups’ average number of concepts or connections at the Analysis level based on maps from stage 2 (end of 10th grade) and stage 4 (end of 12th grade). It shows a significant increase in the average number of concepts used by the Medical Systems students (rising from about 40 to almost 80 between 10th and 12th grade) ($t = 8.48$, $p < 0.001$, Table 1,a), while that of the students in the other group did not rise significantly, staying at only 27 concepts on average.

The concepts in the students’ maps can be divided into three levels of hierarchy—micro, macro and system—and our comparison showed that the MSP students’ maps had a significantly higher average number of concepts in all three levels. The most prominent structural system aspect in the maps of the MSP students throughout the learning process was “macro organs,” meaning organs that can be seen with the naked eye (e.g., lungs, heart, stomach). In 12th grade the gap between the two groups was particularly large, with

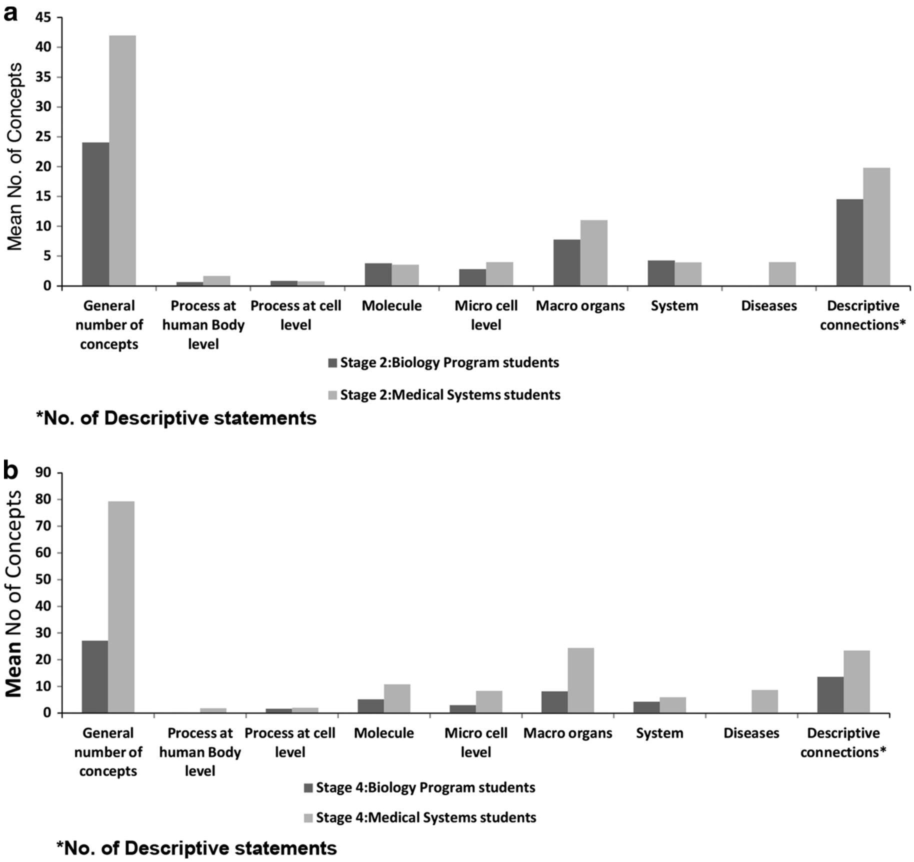

Fig. 1 Level A: Analysis of system components

the MSP students providing an average of 24 such concepts versus just 8 in the BP group ($t = 7.91$, $p < 0.001$; see Table 1,h and Fig. 1).

The micro level refers to microscopic structures in the system that cannot be seen without magnification. In the human body this means concepts at the cellular or molecular level. In concepts referring to the molecular level (e.g., oxygen, hemoglobin, urea), the MSP students gained a statistically significant advantage only at the end of the learning process ($t = 3.18$, $p < 0.001$, Table 1f).

The system level of the hierarchy refers to systems in the human body (e.g., respiratory, circulatory, hormonal). As in the case of the micro level, the MSP students' maps showed a more significant increase in the number of system-level concepts as the learning process progressed, rising from an initial average of 3.6 to 6 in 12th grade ($t = 4.09$, $p < 0.001$, Table 1i).

It is worth noting that despite the fact that simply counting the number of concepts per map shows the MSP students' consistent advantage, a comparison of the percentage of particular concept types in the overall concept count shows a different picture. The MSP students may have noted more concepts at the cellular level than the BP students did, but the number of these concepts in relation to their number of concepts overall was very low. Moreover, an examination of the percentages showed an advantage for the BP students, since concepts reflecting the cellular level constituted only 23.7 % of the 80 concepts noted by the MSP students, but made up 30 % of the 27 concepts noted on average by the BP group. This was also evident with concepts referring to the system level, where in the BP students' maps 15.5 % of the concepts reflected the presence of multiple systems, while in the MSP students' maps these concepts constituted only 7.5 %. However, when comparing percentages there is one aspect in which the MSP students' maps showed an unequivocal advantage, and that is the portrayal of diseases as a characteristic of the human body. Despite the fact that this topic was extensively covered in the biology program too, 11 % of the MSP students' concepts at the end of the learning process addressed diseases, while the BP students made no references to disease at all.

Of all the concepts noted in the maps, the great majority referred to system components and relatively few to processes. This scarcity remained constant in both student groups throughout the 3 year learning process. That said, the BP students showed a marked increase in references to processes on the cellular level (like energy production, cellular respiration, mitosis) between the beginning and end of their biology studies ($F = 11.66$, $p < 0.001$, Table 1e).

Level B: synthesis of system components

The synthesis level refers to the interactions that occur within the human body system, and it is reflected in the concept maps through their connections (see Fig. 2).

One aspect of the synthesis-level analysis of concept maps is counting the number of junctions in each map. A junction in a concept map is a concept that connects to at least three additional concepts, like "homeostasis," "pancreas" and "kidneys" in Tami's map (Fig. 4) or "digestive system," "lungs" and "stomach" in Roni's map (Fig. 5). The number of junctions in a map reflects the student's comprehension of the system's complexity and their ability to portray its interactions as an intricate web. The maps of students in both the MSP and BP groups showed a significant increase in the number of junctions as the learning process progressed ($F = 6.74$, $p < 0.001$ and $F = 3.54$, $p < 0.05$ respectively, see Table 1b). The content of the connections is also relevant to the students' understanding of synthesis, indicating the complexity of the interactions in their system

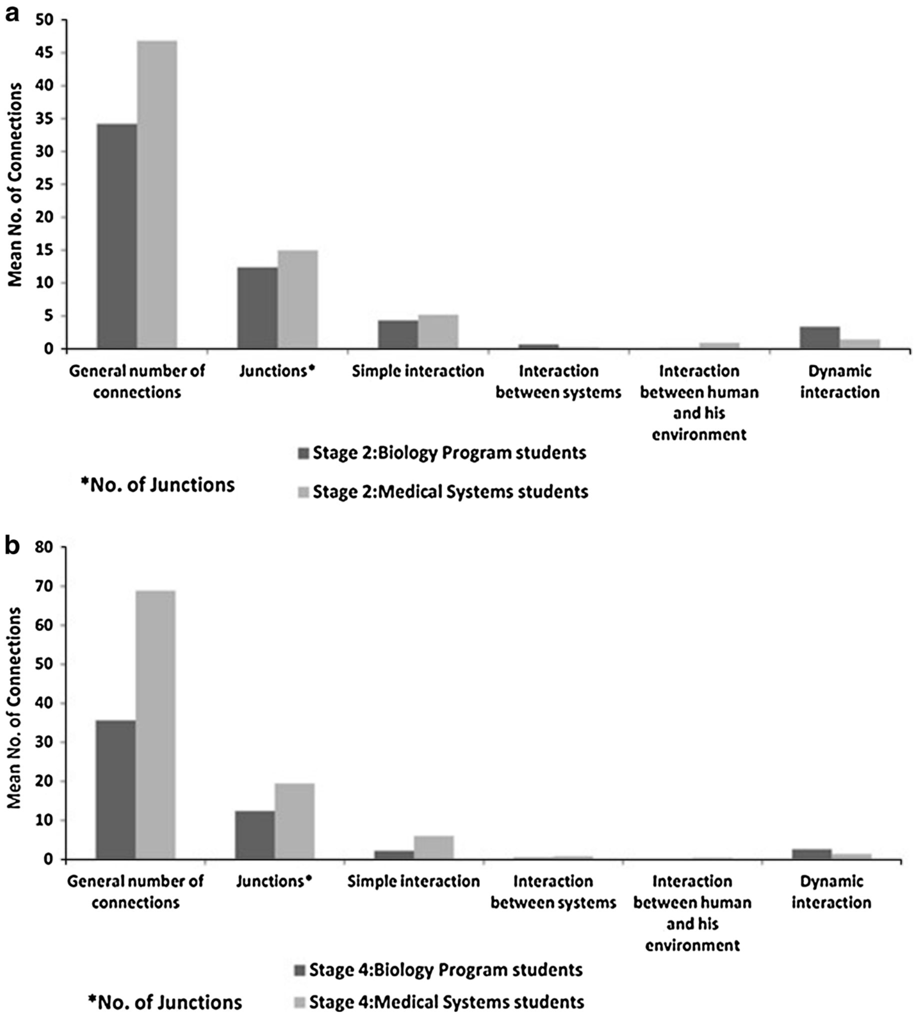

Fig. 2 Level B: Synthesis of system components

model. In addition to simple interactions (e.g., “food travels through the mouth to the esophagus”), we noted two types of complex interactions: “connection between systems” and “dynamic interactions.”

Connection between systems refers to the impact of one system on another (e.g., “the circulatory system provides matter for the muscular system”). Figure 2 shows that connections between systems were almost entirely absent from all of the students’ maps throughout the entire learning process—despite the fact that the students were introduced to 7 human body systems and taught about the connections between them. For example, they learned that food is broken down by the digestive system, then absorbed and moved through the circulatory system, which was also explicitly connected to the respiratory system when they learned about the transmission of oxygen molecules to the cells through the blood.

Dynamic interaction is expressed in the concept maps through connections that describe matter transmission in the human body system. The BP students' maps showed significantly higher expressions of dynamic interaction than those of the MSP students, throughout the learning process ($F = 4.73$, $p < 0.01$ vs. $F = 3.05$, $p < 0.05$, see Table 2d). The difference between the two groups can be seen in the portrayal of the concept "duodenum" in Roni and Tami's 12th grade concept maps (Figs. 4, 5). Roni, a member of the MSP group, presents this component from the digestive system as part of the intestine, and says that "two tubes connect to it"—one from the gall bladder and one from the pancreas. Tami, on the other hand, a student from the BP group, portrays the concept in the context of a dynamic process, showing it "secreting secretin" and noting that it provides "negative feedback" to maintain "homeostasis." In another example, Roni connects the concept "oxygen" to the system's structure, writing "blood with low oxygen passes from the arteria pulmonalis to the lung." Tami, on the other hand, presents this concept from a dynamic aspect, saying "oxygen is absorbed in the blood according to the concentration gradient."

Level C: implementation

The implementation level refers to students' comprehension of the human body system's patterns, its hidden dimensions and its interactions in the time dimension. The patterns (i.e., phenomena that occur at the level of the system as a whole) are in this context divided into three: hierarchy, dynamism and homeostasis. Figure 3 shows the average number of connections in the students' maps that reflect the implementation level. It also includes the average number of concepts in these maps that relate to homeostasis.

An understanding of the human body as an entire system includes references to its hierarchical levels of organization—from the micro level to the level of the whole organism. This pattern was expressed in the maps by connections like "is composed of," "is built from," "is part of" (e.g., "cells are composed of the membrane, cytoplasm, organelles and nucleus"). We found that the MSP students emphasized hierarchy much more strongly than the BP students (Fig. 3). At the end of the learning process, 12.4 out of their average of 15.7 connections related to patterns addressed various aspects of hierarchy in the human body ($F = 12.11$, $p < 0.001$, Table 2h).

Dynamism refers to the transfer of matter between systems (e.g., "hormones are secreted by the endocrine system to the circulatory system," "urea and water move from the circulatory system to the urinary system"). Despite the rise in references to dynamic interaction, references to dynamism as descriptive of the human body system remained very few in relation to the number of connections presented overall in both of the study's populations (Fig. 3).

Homeostasis is a central idea in the biology high school curriculum. Expressions of homeostasis in the concept maps were identified by translating the maps' connections into statements about phenomena and processes that allow us to maintain a stable inner environment, even in the face of changing environmental conditions. This pattern was also represented in the maps by concepts, which we divided into two groups—those that expressed homeostasis according to the curriculum's terminology (e.g., "positive and negative feedback," "control," "regulation and coordination"), and those that the curriculum teaches in the context of homeostasis (e.g., "surface area to volume ratio, "maintaining body temperature," "concentration of substances").

Homeostasis is expressed in the maps through statements that stress the connection between the body's different systems and the mediating systems: the circulatory, nervous

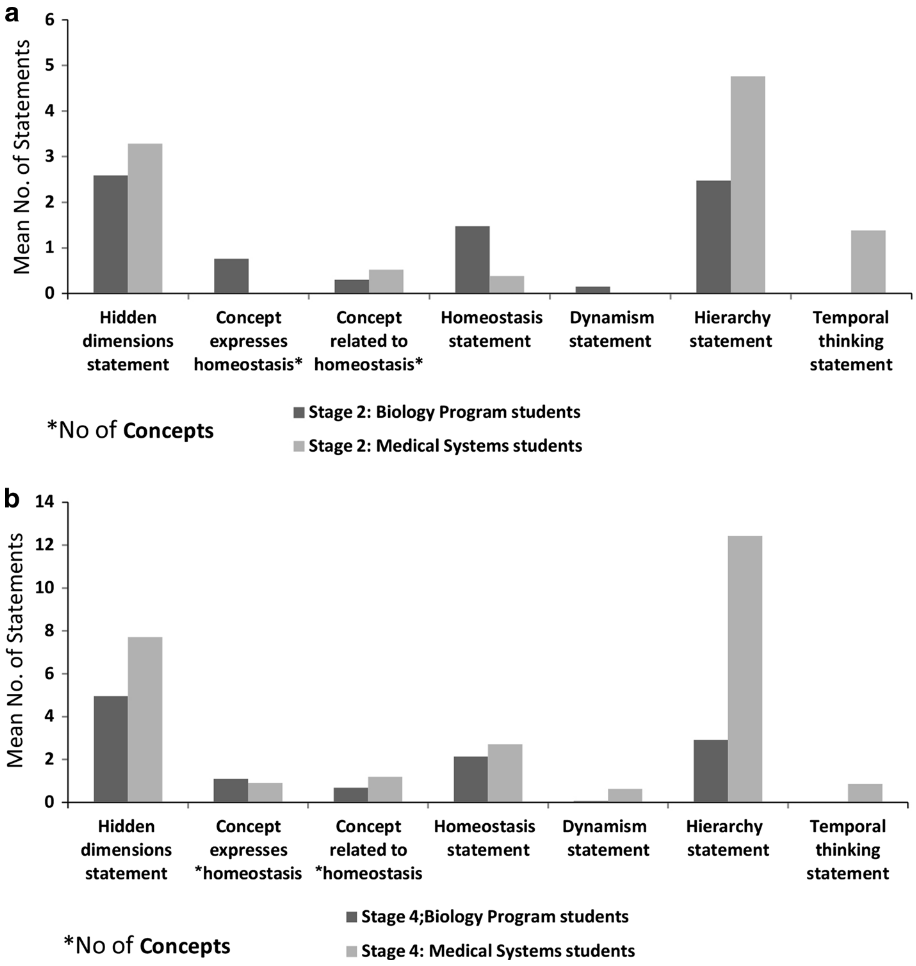

Fig. 3 Level C: Implementation

and hormonal systems. Thus Roni's map from the end of the learning process reflects her understanding of homeostasis in its reference to the regulation of the digestive system in statements like "the hormone gastrin regulates the secretion of HCl," and to the system's acidity in the statement, "HCl causes the PH to be acidic" (Fig. 5). Tami's 12th grade concept map also reflects an awareness of homeostasis. In connection to the circulatory system, she notes that when "body temperature rises…peripheral blood vessels expand." She also notes the possibility of deviation from homeostasis when "plasma volume decreases" or when "body temperature rises" (Fig. 4).

Overall, our analysis showed that the percentage of students in both groups who expressed homeostasis in their concept maps increased gradually as they progressed through the learning process. At the end of 10th grade, in which homeostasis is strongly emphasized, the BP students seemed to favor concepts that express homeostasis in the curriculum's terms more than the MSP students did ($t = 5.08$, $p < 0.001$, Table 1k). This gap was also notable in homeostasis expressed by connections ($t = 3.31$, $p < 0.01$,

Table 2f). 6 % of all the connections made by the BP students (avg. 35.6) referred to homeostasis, in contrast to only 3.9 % of all the connections made by the MSP students (avg. 68.8). Later in the learning process this gap diminished, and after 12th grade there is no longer a significant difference between the two groups in this respect (Fig. 3).

Temporal thinking is expressed in the concept maps through references to interactions that occur in the present and may influence or cause some future occurrence in the human body. This aspect is strongly represented in the Medical Systems curriculum, which emphasizes the recognition of symptoms and their expression over time in the context of disease (e.g., "weight gain can impact blood pressure and the onset of heart attacks"). We found a statistically significant difference between the two groups' expression of the system's temporal aspect throughout the learning process ($t = 4.45$, $p < 0.001$, Table 2i), with the MSP students addressing it more strongly, particularly in the context of diseases.

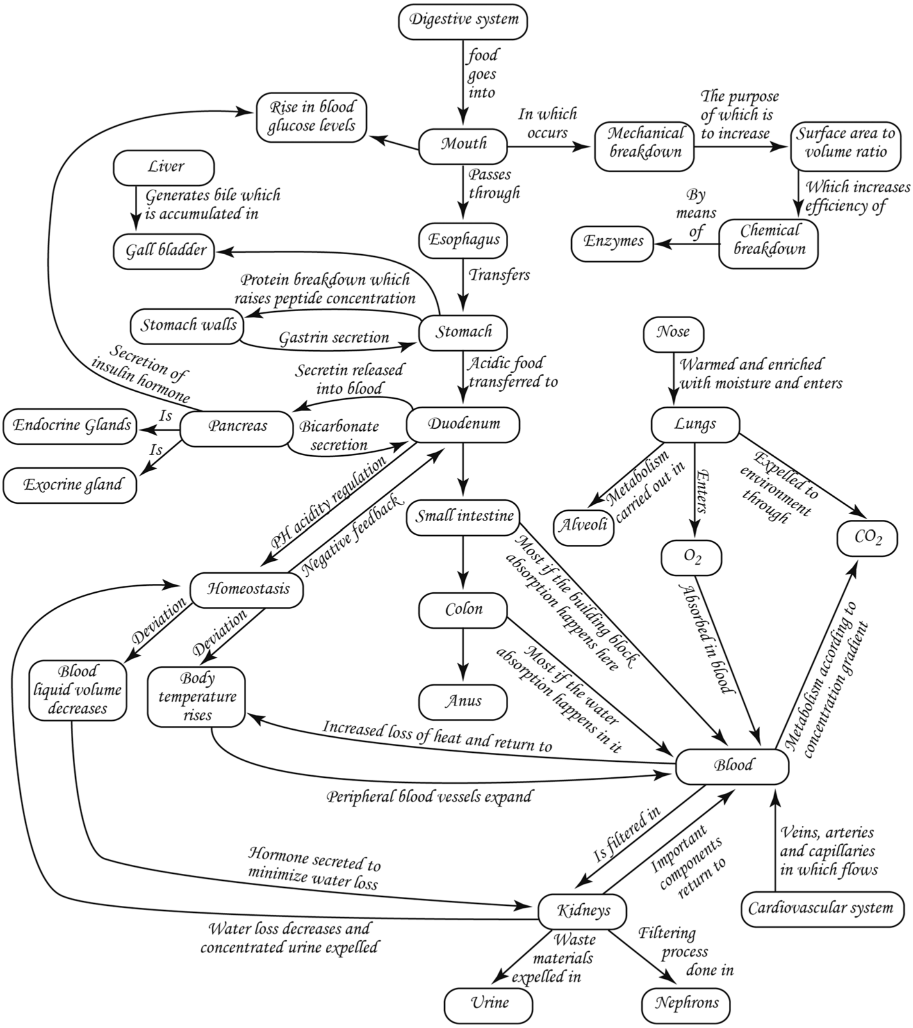

Fig. 4 Tami's concept map in grade 12

Discussion

This study followed the development of high school students' systems thinking, deriving its data from a series of concept maps and organizing it by means of the Systems Thinking Hierarchical model (STH). Our discussion will first address the first research question, noting the students' progress in each of the model's three systems thinking levels and its implications. It will then address the second question, noting the particular contributions of the "Medical Systems" extension program and how these could be further enhanced.

Development of the students' systems thinking

Analysis

As the students (in both groups) progressed through the learning process, their system models became more complex. The range of concepts in their maps grew, spanning hierarchy levels ranging from the molecular and cellular to the system level. However, despite this significant rise in the number of concepts, there was no corresponding rise in the number of processes, indicating that the students' perception of the human body system had remained mostly structural. For example, while we noted an increase in micro level concepts between the beginning and end of the learning process, *processes* on the micro level (e.g., diffusion) remained largely absent. Moreover, when such processes did appear in the concept maps, they were not positioned as connections, which would indicate they were part of an interaction in the system ("oxygen **travels by means of diffusion to** the lungs"), but as concepts, which marks them as a component that either exists in the system or does not ("**diffusion** occurs in the **lungs**").

One pertinent factor in this state of affairs is the biology curriculum, which stresses the system's structural aspects over its processes (Chi et al. 1994; Songer and Mintzes 1994). Because the curriculum stresses structures and their various hierarchies, students place great emphasis on them too (Hmelo-Silver and Pfeffer 2004). Studies have shown that drawing explicit connections between the micro and macro levels of systems improves students' understanding of them and contributes to their meaningful learning of processes from the cellular to the system level (Knippels 2002; Verhoeff 2003). This is important because homeostasis is a phenomenon that occurs at all levels of hierarchy, and without explicit aid in seeing the connection between the micro and macro levels, students have difficulty seeing the interactions that make homeostasis possible (Zion and Klein 2015).

Synthesis

The ability to see the interactions between the hierarchy levels of the organism and the mutual impact of the different components on one another is a necessary part of meaningful biological understanding (Lin and Hu 2003). The students' maps showed a large number of connections early in the learning processes, indicating their ability to recognize interactions. Moreover, a comparison between the maps from the beginning and the end of 10th grade showed an increase in references to dynamic interactions, which are explicitly stressed in the 10th grade curriculum in the context of matter transfer (e.g., the transfer of oxygen to the cells through the blood).

We expected to see another such increase in the maps made after 11th grade, in which the human body curriculum focusses primarily on the cell, with a strong emphasis on interactions and matter transfer between cells and their environment. Our hope was that learning about the cellular level would lead students to incorporate cellular processes into the system models reflected in their concept maps, but this was not the case. Our analysis shows that despite learning extensively about cells, there was no significant increase in the students' use of cellular level processes to explain phenomena that occur at the level of the whole body.

It is possible that this lack of incorporation of new knowledge about the cell into the students' portrayal of the human body system is due partly to how the curriculum is structured—to the fact that the cell is taught in isolation from the human body systems. Verhoeff et al. (2008) noted a similar issue in the Dutch curriculum, where the cell was taught only on the cellular level, without explaining how cells relate to the organism as a whole. We agree with their conclusion that, when teaching about the cell, explicit connections must be made between the cellular level and the other levels in the system's hierarchy.

Another key part of the synthesis level is making connections between systems. The students did reference a larger number of systems as they progressed through the learning process, and by its end their concept maps included an average of four different systems. Nevertheless, most of the students did not indicate connections between these systems in their maps.

It is important to note that the students *were* taught about various connections between systems (for example, the connection between the digestive and circulatory systems was noted when they learned that the products of food digestion were distributed by the circulatory system). However, each system was studied separately from the others, and the students were not given any knowledge organization activities like a multi-system inquiry task. This means that drawing the concept maps for this study was the first and only task where they had been asked to represent all the human body systems together.

Implementation

The biology curriculum studied by the students we examined was designed to emphasize homeostasis. On the one hand, this is reflected in the fact that most of the students' maps - throughout the learning process - included concepts related to homeostasis (e.g., surface area to volume ratio, interdependent relationship between biological structures and their function). On the other hand, these examples represent neither the complex mechanisms nor the micro-level processes associated with homeostasis. Tami (see Fig. 4) was one of the few students who represented the mechanisms, like the secretion of hormones or the action of enzymes, that maintain homeostasis (Fig. 5).

One characteristic of homeostasis is that it is multi-systemic—it relies on cooperative interaction between different body systems. Very few of the students' maps addressed the dynamic interactions between two body systems when explaining a phenomenon at the level of the organism. This is despite the fact that the students were taught about such inter-system cooperation, for instance that the chemical digestion of food is an enzymatic process, regulated by hormonal and neural control mechanisms.

The topics studied by biology majors—the cell, nutrition, evolution and microorganisms, include references to various dynamic aspects related to homeostasis. However, these aspects have often been found to be challenging for students, marked as they are by a complex causality with many intermediate stages (Feltovich et al. 1992). Moreover, homeostasis involves many simultaneous events and interactions, and building a full mental model of these can place a significant burden on students' memories (Graesser 1999; Narayanan and Hegarty 1998).

Recommendations

Our findings regarding the student's expressions of all three levels of system thinking suggest that the high school biology curriculum would benefit from a more extensive use of knowledge integration activities that employ **explicit teaching**. Over the 3 years of their biology education, the students are given a great deal of information about the human body as a system. Much of this information is potentially interconnected, but the students proved largely incapable of connecting knowledge drawn from different contexts to form a more complex system model without being explicitly helped to do so. We suggest that in order to help students succeed both as learners and in life, teachers must provide explicit teaching for specific ideas that encourages students to engage in metacognitive thinking processes.

For example, we recommend the use of knowledge integration activities like the reflective interview described in Tripto, Ben-Zvi Assaraf, Snapir and Amit (2016). In this interview, the students examined two different concept maps they themselves had generated at two different points in the learning process. Guided by a series of explicit questions designed to elicit "systems language," the students reflected on their own knowledge and learning, comparing the system models represented their two maps, drawing conclusions about their past decisions and positing possible improvements to their system models based on their newly acquired understanding. We suggest that, coupled with a reflective interview, concept maps can be employed not just as a means of gathering data, but also as a useful teaching tool with which to help students make connections between elements of system knowledge that they have encountered in different contexts and at different times.

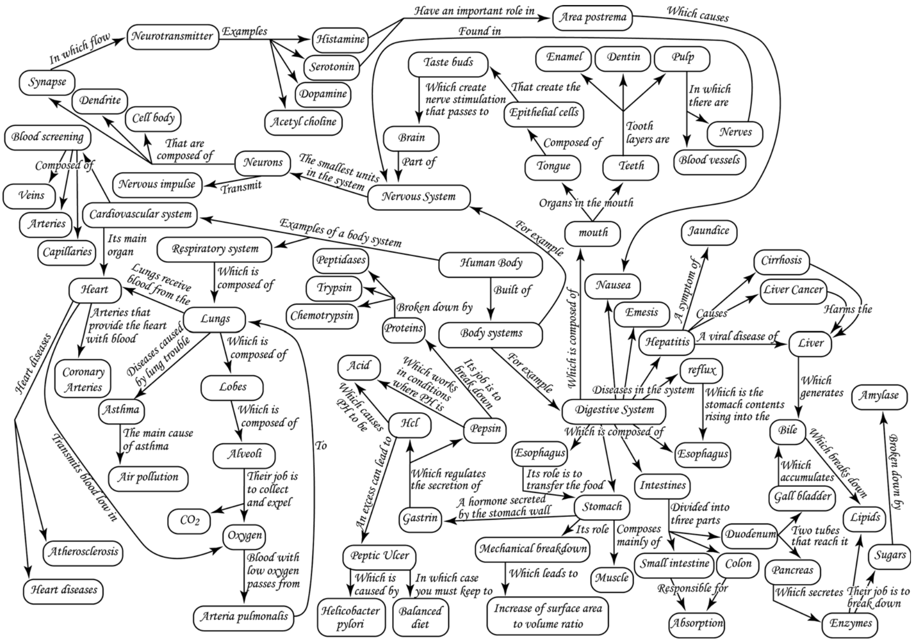

Fig. 5 Roni's concept map in grade 12

Contribution of the Medical Systems program

The theoretical portion of the Medical Systems curriculum is based on the PBL (problem-based learning) method currently employed in many medical schools. This method uses a problem as the focal point for a learning process that emphasizes deductive thinking (Barrows and Tamblyn 1980) and introduces students to complex clinical problems that require the implementation of knowledge from different scientific and clinical areas to solve. The impact of the PBL teaching method was strongly evident in the complexity of the MSP students' concept maps, though its contribution was limited primarily to the structural aspects of the system, which these students were able to describe in great detail. The maps also reflected the range of diseases that were taught in the program from a variety of different directions (e.g., causes, risk factors, symptoms, methods of diagnosis and methods of medical care) (Ben-Zvi Assaraf and Even-Israel 2011).

Another aspect of systems that was prominent in the MSP students' concept maps is temporal thinking, in which students look forward in time, predicting the expected result of multiple earlier interactions from the past or present. For example, their maps reflect an understanding that weight gain instigates a range of interconnected processes that gradually, over time, lead to an inability to control glucose levels in the blood. The Medical Systems program's PBL method of teaching by means of a clinical problem (i.e., an illness) is fertile ground for encouraging students to address interactions in the time dimension in their solutions.

It is also important to note that the Medical Systems program carried various additional benefits that were not revealed in the results of this study, since its research tools and questions were not designed to reflect them. For example, there is no doubt that exposure to the world of medicine through visits to hospitals and volunteering for the ambulance service increased the students' motivation to pursue medicine in the future. Their emotional involvement in the learning process was very high and their awareness of the range of concepts that relate to medical practice and advanced technological research rose considerably throughout the learning process. However, the concept maps about the human body did not give the Medical Systems students the opportunity to express knowledge about things like the connections between the complexity of the human body and technologies like MRI (magnetic resonance imaging), or the genetic mapping and counseling offered in hospitals.

Despite the Medical Systems program's various other contributions, it seems that the students who participated in it were not able to effectively connect what they had learned about homeostasis in biology class to the homeostasis disruption mechanisms associated with the diseases they learned about in Medical Systems. It is important to note that the Medical Systems program was entirely separate from the students' regular biology studies, and no explicit connections were made for the students between the issues they studied in the program and the human body systems they learned about in biology.

Recommendations

Our results suggest that introducing students to problems based on clinical cases does not guarantee their meaningful learning of the biological mechanisms associated with the disease, but that the method is remarkably effective in instilling other elements—like the systems' structural elements and where diseases fit into them. Furthermore, the results indicate that learning about these mechanisms in another context was not sufficient to induce the students to integrate the information into the meaningful learning they had gained from the Medical Systems program. It is important to remember in this context that the scenarios and clinical case studies to which the "Medical Systems" students were introduced were designed and developed by doctors for medical students. The PBL method the program employs is designed to provide students with a problem that requires them to call upon knowledge from several different fields, and to adopt a holistic, interdisciplinary point of view. Solving such a problem requires students to define its components, raise hypotheses, gather data, suggest possible solutions and assess their viability, while taking various additional factors—such as ethics—into account. The program was developed with the underlying assumption the medical students are capable of coping with the strong cognitive demands of this approach. However, it seems that the high school students had difficulty bridging the gap between the language of the "Medical Systems" program, which focusses on the human body from a medical standpoint and describes it using medical terminology, and the language of the regular biology curriculum, which focusses describing biochemical and physiological processes and mechanisms at the system level. As a result, the students were not fully able to draw upon the knowledge gained in one context to enrich their understanding of the other.

Dolmans and Gijbels (2013) claim that in order to create effective PBL scenarios the basic science should be presented in the context of a clinical scenario to encourage integration of knowledge. We therefore suggest that in order to maximize the benefits of the Medical Systems program's method, the basic science necessary to understand the mechanisms must be "imported" from the regular biology curriculum and concretely and explicitly connected to the clinical issues in the students' tasks. This would, perhaps, extend the systems thinking development potential of a program like "Medical Systems" beyond the structural and help it utilize the benefits of its authenticity and relevance to lead students to a greater understanding of the human body system's full complexity.

Acknowledgments This research was supported by the Israel Science Foundation, Research Grant Application no. 718/11.

References

AAAS. (2009). *Vision and change in undergraduate biology education: A call to action*. Washington, DC: American Association for the Advancement of Science.

Arndt, H. (2006). Enhancing system thinking in education using system dynamics. *Journal of Simulation, 82*(11), 795–806. doi:10.1177/0037549706075250.

Barrows, H. S., & Tamblyn, R. (1980). *Problem-based learning: An approach to medical education*. New York: Springer.

Ben-Zvi Assaraf, O., Dodick, J., & Tripto, J. (2013). High school students' understanding of the human body system. *Research in Science Education, 43*(1), 33–56. doi:10.1007/s11165-011-9245-2.

Ben-Zvi Assaraf, O., & Even - Israel, H. (2011). Positions toward science studies in medicine among Israeli University Graduates of medicine and the high school participants of the "Medical Systems" study program. *Journal of Science Education and Technology, 20*(4), 317–332. doi:10.1007/s10956-010-9255-2.

Ben-Zvi Assaraf, O., & Orion, N. (2005). Development of system thinking skills in the context of earth system education. *Journal of Research in Science Teaching, 42*(5), 518–560. doi:10.1002/tea.20061.

Booth Sweeney, L., & Sterman, J. D. (2007). Thinking about systems: Student and teacher conceptions of natural and social systems. *System Dynamics Review, 23*(2/3), 285–312.

Bramwell-Lalor, S., & Rainford, M. (2014). The effects of using concept mapping for improving advanced level biology students' lower- and higher-order cognitive skills. *International Journal of Science Education, 36*(5), 839–864. doi:10.1080/09500693.2013.829255.

Chang, S. N. (2007). Externalising students' mental models through concept maps. *Journal of Biological Education, 41*(3), 107–112. doi:10.1080/00219266.2007.9656078.

Chang, S. N., & Chiu, M. H. (2004). Probing students' conceptions concerning homeostasis of blood sugar via concept mapping. *Proceedings of the Annual Meeting of the National Association for Research in Science Teaching* (pp. 1–4). Vancouver/Canada.

Chi, M. T. (2005). Commonsense conceptions of emergent processes: Why some misconceptions are robust. *Journal of Learning Science, 14*, 161–199. doi:10.1207/s15327809jls1402_1.

Chi, M. T. H., Slotta, J. D., & Leeuw, N. D. (1994). From things to processes: A theory for conceptual change for learning science concepts. *Learning and Instruction, 4*, 27–43.

Dolmans, D., & Gijbels, D. (2013). Research on problem-based learning: Future challenges. *Medical Education, 47*(2), 214–218. doi:10.1111/medu.12105.

Duncan, R.G., & Reiser, B.J. (2005). Designing for complex system understanding in the high school biology classroom. Paper presented at the Annual Meeting of the National Association for Research in Science Teaching, Dallas, TX.

Duncan, R. G., & Reiser, B. J. (2007). Reasoning across ontologically distinct levels: Students' understandings of molecular genetics. *Journal of Research in Science Teaching, 44*(7), 938–959. doi:10.1002/tea.20186.

Eilam, B. (2012). System thinking and feeding relations: Learning with a live ecosystem model. *Instructional Science, 40*, 213–239. doi:10.1007/s11251-011-9175-4.

Evans, D. H., Piermarini, P. M., & Choe, K. P. (2005). The multifunctional fish gill: Dominant site of gas exchange, osmoregulation, acid–base regulation, and excretion of nitrogenous waste. *Physiological Reviews, 85*, 97–177.

Feltovich, P. J., Coulsen, R. L., Spiro, R. J., & Dawson-Saunders, B. K. (1992). Knowledge application and transfer for complex tasks in ill-structured domains: Implications for instruction and testing in biomedicine. In D. Evans & V. L. Patel (Eds.), *Advanced models of cognition for medical training and practice* (pp. 213–244). Berlin: Springer.

Goldstone, R. L., & Wilensky, U. (2008). Promoting transfer by grounding complex systems principles. *Journal of the Learning Sciences, 17*(4), 465–516. doi:10.1080/10508400802394898.

Graesser, A. C. (1999). How do adults comprehend the mechanisms of everyday devices: Texts, illustrations and breakdown scenarios. Paper presented at the Annual Meeting of the American Educational Research Association, Montreal, Canada.

Greenwald, E., Segre, E., & Feinerman, O. (2015). Ant trophallactic networks: Simultaneous measurement of interaction patterns and food dissemination. *Scientific Reports*. doi:10.1038/srep12496.

Henige, K. (2012). Use of concept mapping in an undergraduate introductory exercise physiology course. *Advances in Physiology Education, 36*(3), 197–206. doi:10.1152/advan.00001.2012.

Hmelo-Silver, C. E., & Azevedo, R. (2006). Understanding complex systems: Some core challenges. *Journal of the Learning Sciences, 15*(1), 53–61. doi:10.1207/s15327809jls1501_7.

Hmelo-Silver, C. E., Holton, D. L., & Kolodner, J. L. (2000). Designing learning about complex systems. *Journal of the learning Science, 9*(3), 247–298. doi:10.1207/S15327809JLS0903_2.

Hmelo-Silver, C. E., Liu, L., Gray, S., & Jordan, R. (2015). Using representational tools to learn about complex systems: A tale of two classrooms. *Journal of Research in Science Teaching, 52*, 6–35. doi:10.1002/tea.21187.

Hmelo-Silver, C. E., Marathe, S., & Liu, L. (2007). Fish swim, rocks sit; and lungs breathe: Expert-novice understending of complex systems. *Journal of the Learning Science, 16*(3), 307–331. doi:10.1080/10508400701413401.

Hmelo-Silver, C. E., & Pfeffer, M. G. (2004). Comparing expert and novice understanding of a complex system from the perspective of structures, behaviors, and functions. *Cognitive Science, 28*, 127–138. doi:10.1016/S0364-0213(03)00065-X.

Holland, J. H. (1995). *Hidden order: How adaptation builds complexity*. New York: Addison-Wesley.

Horwitz, E. K. (1996). Even teachers get the blues: Recognizing and alleviating language teachers' feelings of foreign language anxiety. *Foreign Language Annals, 29*, 365–372.

Jacobson, M. J. (2001). Problem solving, cognition, and complex systems: Differences between experts and novices. *Journal of Complexity, 6*(3), 41–49. doi:10.1002/cplx.1027.

Jacobson, M. J., & Wilensky, U. (2006). Complex systems in education: Scientific and educational importance and implications for the learning sciences. *Journal of the Learning Sciences, 15*(1), 11–34.

Jordan, R. C., Brooks, W. R., Hmelo-Silver, C., Eberbach, C., & Sinha, S. (2014). Balancing broad ideas with context: An evaluation of student accuracy in describing ecosystem processes after a system-level intervention. *Journal of Biological Education, 48*(2), 57–62.

Kaufman, D. M., & Mann, K. V. (1997). Basic sciences in problem-based learning and conventional curricula: Students' attitudes. *Medical Education, 3*, 177–180.

Keynan, A., Ben-Zvi Assaraf, O., & Goldman, D. (2014). The repertory grid as a tool for evaluating the development of students' ecological system thinking abilities. *Studies in Educational Evaluation, 41*, 90–105. doi:10.1016/j.stueduc.2013.09.012.

Kinchin, I. M., Hay, D. B., & Adams, A. (2000). How a qualitative approach to concept map analysis can be used to aid learning by illustrating patterns of conceptual development. *Educational Research, 42*(1), 43–57. doi:10.1080/001318800363908.

Knipples, M. C. P. J. (2002). Coping with the abstract and complex nature of genetics in biology education: The yo-yo teaching and learning Strategy. PhD Dissertation, Proefschrift Universiteit Utrecht. Retrieved from http://dspace.library.uu.nl/handle/1874/219

Lin, C. Y., & Hu, R. (2003). Students' understanding of energy flow and matter cycling in the context of the food chain, photosynthesis, and respiration. *Journal of Science Education, 25*(12), 1529–1544. doi:10.1080/0950069032000052045.

Liu, L., & Hmelo-Silver, C. E. (2009). Promoting complex systems learning through the use of conceptual representations in hypermedia. *Journal of Research in Science Teaching, 46*(9), 1023–1040. doi:10.1002/tea.20297.

Maani, K. E., & Maharaj, V. (2004). Links between systems thinking and complex decision making. *System Dynamics Review, 20*(1), 21.

McDermott, T. (2015). Systems thinking. *Modeling and simulation in the systems engineering life cycle* (pp. 273–297). London: Springer.

Narayanan, N. H., & Hegarty, M. (1998). On designing comprehensible interactive hypermedia manuals. *International Journal of Human-Computer Studies, 48*, 267–301.

National Research Council. (2011). *A framework for K-12 science education: Practices, cross-cutting concepts, and core ideas*. Washington, DC: National Academies Press.

NGSS Lead States. (2013). Next generation science standards: For states, by states Washington DC: National Academy Press.

Penner, D. E. (2000). Explaining systems: Investigating middle school students' understanding of emergent phenomena. *Journal of Research in Science Teaching, 37*(8), 784–806.

Raved, L., & Yarden, A. (2014). Developing seventh grade students' systems thinking skills in the context of the human circulatory system. *Frontiers in Public Health, 2*, 60. doi:10.3389/fpubh.2014.00260.

Sabelli, N. H. (2006). Complexity, technology, science, and education. *Journal of the Learning Sciences, 15*, 5–9.

Songer, C. J., & Mintzes, J. J. (1994). Understanding cellular respiration: An analysis of conceptual change in college biology. *Journal of Research in Science Teaching, 31*(6), 621–637. doi:10.1002/tea.3660310605.

Stewart, M. (2012). Joined up thinking? *Evaluating the use of concept-mapping to develop complex system learning, Assessment & Evaluation in Higher Education, 37*(3), 349–368. doi:10.1080/02602938.2010.534764.

Tripto, J., Ben-Zvi – Assaraf, O., & Amit, A. (2013). Mapping what they know: Concept maps as an effective tool for assessing students' systems thinking. *American Journal of Operations Research (AJOR), 3*(1), 245–258. doi:10.4236/ajor.2013.31A022.

Tripto, J., Ben-Zvi Assaraf, O., Snapir, Z., & Amit, M. (2016). The "What is a system" Reflection Interview as a knowledge integration activity for high school students' understanding of complex systems in human biology. International Journal of Science, 1–32.

Verhoeff, R.P. (2003). Towards systems thinking in cell biology education. PhD Dissertation, Utrecht, The Netherlands: CD- b Press.

Verhoeff, R. P., Waarlo, A. J., & Boersma, K. T. (2008). Systems modelling and the development of coherent understanding of cell biology. *International Journal of Science Education, 30*(4), 543–568. doi:10.1080/09500690701237780.

Walton, H. J., & Mathews, M. B. (1989). Essentials of problem based learning. *Medical Education, 23*, 542–558.

Westbrook, S. L., & Marek, E. A. (1992). A cross-age study of student understanding of the concept of homeostasis. *Journal of Research in Science Teaching, 29*(1), 51–61. doi:10.1002/tea.3660290106.

Wilensky, U., & Reisman, K. (2006). Thinking like a wolf, a sheep, or a firefly: Learning biology through constructing and testing computational theories—an embodied modeling approach. *Cognition and Instruction, 24*(2), 171–209. doi:10.1207/s1532690xci2402_1.

Yoon, S. A. (2008). An evolutionary approach to harnessing complex systems thinking in the science and technology classroom. *International Journal of Science Education, 30*(1), 1–32.

Zion, M., & Klein, S. (2015). Conceptual understanding of homeostasis. *International Journal of Biology Education, 4*(1), 1–27.