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Characterising the development of the understanding of human body systems in high-school biology students – a longitudinal study

Zohar Snapir[a], Catherine Eberbach[b], Orit Ben-Zvi-Assaraf[a], Cindy Hmelo-Silver[c] and Jaklin Tripto[a]

[a]Department of Science and Technology Education, Ben-Gurion University of the Negev, Beersheba, Israel; [b]National Science Foundation, Division of Research on Learning in Formal and Informal Settings, Arlington, VA, USA; [c]School of Education, Center for Research on Learning and Technology, Indiana University, Blooming, Indiana, USA

ABSTRACT
Science education today has become increasingly focused on research into complex natural, social and technological systems. In this study, we examined the development of high-school biology students' systems understanding of the human body, in a three-year longitudinal study. The development of the students' system understanding was evaluated using the Components Mechanisms Phenomena (CMP) framework for conceptual representation. We coded and analysed the repertory grid personal constructs of 67 high-school biology students at 4 points throughout the study. Our data analysis builds on the assumption that systems understanding entails a perception of all the system categories, including structures within the system (its Components), specific processes and interactions at the macro and micro levels (Mechanisms), and the Phenomena that present the macro scale of processes and patterns within a system. Our findings suggest that as the learning process progressed, the systems understanding of our students became more advanced, moving forward within each of the major CMP categories. Moreover, there was an increase in the mechanism complexity presented by the students, manifested by more students describing mechanisms at the molecular level. Thus, the 'mechanism' category and the micro level are critical components that enable students to understand system-level phenomena such as homeostasis.

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Introduction

Science education research is becoming increasingly focused on the study of complex systems, based on the notion that understanding complex systems is a necessary part of being a scientifically literate citizen (NGSS, 2013). The perception of complex systems and their function has become central to various disciplines, including the different scientific disciplines, sociology and economics (Yoon, 2008).

CONTACT Orit Ben-Zvi-Assaraf ntorit@bgu.ac.il

This centrality is due in part to the fact that complex systems are a fundamental aspect of many different scientific domains. This is especially true of the biological sciences. For example, the processes that take place within an organism (physiology), the interaction between organism and environment (environmental biology), and interactions among different organisms within and across species (ecology) are all best described in terms of complex systems (Hmelo-Silver, Marathe, & Liu, 2007).

Another factor that contributes to their prominence is the fact that complex systems are prevalent at all scales – from the micro scale of a single cell (such as a fertilised human egg) to macro complex systems such as cities or ecosystems (Yoon et al., 2016). In the field of biology, complex systems are ubiquitous at all levels. For example, complex molecular networks are found within individual cells, connecting signals from the extra-cellular environment to intracellular responses (Chasman, Siahpirani, & Roy, 2016). Complex systems are also found in the physiology of individual organisms, maintaining homeostasis in a variety of different dimensions, like blood sugar and body weight (Rosenbaum & Leibel, 2016). In biological societies, such as social insect colonies (ants for example), interactions between organisms, which are complex systems of their own, form additional complex systems (Greenwald, Segre, & Feinerman, 2015). 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).

As the study of complex systems has grown over the past two decades, and much of scientific inquiry has become involved in working to understand complex systems (Bar-Yam, 1997), the science education curriculum has become increasingly focused on the study of complex systems as well. This is unsurprising considering the nature of the world in which our students live – one increasingly governed by complex systems that are dynamic, self-organising and continually adapting (Jacobson & Wilensky, 2006; Lesh, 2006). The Next Generation Science Standards (NGSS, 2013) highlight the value of engaging in systems thinking, relating structure and function, and engaging in scientific practices such as modelling to address themes that cross-cut the sciences. As a result of this focus on students' comprehension of systems, science education has seen a substantial growth in research into complex systems understanding, as well as into students' abilities to deal with complex natural, social and technological systems (Hmelo-Silver & Azevedo, 2006; Jacobson, 2001).

This focus on complex systems studies has brought with it challenges for both learners and educators (Ben-Zvi Assaraf & Orion, 2005; Hmelo-Silver & Pfeffer, 2004; Plate, 2010). Several studies have shown that understanding the structural and behavioural aspects of complex systems is challenging for science students (Jacobson & Wilensky, 2006), since understanding complex systems does not only require looking at their parts in the context of the whole system, but also at their interactions with other complex systems that surround them (Bar-Yam, 1997). Developing a broad and logical perception of the structures in systems and of the multi-variable web of relationships between them is difficult, because these relationships are not intuitively obvious (Duncan & Reiser, 2007; Jacobson, 2001). Relationships across different levels of complex systems are also often implicit, with subsidiary causality (Hmelo-Silver & Azevedo, 2006; Jacobson, 2001).

It is possible that some of these challenges could be addressed by teaching systems from a broader point of view, one which includes references to the variety of scientific and social aspects that a complex system can incorporate. This novel approach to science education, spearheaded by the Next Generation Science Standards (NGSS, 2013), posits that science education should develop a scientific literacy that allows students to look broadly at – and think intelligently about – topics in science and technology, as well as their social implications (i.e. science, technology, society – STS). According to this approach, science education should include references to socio-scientific issues (SSI), which 'represent real problems, faced by scientists and other citizens, whose solutions remain undetermined and are not problems merely in the context of classroom explorations' (Zeidler & Sadler, 2007, p. 201). Fensham (2012) notes that SSIs can vary widely in complexity, based on the degree of interdisciplinarity and uncertainty they involve, and that different levels of complexity require different approaches on the part of teachers wishing to teach them. While Fensham acknowledges that SSIs rating high on the complexity scale can be daunting topics, to which 'few science teachers are equipped to do justice,' he adds that 'the urgency and responsibility of including key SSI that relate to social and environmental health in school science is so great that they cannot be avoided on these grounds' (p. 15).

One of the core topics taught in the Israeli high-school biology curriculum is the human body. The human body is highly relevant to students, and engaging them in its complexity can therefore promote not only the contextual understanding of the human body, but also a more generalised scientific conception of how complex systems operate. Conceiving the human body as complex system, composed of multiple components at various organisation levels that interact with each other, may also promote broader understanding of biological processes in general (Raved & Yarden, 2014).

The human body is a highly complex system, since each of its subsystems is a complex system on its own. Understanding the systemic nature of the human body is therefore challenging for students (Ben-Zvi Assaraf, Dodick, & Tripto, 2013; Hmelo-Silver & Azevedo, 2006). This paper presents a three-year longitudinal study in which we characterised the long-term development of human body systems understanding amongst high-school biology students. We used the Repertory Grid tool (Kelly, 1955) to gather data about the students' systems understanding, and mapped the gradual development of that understanding using the Components Mechanisms Phenomena (CMP) model proposed by 2nd and 4th authors (Hmelo-Silver, Jordan, Eberbach, & Sinha, 2016). In doing so, we sought to answer the question: Does the students' perception of the human body system change as they move through their three years of biology studies? If so, how?

Theoretical background

What are complex systems?

A complex system functions through the mutual interaction of its various components, which work together to bring about a singular function. The interactions within the system are influenced by feedback loops and they are usually nonlinear (Ladyman, Lambert, & Wiesner, 2013; Richardson, Cilliers, & Lissack, 2001). Understanding complex systems is fundamental to understanding science. But, because they are composed of multiple interconnected levels that interact with one another in dynamic ways, complex systems are very difficult to understand (Hmelo-Silver et al., 2007).

A complex system can be generally described as an entity consisting of a large number of structures, at different levels of organisation (micro and macro), in which various processes occur. With regard to biological systems, 4th author (Hmelo-Silver et al., 2007) defined structures as either microscopic (like cells) or macroscopic (like organs), adding that 'the micro level refers to the level of individual elements of a system, whereas macro refers to the aggregate level' (pp. 308–309). Thus, in the context of the human body, the micro level includes cells and molecules, and the macro level includes tissues, organs and systems. Marbach-Ad and Stavy (2000), who investigated students' explanations of genetic phenomena, also divided these explanations into references to the micro level and the macro level. They found that the micro level included both references to the microscopic/cellular level (i.e. to genes and chromosomes) and to the submicroscopic/molecular level (e.g. DNA, genetic material). In the context of genetics, the macro level included references to genetic 'traits' (e.g. eye colour).

Another key aspect of a complex system is its dynamism and self-organisation. Hmelo-Silver, Holton, and Kolodner (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 & Azevedo, 2006). A nonlinear complex dynamic system is made up of numerous individual agents (or elements) whose independent interactions result in emergent and complex behaviour not exhibited at the level of the individual elements (Chi, 2005). Natural science literature refers to this kind of phenomenon as self-organisation, in which macroscopic order emerges spontaneously without plan, algorithm or control structure. The manner in which complex systems communicate, respond to perturbations, and self-organise is understood by studying the dynamic processes through which they evolve over time, but studies have shown that students still lack a basic understanding of central complex systems ideas like self-organisation and evolution by natural selection (Yoon, 2008). As Kitano (2002) has noted, to understand (biological) systems we must

> shift our notion of 'what to look for' in biology from a mere examination of the system's components, to an understanding of its structure and dynamics. This is due to the fact that a system is not just an assembly of genes and proteins; its properties cannot be fully understood merely by drawing diagrams of their interconnections. (p. 1662)

Even though the research on complex systems is diverse, it shares some basic common assumptions about complex systems. Goldstone and Wilensky (2008) summarised these as follows: (a) many natural systems operate at multiple distinct levels of organisation; (b) such systems involve 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-organised 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 (p. 467).

The human body as a complex system

The literature on systems understanding provides various definitions of the term 'system.' Broad definitions emphasise the significance of the interactions between the system components, such as – 'A system is an entity that maintains its existence and functions as a whole through the interaction of its parts.' This group of interacting, interrelated or interdependent parts that form a complex and unified whole also has a specific purpose, which is the outcome of the interactions between the system's components (Bar-Yam, 1997; Ben-Zvi Assaraf & Orion, 2005).

The human body is a complex biological system composed of multiple subsystems working in coordination. Its function can be viewed as a set of structures that interact with each other to create a chain of events, operating the entire system. The interactions between components at various organisation levels permit the whole human body system to act as more than the sum of its parts, and to maintain stability (Ben-Zvi Assaraf et al., 2013).

The subsystems of the human body are also complex. The human cardiovascular system, for example, is composed of many different kinds of cells (representing a micro level of the system), which form the tissues of the organs (at the macro level) that work together as a system. The blood is composed of several different kinds of cells suspended in plasma. All of these are components of the system, representing the various levels of its hierarchy. The system's functions include cells and plasma transporting oxygen, carbon dioxide and nutrients, fighting infections, and clotting, all representing matter transport both within the system and to other body systems (i.e. the system's dynamism). The blood is circulated in the body through different blood vessels – arteries, veins and capillaries (each of which has a different structure that serves its function), and the heart pumps the blood by creating pressure differentials that drive movement through the vessels (Marieb & Hoehn, 2012).

Adding to the intrinsic complexity of the cardiovascular system is the fact that it is in constant interaction with other systems in the body. These interactions with other body systems are what allows the body to maintain homeostasis. What happens in the body during physical exercise, for example, highlights the interaction between the circulatory and the respiratory systems, which is integrated by the nervous system. At the onset of physical exercise, elevated carbon dioxide and H^+ levels serve as signals at the micro level. These signals are processed in the nervous system, which in turn influences the pacemaker in the heart at the macro level, so that the heart beats faster. Blood flow to the working muscles is also increased (Randall, Burggren, French, & Eckert, 2002). At the same time, the respiratory system is also influenced by the same signals processed in the nervous system, so that the respiration rate increases. Breathing occurs constantly throughout life, enabling the exchange of oxygen and carbon dioxide in the lungs' alveoli, regulating their levels in the body. The respiratory movements are driven by neural circuits in the central nervous system (i.e. the brainstem and the spinal cord). Breathing is under precise control, so gas exchange is matched to the metabolic demand in the body tissues. This is true during resting breathing, and also during times of increased metabolism and demand for oxygen such as physical exercise (Bell, 2006; Smith, Abdala, Borgmann, Rybak, & Paton, 2013).

As this example shows, exercise promotes a complex chain of integrated changes that enables the delivery of sufficient oxygen and nutrients to the working muscle. As a result of this integrated activity, during physical exercise more oxygen is delivered to the mitochondria in the cells, and cellular respiration provides enough ATP, through the process of cellular respiration, to carry on the tissue demand. This example serves as a glimpse of the incredible complexity and interconnectivity that enables the human body to maintain homeostasis, which is crucial for its ability to remain alive and functional.

The importance of understanding the complexity of the human body

Understanding complex systems can promote knowledge transfer and enable cross-fertilisation between disciplines (Goldstone & Wilensky, 2008). There are two large-scale approaches commonly used in promoting and analysing systems understanding. The first, which was explicated by – among others – Yoon (2008), Wilensky and Reisman (2006) and Jacobson and Wilensky (2006), is a domain general approach in which students must first understand the attributes that are common to different systems and then apply them to a specific context. The second approach is domain specific, in which students analyse the behaviour of a particular system in the context of solving a problem. In this approach, system understanding skills act as a cognitive tool that permits a student to analyse different characteristics of a system (Ben-Zvi Assaraf & Orion, 2005; Duncan & Reiser, 2007).

The Structure, Behaviour, and Function (SBF) Model of systems understanding posited by Liu and Hmelo-Silver (2009) and Goel, Rugaber, and Vattam (2009) expresses this domain specific approach. The constituents of the SBF model are: Structures – the physical structures in the system (like the lungs in the respiratory system, the alveoli in the lungs), Behaviour – the mechanism that allows the structures to carry out their function (like the chest moving to allow for gas exchange, the electrical pulses moving through the nerve cells), Function – the output of the system (e.g. the respiratory system transports oxygen to the organs) (Hmelo-Silver et al., 2000).

Though the SBF is widely used to analyse systems understanding (Goel et al., 1996; Hmelo-Silver et al., 2007; Hmelo-Silver & Pfeffer, 2004), it is not without its challenges. The distinction between behaviour and function can be confusing, as it depends on context. For example, in an aquarium system, fish respiration is a behaviour that releases waste products, but when analysing the fish as a system, respiration can be viewed as a function and gas exchange and various cellular reactions as behaviours (Hmelo-Silver & Pfeffer, 2004). Thus, 2nd and 4th authors (Hmelo-Silver et al., 2016), modified the Structure Behavior Function (SBF) model, creating an alternative conceptual framework called CMP. This framework provides a representation of all the system's attributes, including the structures (Components) within the system, the specific processes and interactions (Mechanisms) that occur between them, and the macro scale of processes and patterns within a system – the Phenomena.

With regard to the human body, using the CMP conceptual framework can also be a useful scaffolding tool. For example, it can help students understand key concepts like negative feedback – an increase in a system variable that prompts action in the system which leads to a decrease in that same variable. Negative feedback is fundamental to maintaining homeostasis in systems like the human body. The body's blood sugar level, for example, is maintained at a homeostatic level of about 70–110 mg glucose/dL. This occurs through negative feedback: following the digestion of carbohydrates, glucose is absorbed from the small intestine (i.e. the digestive system) into the blood. The elevated blood glucose level serves as a signal, promoting the secretion of insulin from the pancreatic beta cells. Insulin promotes the absorption of glucose from the blood into the body cells, thus decreasing the blood glucose level. To understand the phenomenon of negative feedback, one must recognise the components (e.g. small intestine, carbohydrates, glucose and insulin), and the mechanisms (digestion, secretion and absorption) involved. Thus, the systemic nature of the human body, and that of other biological systems, maps well to CMP.

The principle of negative feedback also applies to the activity of other hormones in the body, to maintaining regular body temperature, and even to 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. This is also true for other common principles in complex systems, so that learning about such complex systems exposes students to new frameworks of explanations, and to methodologies that are important in various environments (Jacobson & Wilensky, 2006).

To understand complex systems, including the human body, one must be able to recognise not only the structures in the system, but also the mechanisms of the interactions between them, and the outcomes of these interactions (Bechtel & Abrahamsen, 2005; Goldstone & Wilensky, 2008). What makes the interactions between the system's components hard to understand is that they constantly change, as they are influenced by changes within the system and in its surrounding environment (Hmelo-Silver et al., 2007). Experts' understanding of complex systems is characterised by being able to reason effectively about the functional roles and behavioural mechanisms that the structural elements in the system play (Hmelo-Silver et al., 2007). An understanding of the system's behaviours and functions should therefore correlate to an elaborate network of ideas representing key phenomena and their interrelationship, representing a deep understanding of a complex system. Experts have also been shown to be capable of explaining the perceptually salient aspects of the system (e.g. external respiration) in terms of phenomena that are less perceptually salient (e.g. central nervous system control, cellular level phenomena) (Liu & Hmelo-Silver, 2009). Thus, understanding the mechanisms – the interactions between the system's components – is a characteristic of an expert's mental model of a system, and has been found to be lacking in novices (Hmelo-Silver & Pfeffer, 2004).

To overcome the difficulties of understanding the systemic nature of the human body, a new biology curriculum called 'Human Biology: Emphasising the Role of Homeostasis' was introduced into the Israeli high-school education system in 2003. It was thought that unifying human biology around homeostasis would provide students with a more complete picture of the human body, allowing them to integrate its multiple components. Exploring homeostasis should also enable a deeper understanding of the complexity of the human body, as homeostasis explains both the interactions between the body and its environment, and the processes that occur on different organisational levels within the system (Tripto, Ben-Zvi Assaraf, & Amit, 2013).

The students studied the standard national curriculum for biology majors. The 10th and 11th grade curriculum included three mandatory chapters that represent three levels of organisation: the micro level of the cell, and the macro levels of (a) organism and (b) society and eco system. In 10th grade the curriculum includes 3–4 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 communication 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 5–6 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 organisms. 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 reviewing the material on all the human body systems, emphasising 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 population studied nutrition, evolution and microorganisms.

Methodology

Methodological framework for exploring systems understanding – CMP

The assessment of systems understanding and its development should be based on a conceptual framework that makes it possible to identify the participants' level of systems understanding (Keynan, Ben-Zvi Assaraf, & Goldman, 2014). In this study, we used the CMP framework (Hmelo-Silver et al., 2016) to evaluate the development of human body systems understanding in high-school students. Hmelo-Silver et al. (2016) described the CMP framework as a conceptual representation designed to support student learning about ecosystems by connecting evidence to models in order to construct explanations. In

Table 1. CMP model categories.

	Category	Definition
Components	C1	Location of component
	C2	Description of property or properties of component(s)
	C3	Description of component's feature or property in relation to mechanism(s)
Mechanisms	M1	Location of a process or a description of some interaction or activity between components and processes or between processes
	M2	M1 category and some description or identification of materials taking part f a specific mechanism
	M3	M2 category and (a) *how* processes use components; or (b) the sequence of the process
Phenomena	P1	Definition of problem context broadly speaking. The overall behaviour or property of the system that results from a certain mechanism or a process
	P2	Definition of problem context broadly speaking. The overall behaviour or property of the system that results from many interactions
	P3	P2 category, and some description of what materials are a part of the mechanism contributing to the phenomena, or how the phenomena are achieved

our study we adapted and expanded this model by further dividing each of the three CMP dimensions into multiple, increasingly complex levels (Table 1). The CMP framework builds on the assumption that systems understanding entails a perception of all the system's categories, including structures (components) within the system, specific processes and interactions (mechanisms), and phenomena that present the macro scale of processes and patterns within a system.

This study examined high-school students' understanding of the body's systemic nature throughout the three years of their high-school biology education. To do this, we characterised the students' perceptions according to their place within the CMP framework at several stages during the study. Using the detailed CMP framework allowed us to notice subtle changes in the students' systems perception, thus providing a picture of the development of their human body system understanding. In this paper, we will present the changes that occurred in the students' perception of the human body system over the three years of the study.

Research setting

The study was conducted in 4 stages, with 67 high-school students who chose to study biology as one of their high-school majors. We followed these students over the three years of their high-school biology studies. Data were collected at four stages of the learning process: the beginning of 10th grade (stage 1), the end of 10th grade (stage 2), the end of 11th grade (stage 3) and the end of 12th grade (stage 4).

Research population

The research population consisted of high-school biology students ($n = 67$). All of the students studied the same curriculum, since Israel has a centralised education system. The biology syllabus for this age group centres around a curriculum called 'Human Biology: Emphasizing the Role of Homeostasis.' The students were gathered from two schools in two different school districts, which were chosen for their willingness to cooperate with the researchers. We took care to ensure that urban and rural schools, boys and girls, should all be represented in similar proportions. All of the students in the study had chosen biology as their major, and had learned about seven human body systems overall (cardiovascular, nervous, immune, endocrine, respiratory, digestive and urinary), with an emphasis on human body homeostasis.

Research approach

In this study we collected extensive, in-depth data from a large number of individual participants. Our strategy was first to 'zoom in' on the individual students, gathering as much information about each as possible, and then to 'zoom back out' – generalising from this information to identify their system language and comparing their products (repertory grids) in four stages of the learning process. This methodology can provide important insights and knowledge – in this case about how students perceive the complexity of the human body as a system.

Research tools and their analysis

The repertory grid technique

The data that we analysed using the CMP framework was obtained through the Repertory Grid Technique, which is based on Kelly's Personal Constructs Psychology. Kelly's personal construct psychology states that the world is 'perceived' by a person in terms of the 'meaning' that person applies to it, and that people develop their personality, attitudes, concepts and perception of reality upon systems of 'personal constructs.' Kelly developed a methodology for exploring these systems of personal constructs using repertory grids. This technique is a form of highly structured interview, which assigns relationships to personal constructs and given objects of discourse (Kelly, 1955).

Although originally developed for the field of psychology, the repertory grid technique is generally acknowledged as a reliable way to represent how a person thinks (Ben-Zvi Assaraf & Orion, 2010; Bencze, Bowen, & Alsop, 2006; Bezzi, 1999; Rozenszajn & Yarden, 2015). As such, the repertory grid technique has been used for qualitative, interpretive research (Edwards, McDonald, & Young, 2009), including education research. In relation to system understanding, Latta and Swigger (1992) argue that the repertory grid can identify a subject's conceptual models, and thus identify the aspects of a system that are most commonly misunderstood.

Kelly's repertory grid technique is used in educational research to explore learners' perceptions through the personal constructs they create. It has been used to provide insight about subjects' capacity to identify dynamic relationships within systems, to make generalisations and to identify hidden dimensions of systems. Repertory grids have also been used to track systems understanding of earth systems (Ben-Zvi Assaraf & Orion, 2010), of the human body system (Ben-Zvi Assaraf et al., 2013), and of ecological systems (Keynan et al., 2014). In the current study we used the Repertory Grid as a tool for evaluating the development of systems understanding in the context of the human body, as reflected in the study participants' position within the CMP framework.

The building blocks of the repertory grids are *elements* (the topics of study, within the domain of the investigation), *constructs* (the participants' ideas about these elements) and *ratings* (relations among elements and constructs as viewed by the participants). Elements can be obtained in two ways. In one, the researcher supplies the elements to the participants, who focus only on creating the constructs. The second approach is to ask the participants to provide the elements themselves (Latta & Swigger, 1992). In this study, the elements were 15 terms related to the human body system, which were provided by the researchers. The elements were: enzymes, cellular respiration, diffusion, metabolism, surface area to volume ratio, cell membrane, internal environment, homeostasis, cell, blood circulation, hormones, cardiovascular system, respiratory system, digestive system and endocrine system. These elements, representing components at both the micro and the macro levels of the human body, as well as mechanisms and phenomena, were chosen after consultation with 20 high-school biology teachers, who were asked to list the most important human body system concepts students should know. The reasoning for using elements provided by the researchers was to provide a shared basis of comparison for exploring the development of the students' understanding of the human body system (Keynan et al., 2014). Using this single list of elements made it possible to: (a) compare the perception of these elements amongst multiple students; (b) compare the change in how individual students perceived and used each element over time; (c) determine how the concepts that the biology teachers deemed most important were being employed by the students in their constructs.

Constructs represent the participants' interpretations of the elements and the relationships between them. There are different processes to elicit constructs. This study employed the most common method – the triadic elicitation process, in which the participants are asked to compare three elements and describe in what ways two are alike and differ from the third (Edwards et al., 2009; Hunter & Beck, 2000). The students were asked to randomly choose three elements and explain to the interviewer some aspects in which two of the elements are similar and the third is different (see examples below). This triad game process was repeated eight times for each participant. Throughout all eight cycles, the students were interviewed about the answers they provided – the interviewer asked questions to clarify the differences and similarities between the elements as these students perceived them. Thus, the constructs were elicited by the researchers, during the interview, from the students' explanations of similarities and differences. This process produced eight constructs for each student, representing his/her own mental model.

A construct, according to Kelly, is a complex image or idea, and understanding the nature of a construct requires knowledge of both the similarities and the differences between a triad of elements. The word or phrase used to describe the similarity and the difference is determined by the research participant, who uses it to create a bipolar description relating to one component of the investigation (Hunter & Beck, 2000). For example, a student given the three terms 'digestive system,' 'respiratory system' and 'diffusion' might say 'digestive system and respiratory system are similar because they are both systems, and diffusion is different because it is matter transfer.' From this sentence, the researcher would deduce the construct 'a system/not a system.'

In the second stage of the interview, the students were given a grid with 15 columns and 8 lines. In the columns were written the 15 system-related terms, and each line contained one of the 8 bipolar constructs the students had created earlier. The students were then asked to rate, on a scale of 1–5, the strength of relation between each element and each of their constructs. For example, for the construct a system/not a system, the students could indicate a connection of 5 to the digestive system, but a connection of 1 for homeostasis. The grid presented in Figure 1 is an exemplar repertory grid generated by Keren, one of the study participants, during stage one of her learning process. The vertical list on the bottom right shows the elements (related to the human body system, provided by the researchers). The horizontal statements on either side of the grid are the (bipolar) constructs Keren created from the element triads. The central grid numbers represent the ratings of connections between the elements and constructs she made.

The elements, the constructs created by each student, and their ratings for connections between elements and constructs, were mapped on the grid using RepGrid&RepNet software. Building on the ratings for the strength of relation between each element and the constructs, the software calculates correlations between the elements and between the constructs, presenting them as trees of relations – a tree of relations for the elements (lower right in Figure 1) and a tree of relations for the constructs (upper right in Figure 1).

The more similar the ratings are for two constructs or for two elements, the higher they are correlated by the programme. For example, in the grid presented in Figure 1, the

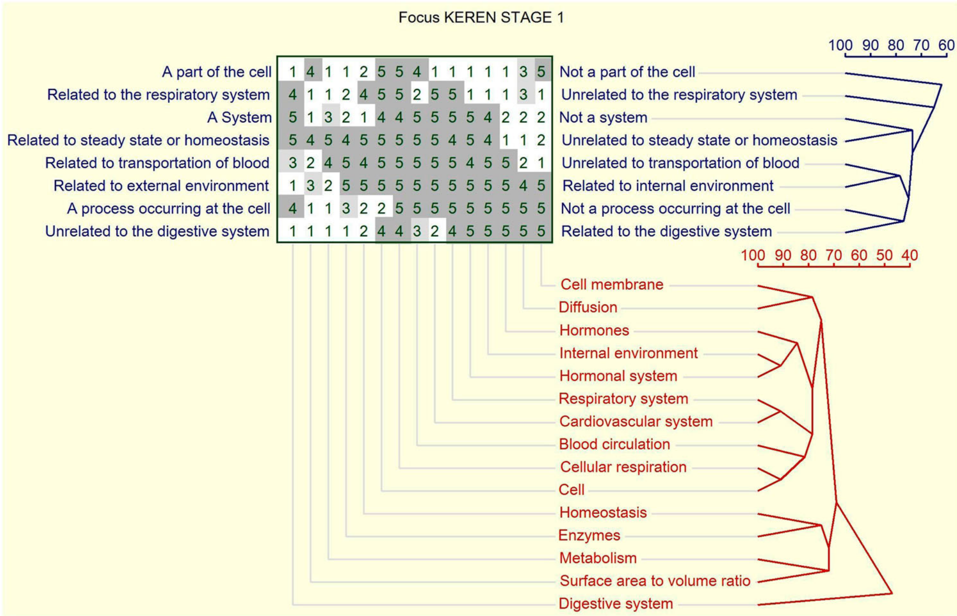

Figure 1. An exemplar repertory grid of the first stage of the study.

elements 'cellular respiration' and 'cell' are highly related, as the student rated their relations to the constructs at almost the same value for all constructs (see the central grid numbers). Thus, the programme calculated the correlations between this pair of elements at about 90%. Such a correlation indicates a high cognitive link between these elements in the student's mind (Jankowicz, 2004). On the other hand, the elements 'metabolism' and 'surface area to volume ratio' are correlated at only 70% by the programme, since the ratings for their relations with the constructs are different in most cases.

A high level of connection between particular elements or constructs allows us to identify cognitive links between those elements or constructs, thus presenting an image of the participant's personal mental model – a precise statement of the way in which the participant thinks about or gives meaning to the topic in question (Jankowicz, 2004).

Analysis of repertory grid data

Prediger and Lengnink (2003) grounded the repertory grid technique as a method within qualitative research by positioning it between two methodological extremes. One extreme is the completely standardised questionnaire offering multiple choice answers only, which does not give participants the opportunity to express their thoughts in their own language, and thus produces reductive results that sometimes cannot adequately explore their implicit theories. The other extreme is the free interview without any structured guidelines. This kind of knowledge elicitation is not reductive, its results are not easily comparable and the processes of interpretative analysis are, in some cases, too sophisticated for evaluating learning processes. Kelly (1955) developed the repertory grid technique as a highly structured interview, formalising the interactions of interviewer and interviewee and putting into relations personal constructs and given objects of discourse (the repertory grid elements). Repertory grids provide a structured method of data collection that simplifies the analysis of the interview, but without imposing the language in which the participants express their implicit theories and personal constructs.

Our repertory grid data was analysed in three stages. The first was eliciting the constructs from the students' explanations about the similarities and differences among the three elements in each triad game (see detailed explanation above). In the second stage of analysis, the elicited constructs were grouped into primary categories according to the CMP framework, namely components (C), mechanisms (M) and phenomena (P) (Hmelo-Silver et al., 2016). Then subcategories (see Table 1) were developed using qualitative data analysis (Creswell, 2007). This third stage was an inductive process, which included several steps. First, we adapted the CMP conceptual framework, proposed by Hmelo-Silver et al. (2016) to the context of the human body. For the constructs created by the study participants to be fully reflected by the CMP conceptual framework, we then used the data (constructs) gathered by the repertory grid technique at the first stage of the study to define the CMP subcategories (Table 1). The subcategories then went through several iterations of adjustment and refinement. The subcategories under each major category were divided by level of complexity, with an intrinsic hierarchy. For example, constructs falling under the mechanism category were divided into three levels: first, constructs referring mainly to the location of a process or describing some interaction or activity between components and processes were categorised under the category 'M1' ('Related/unrelated to blood circulation *in* the cardiovascular system'). Next, constructs presenting *not only* the mechanism's location but also referring to the materials taking part in it were categorised into the mechanism category 'M2' ('Related/unrelated to blood circulation *providing materials to cells*'). This constructs that *in addition to the previous criteria,* also contained a description of how the process is performed or its sequence were categorised into the category 'M3' ('Related/unrelated to transportation of oxygen to cells *by diffusion*'). Upon completion of this process, we used the revised CMP subcategories to further analyse the data.

Upon completion of this process, we used the revised CMP subcategories to further analyse the data. The following is a brief description of the nine CMP subcategories.

Components

The most basic feature of each system, including that of the human body, is its structural components. This is presented in its simplest form at the *C1* category, which refers to the *location* of body system components (e.g. *Related/unrelated to enzymes* ***in*** *the digestive system*).

The *C2* category refers to a description of component *properties*. For example, a student's explanation of the connection between the elements 'enzymes,' 'diffusion' and 'cellular respiration' as 'Enzymes are different from diffusion and cellular respiration, since they are proteins' refers to the enzymes' property of 'being proteins.' A construct formed from this explanation is *Related/unrelated to enzymes* ***as*** *proteins*. The *C3* category includes descriptions of components *in relation to mechanisms* (*Related/unrelated to increase of surface area to volume ratio* 'The endocrine system is the exception; the larger the surface area to volume ratio is, the faster and more efficiently enzymes work).' This category bridges the component and the mechanism categories.

Mechanisms

Understanding complex systems like the human body requires the ability to recognise the processes occurring within them that enable them to function (e.g. osmosis, oxygen transportation and degradation). In the CMP framework, constructs referring to processes are included in the mechanism categories. The *M1* category refers to the *location* of processes or descriptions of *interactions between components or processes*, the most basic conception of processes within the system (e.g. *Related/unrelated to blood circulation in the cardiovascular system*, *Related/unrelated to diffusion in blood circulation*). Systems understanding requires the identification not just of mechanisms, but also of the molecules taking part in them. This is presented in the *M2* category, which addresses the micro level of *molecular processes* in the system. Students presenting this level mention processes while using molecules to build relationships within the system (e.g. *Related/unrelated to blood circulation transporting materials for cellular respiration* 'Homeostasis is the exception; blood circulation provides oxygen for cellular respiration).'

Thorough systems understanding also requires a comprehension of how the processes occurring in a system use the components in that system. The *M3* category represents such sophisticated systems understanding. This category refers not only to the materials (at the micro level) taking part in a process, but also to *how processes use the components* in the system, or to the sequence occurring in a process. For example: *Related/unrelated to effect of hormone secretion on target organs* 'Metabolism is the exception. The endocrine system secretes hormones to the blood stream, and these hormones signal the target organs to secrete hormones or other materials.'

Phenomena

To understand the complexity of the human body, as well as that of other complex systems, one must be able to recognise the outcomes of the various mechanisms operating in the system, leading into the general patterns affecting the behaviour of the system as a whole. These outcomes of the system's mechanisms are represented by the phenomena categories in the CMP framework.

The first phenomena category, *P1*, refers to an overall behaviour or property of a system that is *the result of an interaction* within that system. Students presenting this level demonstrate some recognition of the patterns characterising a system's behaviour (e.g. *Related/unrelated to maintaining homeostasis by providing oxygen by the respiratory system* 'The respiratory system needs to work, supply oxygen to the body to maintain homeostasis in the human body').

Higher systems understanding requires the ability to recognise that phenomena are not achieved by a single interaction within the system, but due to a *network of interactions* leading to the system's overall behaviour. The *P2* category represents this level of systems understanding (*Related/unrelated to homeostasis maintaining a stable internal environment*).

The *P3* category refers to the ability to *integrate the different processes* that bring about the phenomena in the system, including the sequence of events and the materials/molecules participating in the various processes. For example: *Related/unrelated to* *maintaining homeostasis and transportation of materials in the cardiovascular system,* 'The endocrine system is the exception. The cardiovascular system transports food matter and gasses into the cells and enables their performance of their required activities, thus maintaining homeostasis – internal environment.' In this example, the materials 'food' and 'gasses' (molecules) are transferred (a process) via the cardiovascular system to the cells, enabling the phenomenon of homeostasis.

Table 2 provides additional examples of constructs in the various CMP subcategories.

In order to investigate the influence of studying high-school biology on the development of the students' system understanding of the human body, the distribution of the number of students who demonstrated constructs in each of the nine CMP subcategories was calculated, for each of the study's stages (see Figure 2 in the results section). For validity purposes, the researchers worked separately on analysing the repertory grid data and dividing it into the CMP subcategories, and the results were compared and discussed until agreement was reached. Finally, the unit of analysis was the grid constructed by the RepGrid&RepNet software (see Figure 1 for exemplar grid) for each of the 67 participating students.

It is important to emphasise that in the context of repertory grids in educational research, bipolarity can refer to one of two situations. It can be used to describe objects using characteristics that are bipolar by nature, like *a system/not a system*, *a part of blood circulation/not a part of blood circulation*. But it can also refer to characteristics that are not bipolar by nature, like *related/unrelated to enzymes in the internal environment, related/unrelated to cells*. The strength stated by the participant would then refer to how much this characteristic is or is not expressed. In both situations, the constructs reflect the participants' views and understandings, allowing the researchers to identify what the participants mean without putting words in their mouths (Jankowicz, 2004). The aim of the grid analysis was to identify significant relations among the elements and constructs, as reflected in the trees of relations created by the software. Correlations of 80% and above are considered significant (Kelly, 1969).

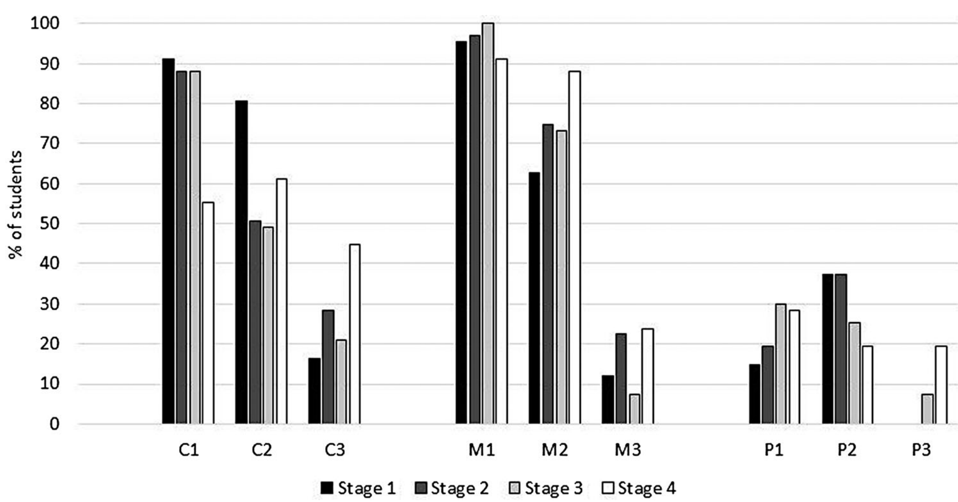

Figure 2. Percentage of students ($N = 67$) presenting each CMP subcategory at each stage of the study.

Table 2. Examples of constructs in the various CMP subcategories.

	Category	Definition	Examples of constructs	Examples of students responses
Components	C1	Location of component	Related/unrelated to enzymes in the internal environment	'Diffusion is the exception; there are enzymes in the internal environment.'
			Related/unrelated to enzymes in the digestive system	'The cardiovascular system is the exception; there are enzymes in the digestive system.'
			A part/not a part of the cell	'Enzymes are the exception, the cell membrane is a part of the cell.'
			A part/ not a part of the cardiovascular system	'Internal environment is the exception; there are cells in the cardiovascular system.'
	C2	Description of property or properties of component(s).	A system/not a system	'The internal environment is different from the respiratory system and the digestive system as it not a system.'
			A process/not a process	'Cellular respiration is different from cells and enzymes, as cellular respiration is a process.'
			Related/unrelated to enzymes as proteins	'Enzymes are different from diffusion and cellular respiration, as they are proteins.'
			Related/unrelated to the internal environment being composed of cells	'Enzymes are the exception; the internal environment is composed of cells.'
	C3	Description of component's feature or property in relation to mechanism(s).	Related/unrelated to increased surface area to volume ratio influencing enzymatic activity	'The endocrine system is the exception; the larger the surface area to volume ratio is, the faster and more efficiently enzymes work.'
			Related/unrelated to increased surface area to volume ratio influencing diffusion	'Cellular respiration is the exception; when the surface area to volume ratio is large, there is more surface area through which diffusion occurs'
			Related/unrelated to increased surface area influencing materials absorption in the blood	'The endocrine system is the exception of blood circulation and surface area to volume ratio, as when the ratio is larger more substances are absorbed to the blood'
			Related/unrelated to increased surface area to volume ratio in the digestive system influencing digestion	Blood circulation is the exception; the increased surface area to volume ratio in the digestive system enables efficient food digestion.
Mechanisms	M1	Location of a process or a description of some interaction or activity between components and processes or between processes.	Related/unrelated to metabolism in cells	'The digestive system is the exception; there is metabolism in cells.'
			Related/unrelated to blood circulation through the respiratory system	'Cell membrane is the exception; blood circulation flows through the respiratory system.'
			Related/unrelated to diffusion through the cell membrane	'The endocrine system is the exception; diffusion in cells occurs through the cell membrane.'

(*Continued*)

Table 2. Continued.

	Category	Definition	Examples of constructs	Examples of students responses
			Related/unrelated to diffusion in cellular respiration	'Enzymes are the exception; there is diffusion during cellular respiration.'
	M2	M1 category and some description or identification of materials taking part of a specific mechanism.	Related/unrelated to transportation of oxygen to cells	'Metabolism is the exception; the oxygen for cellular respiration reaches the cells through the respiratory system.'
			Related/unrelated to hormones transportation in the cardiovascular system	'Diffusion is the exception; the endocrine system transports hormones through the cardiovascular system.'
			Related/unrelated to diffusion of materials in the cardiovascular system	'The digestive system is the exception of cardiovascular system and diffusion, as diffusion of materials from the capillaries to the cells takes place in the cardiovascular system.'
			Related/unrelated to diffusion of materials through cell membrane	'Enzymes are the exception; cell membrane is highly related to the process of diffusion, as materials pass through the cell membrane.'
	M3	M2 category and (a) *how* processes use components; or (b) the sequence of process.	Related/unrelated to transportation of molecules to cells for cellular respiration by the cardiovascular system	'The digestive system is the exception; the cardiovascular system transports glucose and oxygen to the cells to maintain cellular respiration.'
			Related/unrelated to oxygen and carbon dioxide circulation in the body	'Enzymes are the exception; The lungs in the respiratory system intake oxygen and transfer it in the blood until it reaches all the cells. Cellular respiration uses oxygen and produces carbon dioxide, exhaled from the lungs.'
			Related/unrelated to absorption of molecules from the digestive system to the blood circulation	'Cell membrane is the exception of the digestive system and blood circulation; after the food is digested, the molecules of the various food groups are absorbed to the blood.'
			Related/unrelated to diffusion of nutritions through the cell membrane	'Internal environment is the exception; the nutritional materials enter the cell and pass the cell membrane by means of diffusion.'
Phenomena	P1	Definition of problem context broadly speaking. The overall behaviour or property of the system that results from certain mechanism or a process.	Related/not related to cellular respiration maintaining homeostasis	'Blood circulation is the exception; cellular respiration enables maintaining of homeostasis.'
			Related/unrelated to blood circulation assisting in maintaining homeostasis	'Cell membrane is the exception; blood circulation assists in maintaining body homeostasis.'
			Related/unrelated to energy production in cellular respiration	'Cellular respiration is different from internal environment and diffusion, as cellular respiration occurs in order to produce energy.'

(*Continued*)

Table 2. Continued.

Category	Definition	Examples of constructs	Examples of students responses
		Related/unrelated to diffusion maintaining the cell internal environment	'Cellular respiration is the exception; diffusion occurs in order to maintain the cell internal environment.'
P2	Definition of problem context broadly speaking. The overall behaviour or property of the system that results from many interactions.	Related/unrelated to homeostasis maintaining a stable internal environment	'Surface area to volume ratio is the exception; homeostasis maintains a stable internal environment in the body.'
		Related/unrelated to homeostasis maintaining body temperature	'Homeostasis is different from cells and cell membrane, as it is an activity that maintains body temperature.'
		An activity done in the body to gain stability/not an activity done in the body to gain stability	'Surface area to volume ratio is the exception of homeostasis and diffusion, which are both activities done in the body to gain stability.'
		Related/unrelated to the ability to maintain steady state	'Homeostasis is the exception of the digestive system and the respiratory system, as homeostasis is the ability of the organism to maintain steady state.'
P3	P2 category, and some description of *what* materials are a part of the mechanism contributing to the phenomena, or *how* the phenomena are achieved.	Related/unrelated to homeostasis occurring through feedback mechanisms	'Homeostasis is different from cells and cell membrane, as homeostasis occurs through feedback mechanisms.'
		Related/unrelated to the cardiovascular system maintaining homeostasis by changing blood transportation	'Cellular respiration is the exception; the cardiovascular system maintains homeostasis in the human body. For example, if it is cold, the cardiovascular system transports blood to the heart instead of the fingers.'
		Related/unrelated to cellular respiration producing ATP/energy	'Hormones are the exception; cells perform the process of cellular respiration, a process that produces ATP – energy available for the cell.'
		Related/unrelated to cellular respiration producing ATP/energy required for cell existence	'Metabolism is the exception. Thanks to the respiratory system we breathe and the body receives its energy required to function. Thanks to the oxygen received, the cells perform cellular respiration in the mitochondrion, where ATP is produced, thanks to which energy is produced, enabling the cells existence and the body to function in the best possible way.'

Results

In this section we offer an overall view of the data from all the students in the population, which paints a general picture of the changes in perception that they underwent as a group and shows the development of their human body system understanding throughout their three years of high-school biology education.

Changes in CMP category distribution

To answer our research question, 'Does the students' perception of the human body system change as they move through their three years of biology studies? If so, how?' we followed the changes in the CMP framework category distribution presented by the students over the three years of the study. To do this, we counted the number of students who created constructs in each CMP subcategory at each stage of the study, and calculated their percentage out of the whole study population. The four columns for each of the CMP subcategories in Figure 2 represent the four stages of the study (in which each participant created another repertory grid). Thus, for example, the figure shows that 91% of the students created constructs falling under the C1 subcategory at the first stage of the study, and only 55% did so at the fourth stage. The overall results are shown in Figure 2, in which the CMP framework subcategories are presented in ascending order of complexity.

(1) Components

The Israeli high-school biology curriculum emphasises the human body's systemic nature, focusing on several body systems (e.g. the digestive, cardiovascular and endocrine systems). These systems are taught at all levels – from the micro level of molecules and cells to the macro levels of organs and systems, including their components and the processes occurring within each, culminating in a view of the overall behaviour of the system and the human body as a whole.

The most basic feature of each system is its structural components. Indeed, in the first three stages of the study, over 90% of the students presented constructs in the C1 category (Figure 2), referring to the location of body system components (e.g. *related/unrelated to enzymes in the digestive system*). On the other hand, in the last stage of the study, there was a significant decrease in the number of students presenting constructs in the C1 category ($\chi^2(3, N = 67) = 37.03$, $p < .0001$). Only 55% of the students presented constructs in this category at the end of the study.

Constructs in the C2 category include a description of component properties. For example, a student's explanation of the connection between the elements 'enzymes,' 'diffusion' and 'cellular respiration' as 'Enzymes are different from diffusion and cellular respiration, since they are proteins' refers to the enzymes' property of 'being proteins.' The construct formed from this explanation was *related/unrelated to enzymes as proteins*. At the beginning of the learning process, 81% of the students presented such constructs. At this stage, two constructs were predominant: 'a system/not a system' and 'a process/not a process' (e.g. 'The internal environment is different from the respiratory system and the digestive system because it is not a system'). These two constructs are quite simple and do not require deep scientific systems understanding. At the later stages of the study, as the students' level of systems understanding developed, significantly fewer students presented such constructs ($\chi^2(3, N = 67) = 17.54$, $p = .0005$).

The C3 category includes constructs describing components in relation to mechanisms (e.g. *related/unrelated to increase of surface area to volume ratio* 'The endocrine system is the exception; the larger the surface area to volume ratio is, the faster and more efficiently enzymes work).' This category bridges the component and the mechanism categories. There was a significant rise ($\chi^2(3, N = 67) = 15.61$, $p = .0014$) in the number of students presenting constructs in this category from the beginning of the study to its end. The number of students presenting constructs in the C3 category rose from 16% at the first stage to 28% at the second stage. However, between the second and third stage of the study, the number of students presenting such constructs decreased (from 28% to 21%). It should be noted that the curriculum at this stage of the learning process (the 11th grade) was focused on molecular processes in the cell (e.g. mitosis, osmosis and translation), and ecology (e.g. habitat, food web and energy transfer). Although during this school year the students learned about the micro level, focusing on the cell and molecular processes, the connection to the human body was not emphasised explicitly. The time difference between learning explicitly about the human body and the time the students were interviewed at the third stage of the study might explain the decline in the number of students presenting constructs in the C3 category.

Overall, comparing the end of the study with its beginning shows that fewer students focused on the basic levels of the components categories in the CMP framework, which refer only to the location (C1) or to the obvious properties (C2) of the components. On the other hand, more students represented the more sophisticated C3 category, connecting the system components to mechanisms.

(2) Mechanisms

Understanding complex systems like the human body requires the ability to recognise the processes occurring within them that enable them to function (e.g. osmosis, oxygen transportation and degradation). In the CMP framework, constructs that refer to processes are included in the 'mechanism' categories. The higher levels of this category require recognition of the micro level of the system, since this is the level at which process are explained.

In our study, almost all of the students presented constructs referring to mechanisms right at the beginning of the learning process. It is worth noting that all of these students had chosen to major in biology and had learned biology throughout junior high school, so they began the study with some understanding of the human body.

Constructs in the M1 category, including constructs referring to the location of processes or descriptions of interactions between components or processes, are the most basic constructs referring to processes within the system. As shown in Figure 2, over 96% of the students presented constructs in this category in stage 1 of the study. The processes and body systems referred to in these constructs are varied (*related/unrelated to blood circulation in the cardiovascular system*, *related/unrelated to enzymes supporting the function of the digestive system*, *related/unrelated to diffusion in blood circulation*). Constructs in the M1 category were dominant throughout the study, and there was no significant difference in the number of students presenting constructs of this sort over its various stages ($\chi^2(3, N = 67) = 7.11$, $p = .0685$).

Systems understanding requires the identification not just of mechanisms, but also of the molecules that take part in them, which means referring to the micro level of the system. These references are presented in constructs at the M2 category. In these constructs, the students mention processes while using molecules to build relationships within the system. Over the three years of the study, there was a significant rise ($\chi^2(3, N = 67) = 11.51$, $p = .0093$) in the number of students presenting constructs in the M2 category (from 63% at the first stage to 88% at the last stage).

Systems understanding also requires knowledge of the way the processes in the system use its components. Constructs in the M3 category represent such sophisticated systems understanding. Students presenting M3 constructs describe not only what materials, at the micro level, are taking part in a process within the human body system, but also how processes use the components in the system, or the sequence occurring in a process. There was a significant rise ($\chi^2(3, N = 67) = 9.35$, $p = .0249$) in the number of students presenting constructs in the M3 category, from only 12% at the beginning of the study to 24% at the end (Figure 2). Like the C3 and M2 categories, the M3 category also showed a rise in the number of students presenting such constructs from the first to the second stage of the study (12–22%). During this stage of the participants' biology studies, the curriculum included detailed explanations of the various human body systems and the processes occurring in them, as demonstrated in the constructs the students created (e.g. *related/unrelated to effect of hormone secretion on target organs* 'Metabolism is the exception. The endocrine system secretes hormones to the blood stream, and these hormones signal the target organs to secrete hormones or other materials).'

An overall look at the mechanism categories of the CMP framework throughout the whole study shows that the basic category M1, which requires only the recognition of processes, thus not necessarily involving recognition of the micro level of the system, is represented by almost all students in all the study's stages. Nevertheless, as the study progressed there was a significant increase in the number of students presenting the more complex mechanism levels, including recognising the materials, at the micro level, that participate in processes (M2) or describing the process and its stages (M3). Taken together, these results support a progression in the study participants' systems understanding. However, even at the end of the study only a small percentage of the students created constructs at the M3 category, showing a persistent difficulty in developing this aspect of systems understanding.

(3) Phenomena

To understand the complexity of the human body, as well as that of other complex systems, one must be able to recognise the outcomes of the various mechanisms operating in the system, leading into the general patterns affecting the behaviour of the system as a whole. These outcomes of the system's mechanisms are represented by the phenomena categories in the CMP framework.

The first phenomena category, P1, includes constructs referring to an overall behaviour or property of a system that is the result of an interaction within that system. Students presenting such constructs demonstrate some recognition of the patterns characterising a system's behaviour. The gradual increase in the number of students presenting constructs in the P1 category (from 15% at the beginning of the study to 28% at the end, Figure 2), is statistically insignificant ($\chi^2(3, N = 67) = 5.79$, $p = .1222$). Processes in the body systems and their contribution to homeostasis in the body were stressed in class in all three years of high school, especially in 10th and 12th grade. Though this was reflected in some of the students' constructs (e.g. *related/unrelated to energy production in cellular respiration*, 'Cellular respiration is different from internal environment and diffusion, as cellular respiration occurs in order to produce energy),' at the end of the learning process constructs at the P1 level were still presented by less than one third of the students.

Higher systems understanding requires the ability to recognise that phenomena are not achieved by a single interaction within the system, but due to a network of interactions leading to the system's overall behaviour. Constructs in the P2 category represent this level of systems understanding. Even though constructs in this category require the ability to note patterns and make generalisations when characterising the system, 37% of the students presented such constructs right at the first stage of the study (Figure 2). One would expect that after learning topics such as homeostasis, emphasised in the high-school biology curriculum at all levels, aspects of patterns and generalisations presenting the ways in which homeostasis describes the system's behaviour would emerge. But at the last stage of the study only 19% of the students presented constructs in the P2 category (Figure 2), showing no significant change from the beginning of the study ($\chi^2(3, N = 67) = 7.70$, $p = .0527$).

Higher systems understanding also requires the ability to integrate the different processes that bring about the phenomena in the system, including the sequence of events and the materials participating in the various processes. Students with constructs in the P3 category expressed such systems understanding. An example of a construct in the P3 category is: *Related/unrelated to cellular respiration converting energy required for cell existence,*

> Hormones are the exception. The respiratory system is necessary to remove CO_2 and provide O_2 to all body cells. The body cells use O_2 to perform the process of cellular respiration, during which the converted energy is necessary for the body activity.

In this construct, the materials 'CO_2' and 'O_2' (molecules) are exchanged (a process) in the respiratory system, providing O_2 for cellular respiration to convert energy (a process), enabling the phenomenon of body activity.

Like the C3 category, which includes connecting the 'components' and 'mechanisms' categories, the P3 category reflects a connection between 'phenomena' and 'mechanisms,' representing the transfer of materials in the system. Only students with a high level of systems understanding can create constructs in the P3 category, which requires the integration of several processes and the identification of the materials taking part in them (e.g. *related/unrelated to regulation of the digestive system by the endocrine system* 'The cell membrane is the exception. The endocrine system regulates the digestive system by secreting hormones that cause negative feedback in the digestive system).' As demonstrated by this example, such systems understanding entails a recognition of the interactions, at the molecular micro level (hormones), which enable the phenomena at the macro level (the digestive system). Because such deep understanding and integration is required, constructs in the P3 category were found only in the last two stages of the study, after the students had gained enough knowledge about the human body system (Figure 2). Though by the study's end only 19% of the students demonstrated constructs in the P3 category, this is a significant increase compared to its beginning, when no student presented such constructs at all ($\chi^2(3, N = 67) = 26.92$, $p < .0001$).

Although overall the results showed a progression in the students' systems understanding at the level of phenomena, the total number of students presenting constructs falling under this CMP category remained low throughout the study, indicating that gaining deep systems understanding is still challenging for most students.

Connections between the repertory grid constructs

To get a fuller picture of the students' perception of the human body system, we also examined the connection between their repertory grids' constructs (see the exemplar grid in Figure 1, upper right side). We looked at the trees of relations between constructs in each student's repertory grid, and analysed correlations of 80% or higher between constructs. A high connection between constructs indicates a high cognitive link between them in the student's mind. Since each construct is categorised into a specific CMP category, analysing these connections allowed us to assess the connections students form between the various CMP framework categories.

At the last stage of the study the students' repertory grids presented all the CMP framework categories and included the highest levels of complexity. We therefore analysed the grids created by the students at this stage, examining all the connections between constructs that were higher than 80%, and dividing these constructs into the various CMP framework subcategories. This allowed us to characterise the connections between constructs, which represent the connection between the various CMP framework components. We then calculated the ratio between the number of connections formed by constructs in each category, and the total number of constructs in the same category. This calculation, presented in Table 3, points to the relative centrality of each category of the CMP framework in the students' system perception.

Table 3 indicates that the existence of constructs in the M2 category leads to multiple connections with other constructs (ratio 1.8), and that connections with C1 constructs are also common (ratio 1.5). The connections with the C1 category point in many cases to a structural connection. For example, in the second stage of the study, a student demonstrated a connection of almost 90% between the constructs *Related/unrelated to gas exchange* (M2) and *Related/unrelated to the respiratory system* (C1). Such a connection

Table 3. Connections between the repertory grids constructs at the 4th stage.

Category	No. of connections	No. of constructs	Ratio	Connections with other categories
C1	57	37	1.5	M2 > C1 > M1
C2	24	40	0.6	M1 > M2 > C1
C3	11	28	0.4	M2 > M1 > P3
M1	66	60	1.1	M2 > M1 > C2
M2	108	59	1.8	M2 > M1 = C1
M3	19	18	1.1	M2 > M1 = C1
P1	24	22	1.1	M2 > C1 > M1
P2	10	11	0.9	M1 > M2 = P1
P3	17	13	1.3	M2 > M3 > C1

can be formed through the students' perception that gas exchange occurs in the respiratory system, showing a connection between the gas molecules (oxygen and carbon dioxide), the process of gas exchange, and the location of the process – the respiratory system. At the last stage of the study, the same student created a repertory grid presenting an M2 construct *related/unrelated to diffusion of materials through cell membrane* ('The cell membrane is a part of the cell through which processes (such as diffusion, transportation of gases, etc.) occur)' that was connected at 90% with an M3 construct *related/unrelated to gas diffusion through the respiratory system*

> (Diffusion is a process in which molecules are transported at the direction of the concentration gradient, gas diffusion occurs at the respiratory system, assisting with the system's function. Oxygen is transported into the cells and carbon dioxide is transported out of the cells to the blood).

Both of these constructs are focused on the micro level of the human body system, and are related through an understanding of molecular processes (characterising the M2 and M3 categories). These two examples demonstrate how the M2 category bridges different CMP categories, presenting various aspects of complex systems.

We also examined the *types* of connections between the constructs presented in the students' repertory grids at the 4th stage of the study (see Table 3, right column). For each subcategory, we counted the total number of connections formed with its constructs (presenting a correlation of 80% and above) to each of the CMP subcategories' constructs. For example, one of the connections to constructs at the C1 subcategory was that made between the construct 'unrelated to the digestive system/related to the digestive system' (C1) and the construct 'a process occurring in the cell/not a process occurring in the cell' (M1) (see Figure 1), which are correlated at 80%. We counted all these connections between constructs and then calculated the percentage of the connections with each CMP subcategory out of the total number of connections made with constructs in the examined subcategory. For example, constructs at the C1 category had the most connections with M2 constructs (35% of all connections), followed by C1 constructs (21%) and M1 constructs (16%). Connections to constructs at other subcategories were less common. Table 3 (right column), shows that the most dominant connection for each of the categories is with constructs in the mechanism categories, indicating its centrality in the students' mental framework of the human body system.

Connections between the repertory grid elements

To gain more insight into the students' perception of the human body throughout the progression of the study, we also checked which elements are highly connected in the students' repertory grids (see Figure 1, lower right side). Connections between the repertory grid elements indicate the context in which the system model is built by the students (Jankowicz, 2004). The eight most dominant connections between elements, presented by at least 20% of the students at the last stage of the study, are shown in Table 4. For example, there is a strong connection between the cardiovascular system and blood circulation, which was presented by 55% of the students at the beginning of the study. This connection, which is structural in nature, was presented by almost 69% of

Table 4. Connections between the repertory grid elements.

Elements in the connection		Percentage of students presenting the connection			
Element 1	Element 2	Stage 1	Stage 2	Stage 3	Stage 4
Cardiovascular system	Blood circulation	55.2	52.2	73.1	68.7
Hormones	Endocrine system	31.3	41.8	73.1	62.7
Internal environment	Homeostasis	20.9	20.9	25.4	20.9
Diffusion	Metabolism	17.9	17.9	20.9	25.4
Cell	Cell membrane	11.9	16.4	25.4	38.8
Cell membrane	Diffusion	4.5	19.4	20.9	29.9
Cardiovascular system	Internal environment	6.0	6.0	7.5	22.4
Cell	Diffusion	4.5	6.0	13.4	20.9

the students by the study's final stage. Most of the connections in Table 4 were presented by a greater number of students as the study progressed, which may indicate the dominance of these connections in the biology curriculum. More implications for this analysis are addressed in the discussion section.

Discussion

In this study we examined the development of high-school students' human body systems understanding through the lens of the CMP framework (Hmelo-Silver et al., 2016), examining the manifestation of the framework's various components over the three years of the students' high-school biology studies. The data for analysis were gathered using the repertory grid tool, which revealed the personal constructs of the study participants (Kelly, 1955). These personal constructs represent the students' mental model of a system, allowing us to detect subtle changes in their system perception over time.

Long-term manifestation of CMP framework constituents

The development of high-school biology students' understanding of body systems was marked by a shift from the basic categories to the more complex ones in each of the CMP framework's constituents (Components, Mechanisms, Phenomena).

The 'Components' category was represented in the students' repertory grids throughout the entire learning process. The structures (or components) of complex systems are the most cognitively accessible level of complex systems for novices (Hmelo-Silver & Pfeffer, 2004). Hmelo-Silver et al. (2007) showed that understanding complex systems requires a recognition of the relationships among the system's different levels. For novices, the system's components are easier to comprehend than its functions, while experts organise their knowledge of the system around its behaviour, that is, the phenomena in the system.

At the beginning of the learning process, many students created constructs like 'a system/not a system,' or 'a process/not a process.' These constructs, which fall under the CMP framework's C2 category, refer to the system components' basic properties. They are quite simple, and do not represent deep systems understanding. This is also expressed by 3rd author's STH model (Ben-Zvi Assaraf & Orion, 2005), which categorises how students think about and understand a system according to eight hierarchical characteristics, evinced in an ascending order. The first category in the STH model is identifying the components and processes of a system, reiterating that systems understanding at its most basic level requires a recognition of the system's components.

The end of our study showed a decrease in the number of students presenting the simple C1 category and an increase in the C3 category. The C3 category of the CMP framework acts as a bridge between the 'components' and 'mechanisms' categories. Surface area to volume ratio, for example, is a structural feature that pertains to function, and many of the C3 constructs created by the students deal with surface area to volume ratio ('Related/unrelated to increase of surface area to volume ratio in the digestive system'). Surface area to volume ratio is one of the unifying concepts in biology studies that are taught in high-school biology. It influences various biological processes such as rate of diffusion, enzymatic activity and cell growth. Taylor and Jones (2009) found a relation between students' understanding of this ratio and their ability to solve science problems in different contexts. For example, they showed a relation between knowledge of surface area to volume ratio and the ability to predict which type of fish gill would absorb oxygen at a greater rate. They also found that high-school students show better understanding of surface area to volume ratio compared with middle-school students, as abstract thinking might be required for such understanding (Taylor & Jones, 2013). In light of this, the increase in the number of students demonstrating systems understanding at the C3 category at the end of the study indicates a development of their systems understanding.

Novices tend to focus on structures (components) rather than on function (mechanisms) (Hmelo-Silver et al., 2007; Hmelo-Silver & Pfeffer, 2004; Jordan et al., 2017). They also have trouble connecting structures and function, as was recently shown in college students taking an introductory biology course (Todd & Romine, 2017). Nevertheless, many of the students in our study were able to recognise mechanisms right at the beginning of the study. It should be noted that our participants did not have all the characteristics of novices in the field of human biology. They had all studied human body biology prior to 10th grade, which is when the study began. But though many students recognised mechanisms at the beginning of the study, they referred to them mainly with regard to their location or to some basic interactions between components (the M1 category).

High-school biology education is often focused on memorising structures and describing phenomena, rather than emphasising the system mechanisms that bring about the phenomena. As Wilensky and Reisman (2006) claimed, there is a big difference between the way biology is studied in school and actual research in the field of biology. In school, the focus is usually on classification schemas and established theories. Even when students perform laboratory work, they usually follow a prescribed procedure. Thus, when the students receive the repertory grid elements, even if the elements themselves are mechanistic in nature, many students may find it easier to connect them to their location than to describe their nature.

As the learning process progressed, the complexity of the mechanisms presented by the students increased, as manifested by the fact that more students described mechanisms at the micro level of molecules (the M2 category). This is crucial because recognising that molecules are the entities that enable the interactions in systems is essential to the development of systems understanding, and because understanding cell function at the molecular level is necessary to understanding the multicellular organism (Verhoeff, Waarlo, & Boersma, 2008). Students have been shown to have difficulty linking micro-level processes with macro-level phenomena, that is, relating macroscopic observations to microscopic explanations (Ben-Zvi Assaraf et al., 2013), and explicitly asking students to explain macro level phenomena by referring to the micro level has been shown to promote understanding and knowledge application (Li & Black, 2016). Systems understanding at the level of the M2 category is essential to bridge that gap.

The increase in the number of students who presented the M2 category occurred mainly between the first and the second stages of the study, and between the third and the fourth stages. There was no difference in the number of students presenting M2 constructs between the second (end of 10th grade) and third (end of 11th grade) stages. This might be explained by the 11th grade curriculum being focused mainly on ecology, and not referring directly to the human body. The 11th grade focus on ecology may also explain the decrease in the number of students who presented M3 category constructs at stage 3 of the study. The M3 category requires the ability to describe a process at the molecular level, and though many students recognised that molecules participate in processes in the human body systems, even at the study's end only about 20% of them presented constructs in the M3 category.

This result might be due to the increased systems understanding involved in representing constructs in the M3 category, which reflect the dynamism within the human body system. A dynamic system includes various components that interact with each other, and with the components of other systems (Hmelo-Silver et al., 2000). The mechanism responsible for this interaction is based upon matter transportation between all the levels of a body's hierarchy, from the single cells and the molecules at the micro level to the macro level of the entire body. Studies have suggested that a major obstacle to dynamic thinking is connected to the ability to follow matter as it is transported through a system (Wilson et al., 2006; Zangori & Koontz, 2017). Liu and Hmelo-Silver (2009) showed that experts' explanations of complex systems were focused on the underlying mechanisms within the system, like how cellular respiration and diffusion occur in relation to respiratory system function. They suggested that these cellular level explanations are indicative of deep understanding because the processes at the cellular level explain the macro-level processes of respiration. In light of these results, students creating constructs in the M3 category demonstrated higher systems understanding of the human body compared with other students. The students demonstrating systems understanding at this level were a minority in the study population.

Understanding complex systems requires students to be able to make connections between the components, mechanisms and overall behaviour (phenomena) of the system (Hmelo-Silver et al., 2007). The CMP phenomena category presents the overall behaviour of the human body system, and thus represents systems understanding. The phenomena categories were manifested by a relatively small percentage of the students throughout the whole study. This is consistent with previous studies, which showed that most people understand complex systems as collections of parts, with little understanding of how different processes within the system connect (Brown & Schwartz, 2009) and how the whole system works (Hmelo-Silver et al., 2007; Hmelo-Silver & Pfeffer, 2004). This can be explained by the fact that education about complex phenomena often ignores the phenomena themselves, and instead has learners focus on memorising the names of the system's parts (Hmelo-Silver & Azevedo, 2006), or that teaching systems is focused on fragmented components, ignoring their interactions (Rates, Mulvey, & Feldon, 2016).

Despite the higher level of systems understanding this category implies, some of the students in our study *did* present constructs in the P1 or P2 category right at the beginning of the study. In the Israeli high-school biology curriculum, major biological principles such as homeostasis are taught repeatedly from the beginning of the learning process (Ben-Zvi Assaraf et al., 2013). As a result of the attempt to generalise terms connected to homeostasis (e.g. control, steady state and internal environment), some students tend to use these terms without fully understanding their meaning. For example, in connecting cellular respiration to homeostasis, some students may be displaying an understanding of the connection, whereas others may simply be repeating a generalisation that was mentioned in class. Facilitating students' meta-cognitive awareness of their own learning process could promote a more meaningful understanding of phenomena such as homeostasis. Promoting students' metacognition means teaching them to think about how they are thinking about biology and how they approach learning about biology (Tanner, 2012). Meta-cognitive skill development is typically fostered by asking students to reflect on and explicitly monitor their own learning performance (Zion, Michalsky, & Mevarech, 2005).

The P3 category includes descriptions of the materials that participate in the mechanisms that bring about the phenomena, or explanations of the phenomena. Thus, the students need to connect the generalisations of the phenomena with the specific mechanisms, at the molecular micro level, that explain them. Constructs in the P3 category were represented only in the last two stages of the study, and even at the end of the learning process this category was presented by only 20% of the students. These results indicate that creating constructs in the P3 category was challenging for the students.

The P3 category reflects students' deep understanding of the phenomena they describe. For example, in the human body the process of cellular respiration, which occurs in all body parts, requires the integrative activity of three body systems. Glucose for cellular respiration is provided by the digestive system, oxygen is provided by the respiratory system, and both are transported by the cardiovascular system. Students' constructs from the P3 category addressed this joint activity, demonstrating an understanding of the molecular basis and the mechanisms involved, referring to several components in the system that work in tandem to create the phenomenon. Explanations at such a level require a deep systems understanding that most of the study's participants did not achieve over the course of the study.

Conclusions regarding the efficacy of the current biology curriculum

The study presented here provides an overview of the state of biology education in Israel, in light of the biology curriculum that is currently in use. It seeks to determine the extent to which this curriculum serves the purpose of developing students' system understanding, which is one of its primary goals. The results of the study indicate that the current curriculum, and the way it is taught, are not bringing students to a sufficient understanding of the human body's systemic nature. Overall, our results indicate that although the Israeli high-school biology curriculum includes all the constituents of the CMP framework, and despite a significant shift towards the higher levels of the CMP framework, by the end of their high-school biology education most students in our study lack the ability to fully describe the connections between the components, at the molecular level, that enable the phenomena taking place in the human body system.

Our results show that most students did not demonstrate systems understanding at the high levels of the mechanism and phenomena categories of the CMP framework, even by the end of their high-school biology education. These levels of systems understanding require the recognition and integration of processes at the molecular micro level, which would allow students to explain the overall phenomena that are present at the macro level of the human body as a whole. A recently published study demonstrated that even students engaged with a PBL (Problem Based Learning) programme called the 'Medical Systems' programme, who were required to implement knowledge from different scientific and clinical areas, did not show improved understanding of mechanisms and phenomena compared with other biology students. The students did not make the connection between the phenomenon of homeostasis, a core concept in the high-school biology curriculum, and its disruption in the context of diseases learned in the Medical Systems programme (Tripto, Ben-Zvi Assaraf, Snapir, & Amit, 2016a). The students' inability to show holistic systems understanding might reflect the fact that the curriculum is focused (in both cases) solely on the human body system itself, without wider implications. Students' understanding of the human body's systemic nature might be improved by using SSI modules such as those developed and tried by Zeidler and Sadler (2008) or Fowler and Zeidler (2016).

Another approach designed to promote systems understanding was recently presented in the study that originally proposed and implemented the CMP framework as a scaffolding tool. This study used CMP for the conceptual representation of an ecological system (Hmelo-Silver et al., 2016). It used an explicit approach to teach phenomena – the students were required to represent a complex system around a particular phenomenon that was posed as a problem to motivate students' learning. This encouraged the students to recall mechanisms that may result in the phenomenon, and present the components that interact to result in the mechanisms and phenomena. The study used the CMP framework in conjunction with a curriculum that asked critical questions, so that learners were encouraged to find and generate evidence in support of mechanistic explanations. The mechanisms in the study were made visible to students using simulations, so they could examine their ideas about the interactions in the system. Its results showed that the students who learned in this manner improved their ability to explain phenomena by referring to mechanisms. Moreover, it appeared that using CMP as a means of representation gave the students a useful way of organising and investigating the components involved in the mechanisms. Thus, the study showed that providing students with an explicit mental framework through an intervention that specifically targets thinking about system relations can help them to see more than one link between the mechanism and the component, and promote their systems understanding. We believe such an approach can be adapted to include questions concerning the human body system, and used to improve students' understanding of its systemic nature.

An explicit approach was also employed in another study, which showed that a metacognitive approach to teaching the human body, using a reflective interview that explicitly encourages students to use systems language, was effective in improving high-school biology students' systems thinking and learning processes (Tripto, Ben-Zvi Assaraf, Snapir, & Amit, 2016b). This study employed the interview as a comparative scaffolding strategy in which the students, with the interviewer's explicit guidance, compared two sets of concept maps they had created at different points in the learning process. The concept maps served as scaffolding for the students, allowing them to see, verbalise and assess their own thinking as the interview progressed. The results of this study showed that the interview's explicit intervention can promote systems understanding of the human body.

Jacobson et al. (2017) also described the advantages of integrating the explicit instruction of 'complex systems ideas' into the instruction of a specific scientific topic and of including a reflective, meta-cognitive element in that instruction (p. 2). The ninth grade students in their study learned about climate change as a complex system via a series of 'challenge problems,' which the students worked on in two phases. First, the students worked collaboratively in groups, using their own prior knowledge to try and generate solutions to the problems. Next, with the direct guidance of their teacher, the students engaged in a reflective 'consolidation of knowledge assembly phase,' comparing, contrasting, and critically examining their solution methods (p. 3).

Studies like those described above suggest that explicitly encouraging the students to reflect upon their own systems thinking and make the connections between the mechanisms (which, as indicated by our results, are crucial for systems understanding), while identifying the components and interactions that make these mechanisms possible, will make it easier for students to understand the outcomes – that is, the phenomena exhibited in the human body.

Further study is required to determine whether such approaches can indeed promote an in-depth systems understanding of the human body in high-school biology students.

The human body systems mental model reflected in the students' repertory grids

Kelly's Personal Construct Theory (PCT) is based on a constructivist model of human cognitive processes. Specifically, it describes how concepts are acquired and organised within a learner's cognitive structure (Bradshaw, Ford, Adams-Webber, & Boose, 1993). Efran, McNamee, Warren, and Raskin (2014) have noted the connections between PCT and learning theories like radical constructivism and social constructionism. Using constructivism and repertory grids to collect data can paint a rich picture, representing the personal mental model of each study participant. According to Kelly's PCT, each person makes use of unique personal criteria, or constructs, which help them assign meaning to events (Kelly, 1955). The repertory grid technique was designed by Kelly to elicit these personal constructs.

Both the CMP framework and the repertory grids are highly deductive by nature. Using the repertory grid as a tool for data collection, we were able to gather over 300 constructs, created by the study's 67 participants at its various stages. These constructs represent the personal human body perception of each individual student. Dividing the constructs into the CMP subcategories allowed us to characterise the participants' learning process.

One added value of the repertory grid mapping software is that it allows us to pinpoint the dominant connections, meaning the elements and constructs most prominently involved in the students' system models. The highest number of connections between the repertory grids constructs were formed with constructs in the M2 category (Table 3). System components take part in mechanisms that produce higher level phenomena (Illari & Williamson, 2012; Machamer, Darden, & Craver, 2000). Thus, mechanisms link components and phenomena, which encourages interrelations between constructs in the 'mechanisms' subcategories and constructs in the other two major categories in the CMP framework. The high connection that the various CMP subcategories formed with the M2 subcategory may be related to its molecular nature, which enables its connection to many components and processes. For example, understanding the function of the nervous system in signal transduction requires a recognition of the molecules involved – the neurotransmitters (Marieb & Hoehn, 2012). This high level of connections to the M2 category supports our previous finding regarding the importance of such constructs with regard to dynamism. Furthermore, because connecting molecular mechanisms with the complex phenomena in the cell or the organism is necessary for systems understanding (Southard, Wince, Meddleton, & Bolger, 2016), the high connection between the M2 subcategory and other CMP subcategories demonstrated by the study participants at the end of the study might indicate their perception of the systemic nature of the human body.

The students also presented many constructs that connected to constructs in the C1 category (Table 3). The tendency to observe components before mechanisms has been shown in previous studies (Hmelo-Silver et al., 2007), but it might also be related to the curriculum, which emphasises the structural aspects of the human body system (Ben-Zvi Assaraf et al., 2013). This also supports our finding that components continued to be strongly represented by the students throughout the study (Figure 2, categories C1, C2 and C3).

Analysing the connections between the elements of the repertory grids highlights one of the limitations of the repertory grid technique, namely that by looking at the connections alone, one cannot tell the reason for their existence. For example, the connection between the elements 'cardiovascular system' and 'blood circulation' exists in many students' repertory grids throughout the study (Table 4), but we cannot differentiate between students in whose mental model this connection is mechanistic, for example referring to oxygen transfer in the cardiovascular system performed by the blood circulation, and students for whom this connection is structural, as the blood circulation is a part of the cardiovascular system. Having said that, an increase in the number of students presenting connections between elements that are mechanistic in nature could still be indicative of an increased level of complexity with regard to the CMP framework categories. An example of such a connection is the connection between diffusion and metabolism. Both are processes, so an increase in the connections between these elements might indicate an increase in the students' mechanistic understanding of the human body.

The connections formed between the elements of the repertory grid can indicate the context in which the students build the system model (Jankowicz, 2004). For example, many of the students' grids portray a strong connection between the cardiovascular system and blood circulation, which grew stronger throughout the study (Table 4). During their biology studies the students learned not only about the cardiovascular system but also about its function in connection with other systems and its role in homeostasis. Nevertheless, by the end of the study, most of the students drew primarily structural connection between the cardiovascular system and blood circulation, while less than a quarter of the students drew a connection between the cardiovascular system and the internal environment. This may indicate the importance of teaching various aspects of the CMP framework in connection to blood circulation, so it will not be perceived by the students only in terms of its location. Another example is the connection between hormones and the endocrine system, which is prominent throughout the whole study (Table 4). It appears that it is also important to teach the endocrine system in more detail at the mechanism and phenomena levels, so the students do not associate it only with hormones as components of the system.

In conclusion, our long-term study suggests that, overall, these students' high-school biology education generated a learning environment that allowed them to develop a systems understanding of the human body, as seen by their progression within the CMP framework throughout the study. Using the repertory grid in conjunction with the CMP framework allowed us to compare and contrast the students' perception of various elements in the human body system at different points within the learning process. Moreover, by examining the students' connections between elements and constructs, we were able to identify strategic points that could be particularly fruitful in further developing students' understanding of the human body as a system. For example, we found that – despite the fact that all three of the system characteristics expressed in the CMP framework are important to the construction of a complex mental model of the human body – the 'mechanism' category and the micro level are critical components in students' ability to understand system-level phenomena such as homeostasis.

A systems understanding of the human body is necessary to identifying and analysing multi-system phenomena. Our study suggests that, to achieve this, teaching about the human body as a system must on the one hand place special emphasis on mechanisms at the micro level of molecules, while on the other it must emphasise the patterns that are made possible by the mechanisms' existence. This dual emphasis will provide students with a holistic view of systems, and the ability to look at them both from the inside out, and from the outside in.

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