



# Developing seventh grade students' systems thinking skills in the context of the human circulatory system

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Developing systems thinking skills in school can provide useful tools to deal with a vast amount of medical and health information that may help learners in decision making in their future lives as citizen. Thus, there is a need to develop effective tools that will allow learners to analyze biological systems and organize their knowledge. Here, we examine junior high school students' systems thinking skills in the context of the human circulatory system. A model was formulated for developing teaching and learning materials and for characterizing students' systems thinking skills. Specifically, we asked whether seventh grade students, who studied about the human circulatory system, acquired systems thinking skills, and what are the characteristics of those skills? Concept maps were used to characterize students' systems thinking components and examine possible changes in the students' knowledge structure. These maps were composed by the students before and following the learning process. The study findings indicate a significant improvement in the students' ability to recognize the system components and the processes that occur within the system, as well as the relationships between different levels of organization of the system, following the learning process. Thus, following learning students were able to organize the systems' components and its processes within a framework of relationships, namely the students' systems thinking skills were improved in the course of learning using the teaching and learning materials.

**Keywords:** systems thinking skills, decision making, circulatory system, teaching and learning materials

## INTRODUCTION

Science plays a key role in our culture. As such, the range of issues dealing with decision making, both individually and globally is rising. One of the areas in which we are required to make decisions on a daily basis is medicine and health. As the information is readily available to all, the main difficulty lies in the ability to properly understand and integrate the information. Developing systems thinking skills in school may provide useful tools to deal with the vast amount of information and thus can help learners in developing their decision making skills. Moreover, adopting the approach that views the human body as one complex system that divides into multiple levels of organization and has many components, which interact with each other, may promote a deeper understanding of biological processes. That approach is essential for developing wise decision making skills regarding health issues. In the era of "Science for All," developing these skills in junior high school is more important than ever before.

A systems perception enables an analysis of the learned phenomena from a meta-cognitive perspective emphasizing the entirety, the sum of its components, and the connections and interactions between them (1–3). We describe below the theoretical basis of our study, and specifically what is systems thinking, how does systems thinking skills develop, and what are the difficulties students of various grade levels encounter when learning about various systems in general and about the human circulatory system in particular.

## WHAT IS SYSTEMS THINKING?

The current literature on systems thinking provides various definitions to the term system. From basic definitions, such as "The basic conceptualization of a systems is relatively simple; a system is a collection of parts and/or processes" (4) to broad definitions emphasizing 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. However, this group of interacting, interrelated or interdependent parts that form a complex and unified whole must have a specific purpose, and in order for the system to optimally carry out its purpose all parts must be present. Thus, the system attempts to maintain its stability through feedback" (3). The characteristics of the system whole are often un-identical to the individual system components (3, 5, 6). Therefore, in order to profoundly understand a complex system, an understanding of its individual components is insufficient but rather the net of interactions between all the system components should be addressed. Analysis and understanding of a given system require developing higher order thinking skills and high cognitive abilities.

The recent Framework for K-12 Science Education, published by the United States National Research Council (7), emphasizes the necessity of developing systems thinking skills among students of different age levels. The framework anchored an objective of design principles and standards for science education to suit the twenty-first century education system while reducing curriculum content

and suggesting curriculum reorganization based on a reduced number of concepts. The framework outlines three dimensions: scientific and engineering practices, crosscutting concepts, and core ideas for all content fields. "Systems and system models" is listed as one of the crosscutting concepts in this framework. The recommendation is to expose the students to the systems thinking approach starting from the primary grades. The significance of a system definition for means of research and learning is emphasized in this framework based on the fact that "the natural and designed world is complex; it is too large and complicated to investigate and comprehend all at once. Scientists and students learn to define small portions for the convenience of investigation. The units of investigations can be referred to as 'systems'. . . A system is an organized group of related objects or components that form a whole. . . Although any real system smaller than the entire universe interacts with and is dependent on other (external) systems, it is often useful to conceptually isolate a single system for study. To do this, scientists and engineers imagine an artificial boundary between the system in question and everything else" (7).

### HOW DOES SYSTEMS THINKING SKILLS DEVELOP?

Three models for systems thinking were suggested in the literature (2, 3, 8). Each model clarifies and illuminates a different aspect of developing systems thinking skills among students.

#### **Systems thinking hierarchical model**

A cognitive model presenting eight hierarchical stages of the development of systems thinking skills (3). According to this model, the cognitive skills developed at each stage constitute a basis for developing higher systems thinking skills. The model has been modified and in the study by Ben-Zvi Assaraf et al. (9) the development of a systems thinking skills was described as follows: (1) identifying the components and processes of a system, (2) identifying simple relationships among a system's components, (3) identifying dynamic relationships within a system, (4) organizing the system's components, their processes, and their interactions, within a framework of relationships, (5) identifying matter and energy cycles within a system, (6) recognizing the hidden dimensions of a system (i.e., understanding phenomena through patterns and interrelationships not readily seen), (7) making generalizations about a system, and (8) thinking temporally (i.e., employing retrospection and prediction).

Studies that used this model for examining student systems thinking skills gathered the eight stages into three sequential hierarchical levels: system component analysis (stage 1), synthesis (stages 2–5), and implementation [stages 6–8 (9, 10)]. These studies presented a typical pyramid structure, the wide base of the pyramid representing students possessing analytical skills, and the narrow vertex of the pyramid representing students possessing implementation skills. Going up the pyramid, the systems thinking level increases and the number of students possessing systems thinking skills decreases. A student that had reached the highest thinking level (implementation) had to have successfully completed the prior stages [analysis and synthesis (9, 10)].

#### **Systems thinking competence for cell biology education**

According to this model, systems thinking competence for cell biology education is anchored in four elements: (1) being able

to distinguish between the different levels of organization, and to match biological concepts with specific levels of biological organization; (2) being able to interrelate concepts at the cellular level of organization (horizontal coherence); (3) being able to link cell biology concepts to concepts at higher levels of organization (vertical coherence). An additional element refers to the relationship between systems thinking skills and an understanding of models of the living cell: (4) being able to think back and forth between cell representations ranging from abstract cell models to real cells seen under a microscope. Students have difficulties in differentiating structures and processes at different levels of organization as well as in making connections between structures and functions at different levels of organization, while attempting to provide explanations for biological phenomena. Among others, these difficulties derive from a lack in forming significant relationships between the various organizational levels during the teaching and learning process (1, 2, 11, 12).

#### **Structure-behavior-function model**

At the foundation of this model is the assumption that the organization of knowledge during the learning process may affect the manner in which the learners organize their knowledge regarding a given system (8). This model was developed in the field of engineering and it offers a conceptual representation, which focuses on a causative connection between three system aspects: (1) structure: the system components and the relationships between them, (2) behavior: the dynamic interactions between the system components and existing mechanisms in the system, and (3) function: the essence of the system and its components. For experts, the function and behavior in a system constitute a principle knowledge organizer and a foundation for understanding the system, whereas for beginners the system structure constitutes the principle knowledge (13). In addition, findings show that the use of conceptual representation with an emphasis on a function centered conceptual representation in teaching has numerous significant advantages in comparison with the use of a structure centered conceptual representation. The advantages are in enabling to respond to essential questions regarding the system role, as the broad questions are divided into more specific sub-questions. This type of questions encourages thinking and argument building. Searching for answers to a question encourages meaningful learning. Another advantage is in creating a cognitive challenge for the learners. In the attempt to answer questions regarding the system role, the students are required to gather their prior knowledge and examine the new knowledge acquired in light of their prior knowledge. In addition, it may promote the creation of meaningful connections between the system components at different levels of organization. Thus, organizing the teaching through conceptual representation may facilitate the students and assist their profound understanding of complex systems (8).

Using those three models, we constructed a unified model, which enabled us to both develop learning materials as well as to characterize systems thinking skills in biology (**Table 1**).

The unified model (**Table 1**) emphasize the following three principles, which served as the foundation for our study: (1) the development of systems thinking skills consists of several sequential stages arranged in a hierarchical manner, (2) the conceptual

**Table 1 | A unified model for characterizing systems thinking skills in biology.**

Stages in developing systems thinking	Basic level	High level
The ability to identify components in the system [following (3)]	One organizational level [following (12)]	Different levels of organization [following (12)]
The ability to identify simple relationships between the system components [following (1, 3)]	Between system's components at the same level of organization (horizontal coherence) [following (12)]	Between components at different levels of organization (vertical coherence) [following (12)]
The ability to identify dynamic relationships between the system components [following (1, 3)]	Between system components at the same level of organization (horizontal coherence) [following (12)]	Between components at different levels of organization (vertical coherence) [following (12)]
The ability to organize the system components in a framework of interactions [following (3)]	A framework of concepts and relationships [following (3)]	Branched framework of concepts and relationships [following (3)]

representation of a given system influences the way students perceive it, (3) one cannot understand processes in a biologic system without an understanding of processes and components at different levels of organization.

### DIFFICULTIES IN COMPREHENDING SYSTEMS

Current research on the development of systems thinking argues that students of different age levels, from pre-school to college, face difficulties in understanding various concepts related to systems thinking, such as the respiratory system in biology (1), the water cycle (3), and the rock cycle in Earth Sciences (14). These difficulties are expressed through a superficial understanding of the system, fragmented, and non-coherent knowledge of the biological phenomena as well as misconceptions (12, 13, 15). Those students' difficulties might be a result of the complexity characterizing natural systems, which include multiple components at different organizational levels within which dynamic interactions take place (13). Thus, emphasizing that the components composing the system are insufficiently addressed as well as the processes that take place in the system (9). In addition, in an analysis of Biology text books, findings showed that many books do not attempt to form significant connections between the different organizational levels of biological systems. In this way, for instance, the discussion of the cell concept is often separated from the discussion of the human body systems (2). This raises the necessity for developing effective tools for systems analysis and knowledge organization in the teaching and learning of biological systems. Other research studies in this area address the characterization of systems thinking (3, 10), designing, and examining teaching and learning materials for developing systems thinking skills (3, 8, 12).

The development of cardiovascular health knowledge requires the ability to analyze and understand the heart and blood systems. Due to the complexity of natural systems, students, of all ages, experience great difficulty in understanding and analyzing these systems (3). For example, Hmelo et al. (1) described sixth grade students' difficulties in understanding the human respiratory system. They found that those difficulties derive from a lacking understanding of the existing processes at different organizational levels. They noted that a profound understanding of the functioning systems in the human body entails both an understanding of the existing processes at different organizational levels as well

as an understanding of the systems function as a whole. Similarly, Arnaudin and Mintzes (16) examined misconceptions about the human circulatory system among students at the elementary, secondary, and college levels. Their results indicate that the most resilient to change are understandings of the various organizational levels of the circulatory system and the connections between its components and the processes that take place in the system. A standardized test of cardiovascular health knowledge that was administered to 12–18 years old students and to 20–60 years old adults showed that young students can correctly answer less than half of the items (17). Although this test showed that health knowledge increases gradually during the junior high and high school years, the authors pointed out the importance of developing cardiovascular health knowledge at a young age. We therefore focused our study on the first year of junior high school, and specifically on the seventh grade.

In this study, we characterize students' systems thinking skills in the context of a teaching and learning unit about the human circulatory system, which was developed based on the unified systems thinking model described above (Table 1) and considering students' difficulties in comprehending systems. Specifically, we asked whether seventh grade students, who studied about the human circulatory system, acquired systems thinking skills and what are the characteristics of those skills?

## MATERIALS AND METHODS

### THE CONTEXT OF THE STUDY

Teaching and learning materials focusing on the human circulatory system were developed using the unified model described above (Table 1). Specifically, a unit of 30 teaching hours, which addresses the human circulatory system was developed for seventh grade students (18). The unit was developed in accordance with the requirements from seventh grade students in the new Israeli Ministry of Education Science and Technology curriculum for junior high schools (19). Within this unit, 12 learning activities, organized in a hierarchical order based on the stages in developing systems thinking were integrated. A description of these learning activities appears in Table 2.

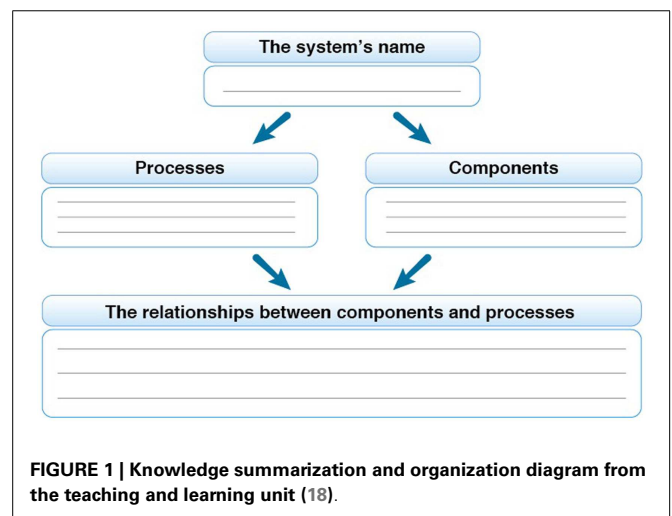
The design of the unit utilized teaching strategies that encourage the learners to construct knowledge while creating learning opportunities in which the learner is active in the organization

**Table 2 | Description of learning activities in the teaching and learning materials.**

Activity number	Description of the activity	The aim of the activity	Stage in developing systems thinking
1	Creating a concept map about the circulatory system in the human body (those maps were used as "pre test")	Eliciting prior knowledge	–
2	Analysis of a familiar system from daily life	Exposing the students to the systems thinking approach, using "knowledge summarization and organization diagram"	The ability to identify components in the system
3	Designing a transport system in an imaginary creature, and Using "knowledge summarization and organization diagram"	Creating motivation for learning Practicing summarizing and organizing knowledge	The ability to identify components in the system
4, 6, 8, 10	Range of activities which encourage formulation of sentences that describe the relationships between the system components	Developing the ability to describe relationships between the system components	The ability to identify simple relationships between the system components The ability to identify dynamic relationships between the system components
5, 7, 9	Analysis of individual components in the cardiovascular system (blood, blood vessels, heart) using the "knowledge summarization and organization diagram"	Developing the ability to analyze small scale systems	The ability to identify components in the system The ability to identify simple relationships between the system components The ability to identify dynamic relationships between the system components
11, 12	Analysis of the cardiovascular system, using the "knowledge summarization and organization diagram"  Creating concept maps about the circulatory system in the human body (those maps were used as "post test")	Developing the ability to analyze complex systems	The ability to identify components in the system The ability to identify simple relationships between the system components The ability to identify dynamic relationships between the system components The ability to organize the system components in a framework of interactions

of his or her own knowledge. This approach is based on the belief that active personal knowledge construction, or knowledge integration, contributes to a meaningful learning process (20). Thus, activities associated with knowledge summarization and organization, constitute a significant portion of the teaching and learning materials. **Figure 1** shows a knowledge summarization and organization diagram integrated in the teaching and learning materials, along with the model for developing systems thinking skills.

The diagram shown in **Figure 1** was designed to promote knowledge organization and analysis of a given system, while specifically differentiating between components, processes, and the relationships between them. The students are initially asked to create a list of the existing components and processes in the system, at different levels of organization. Subsequently, they are asked to connect between the "components" and the "processes."



**FIGURE 1 | Knowledge summarization and organization diagram from the teaching and learning unit (18).**

**RESEARCH POPULATION**

The research population consisted of seventh grade students ( $n = 75$ , 12–13 years old), from three different junior high schools in Israel, and a similar number of boys and girls. The total

number of students who participated in the study was higher (approximately 90 students), but as a few students were absent from the first lesson and a few were absent from the last lesson,

only the concept maps that were formed by students who were present in both time points were taken for analysis.

**CONCEPT MAPS**

In order to characterize student systems thinking skills, concept maps were used. A concept map includes: concepts and relationships. Usually, the concepts appear in circles or rectangles and the relationships between them are indicated by lines and by sentences that are formed between concepts and represent the relationships between the concepts. The relationships describe the bond between each concept pair in one word or sentence (21). In the current study, students were instructed by the researcher to construct concept maps. Initially, they practiced the construction of concept maps using concepts of close interest (for example, family relationships or familiar television programs). This deriving from the assumption that practicing the construction of concept maps is essential for the concept map to serve as a research tool (22). In the next stage, the students were asked to create a concept map of the human circulatory system. The students received a blank page with 12 empty circles, along with instructions for creating a concept map. The instructions did not include any concept and did not address the hierarchy between the concepts, therefore the students were free to elicit any concept they like and to create a personal framework of concepts and relationships matching their perceptions. The process resulted in concept maps with concepts and relationships that were freely elicited by the students and describe the way in which the students organized their knowledge about the human circulatory system.

Analyzing the concept maps (*n* = 150) created by the students enables examining the mental representation of the students. Comparing the concepts elicited by the students as well as the concept maps they created before (*n* = 75) and following (*n* = 75) the learning process enabled us to probe the possible conceptual change the students endured in the course of learning. The analysis of the concept maps was carried out using the unified model for

characterizing systems thinking in biology education, as detailed in **Table 3**.

The analysis started from the left column in **Table 3**, which is hierarchically organized from top to bottom, and continued by moving from left to right in each of the rows in the Table. The second column describes the data analysis of the concept maps. Ten percent of all concept maps were independently analyzed by two researchers and discussed until 95% agreement was achieved. In each row, the basic level is detailed in the third column and the high level in the fourth column, for each of the stages in developing systems thinking skills (**Table 3**). In addition, for measuring students' ability to organize the system components in a framework of interactions, students' concept maps were analyzed in light of four typical concept maps models A–D [see **Figure 2**, following (23)]. The four models describe the complexity level of the interaction framework presented in each map. Model A represents the simplest model (“pairs” model, single, pairs or trios of concepts), model B represents a more complex model (a “spoke” model, one central concept linked to other concepts), model C represents a complex model relative to B (a “chain” model, a few concepts linked to each other), and model D represents the most complex model (a “net” model, a branched framework of concepts).

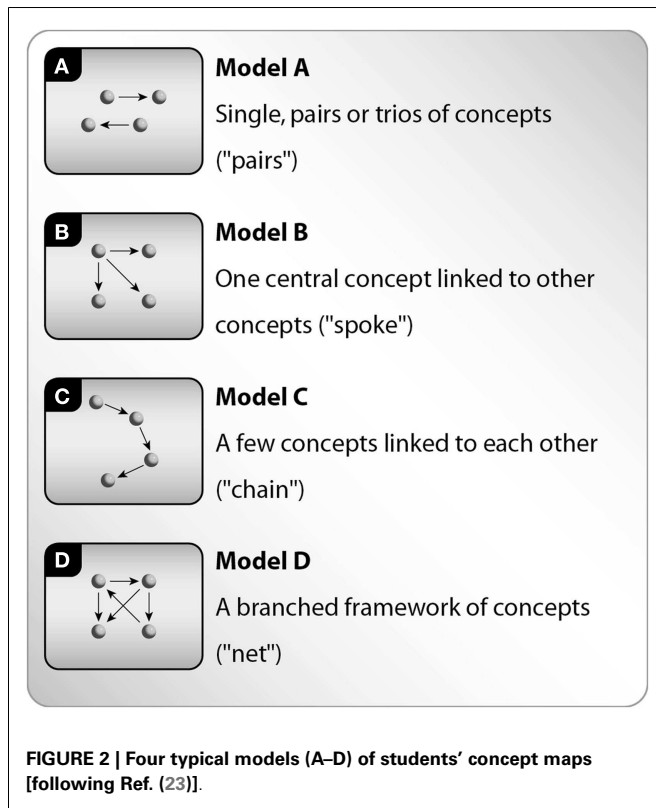
Independent samples *t*-test, Paired *t*-test, as well as  $\chi^2$  test were used for measuring the significance of the observed differences between the two groups (before and following the learning process).

**RESULTS**

Student systems thinking skills were examined in light of the unified systems thinking model presented above. The results are organized according to the four primary systems thinking development stages that are listed in the left column of **Table 1**: (1) the ability to identify components in the system, (2) the ability to identify simple relationships between the system components, (3) the ability to identify dynamic relationships between

**Table 3 | Analysis of the concept maps using the unified model for characterizing systems thinking in biology education.**

Stages in developing systems thinking	Analysis of concept maps	Correlation to the “model for characterizing systems thinking skills in biology”	
		Basic level	High level
The ability to identify components in the system	Counting the number of concepts Classifying the concepts into categories according to the level of organization	Components appear at a single level of organization	Components appear at various levels of organization
The ability to identify simple relationships between the system components	Counting the number of “simple relationships” Classifying the “simple relationships” into categories based on the levels of organization	Simple relationships appear at a single level of organization	Simple relationships appear at various levels of organization
The ability to identify dynamic relationships between the system components	Counting the number of “dynamic relationships” Classifying the “dynamic relationships” into categories based on the levels of organization	Dynamic relationships appear at a single level of organization	Dynamic relationships appear at various levels of organization
The ability to organize the system components in a framework of interactions	Counting the “junctions” (concepts that have connections to at least three other concepts) Classification to models A-D (see <b>Figure 2</b> below)	A poor framework of interactions (A–B)	A rich framework of interactions (C–D)



the system components, (4) the ability to organize the system components in a framework of interactions. The analysis of the students' concept maps ( $n=150$ ) shows that for each of the following parameters a significant increase was noted when comparing between concept maps constructed by the students before ( $n=75$ ) and following ( $n=75$ ) the learning process: number of concepts, number of relations between concepts, number of structural relations between concepts (simple relationships between the system components), number of process relations between concepts (dynamic relationships between the system components), and number of "junctions." The term "junction" refers to a concept that has relations to at least three other concepts on the map, demonstrating students' ability to organize the system components in a framework of interactions (Figure 3), thus implying an improvement in students' acquisition of systems thinking skills, following the learning process.

#### THE ABILITY TO IDENTIFY THE COMPONENTS OF A SYSTEM

The concepts students chose for building their concept maps were examined in light of their organizational level. The concepts were classified into three organizational levels: (1) macro level (organism, system, organ, tissue), (2) micro level (cells, organelles), and (3) sub-micro level [molecules, atoms; following Ref. (24)]. A comparison between the concepts chosen by the students before and following the learning process indicates a significant increase in the average number of concepts in each of the organizational levels, by the end of the learning process (see Figure 4). The highest increase was observed in the number of concepts at the macro

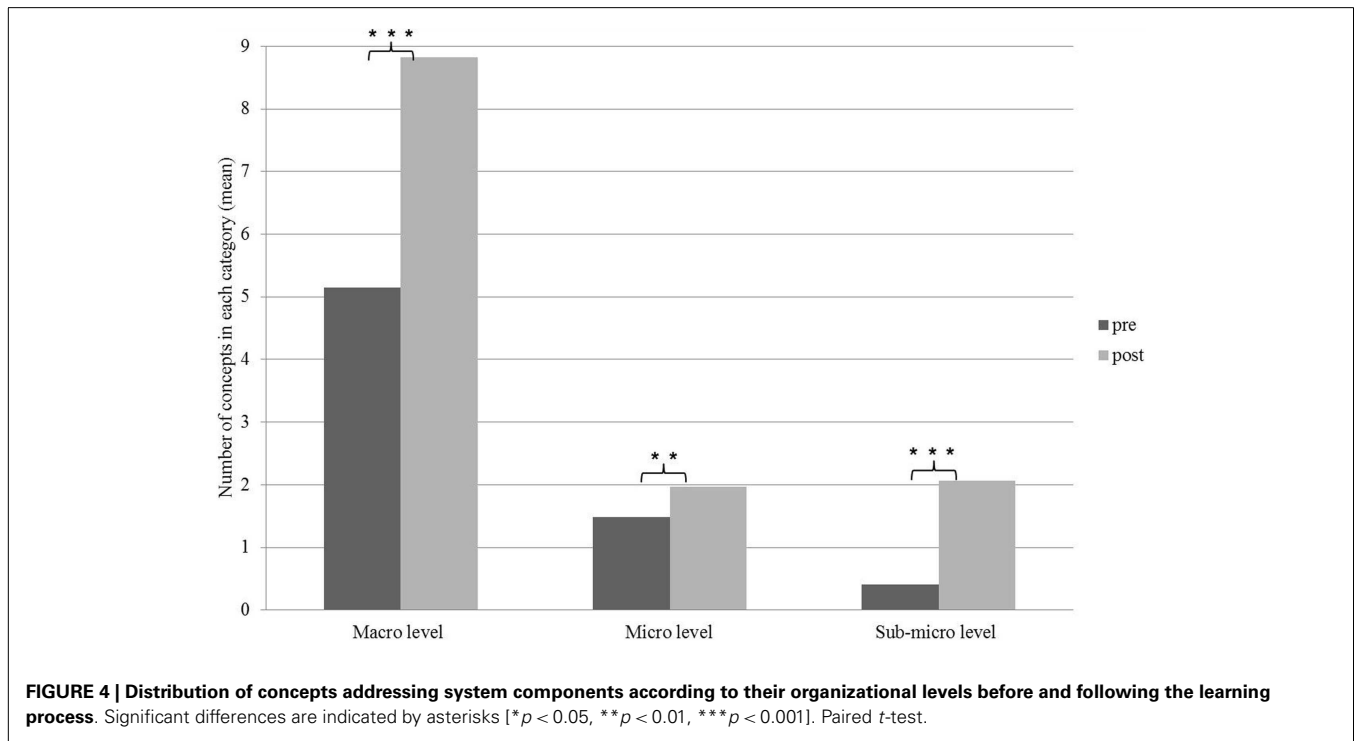
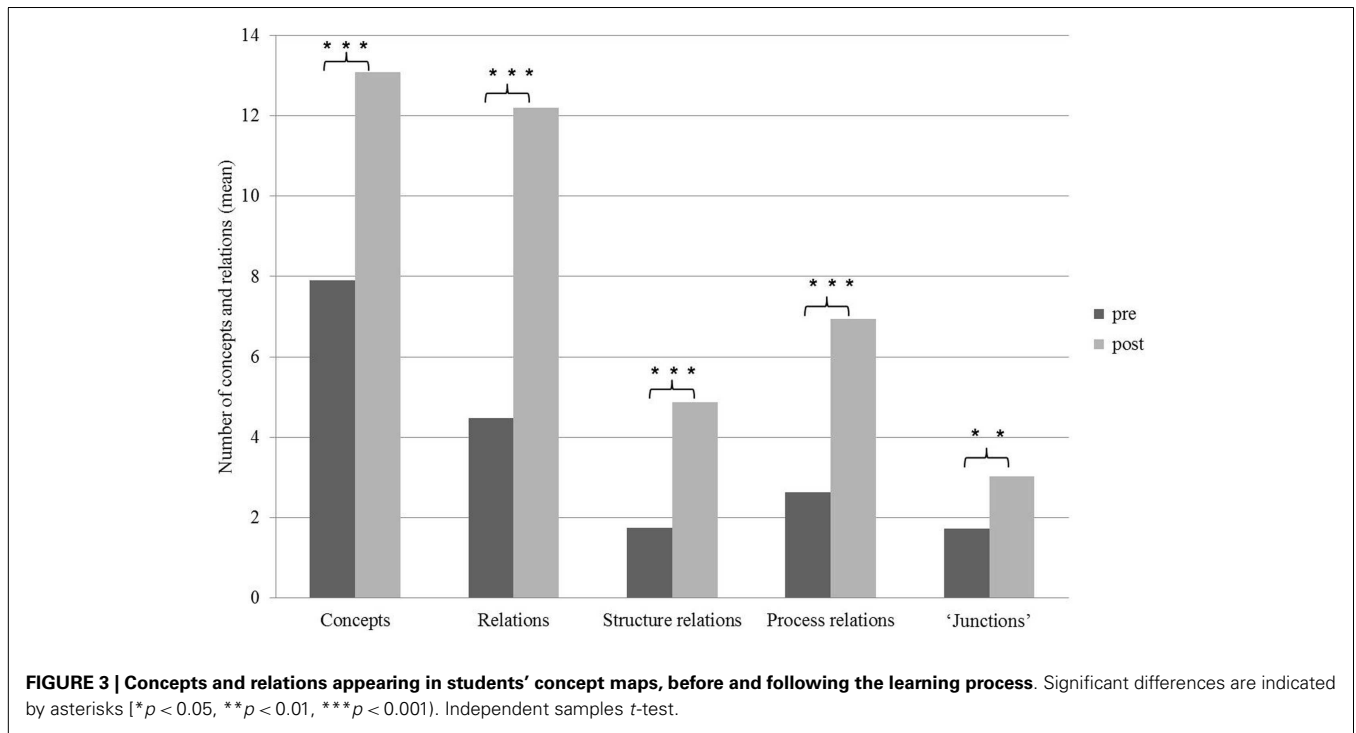
level and the lowest in the number of concepts at the micro and the sub-micro levels.

Examining the concepts themselves revealed that the concepts with the highest incidence in the students' concept maps before the learning process (concepts appearing in 50% of the student entirety word lists) are: heart (100% of the students mentioned this concept), blood (79% of the students mentioned this concept), artery (56% of the students), vein (57% of the students), and red blood cell (53%). However, the highest incidence concepts in students' concept maps following the learning process (concepts appearing in more than 50% of the student entire concept lists) are: heart (100% of the students mentioned this concept), vein (90% of the students mentioned this concept), artery (89% of the students), capillary (78% of the students), blood (71% of the students), oxygen (68% of the students), red blood cell (67% of the students), blood cells (57% of the students), and lungs (53% of the students). It is interesting to note that the concept capillary, mentioned by 78% of the students at the end of the learning process, was mentioned only among 23% of the students before the learning process. The concept oxygen, mentioned by 68% of the students at the end of the learning process, was mentioned only by 24% of the students before the learning process, whereas the concept lungs, mentioned by 54% of the students at the end of the learning process, was mentioned only among 17% of the students before the learning process. Identifying these components as significant in the human circulatory system, by a high percentage of students, may indicate a connection the students form between the human circulatory system and the respiratory system. This connection is not trivial and it may imply an understanding of the system as a whole.

#### THE ABILITY TO IDENTIFY SIMPLE AND DYNAMIC RELATIONSHIPS AMONG A SYSTEM'S COMPONENTS

As mentioned above, following the learning process the students formed more relations between the concepts (Figure 3). The increase in the number of relations is expressed both among the structural relations (or simple relationships, Table 1) as well as among the process relations (or dynamic relationships, Table 1). Interestingly, differences were similarly detected in both the simple as well as in the dynamic relationships, and the process relations were even more pronounced in the concept maps than the structural relations (Figure 3), even though the ability to identify dynamic relationships was previously reported to be more difficult for learners (3).

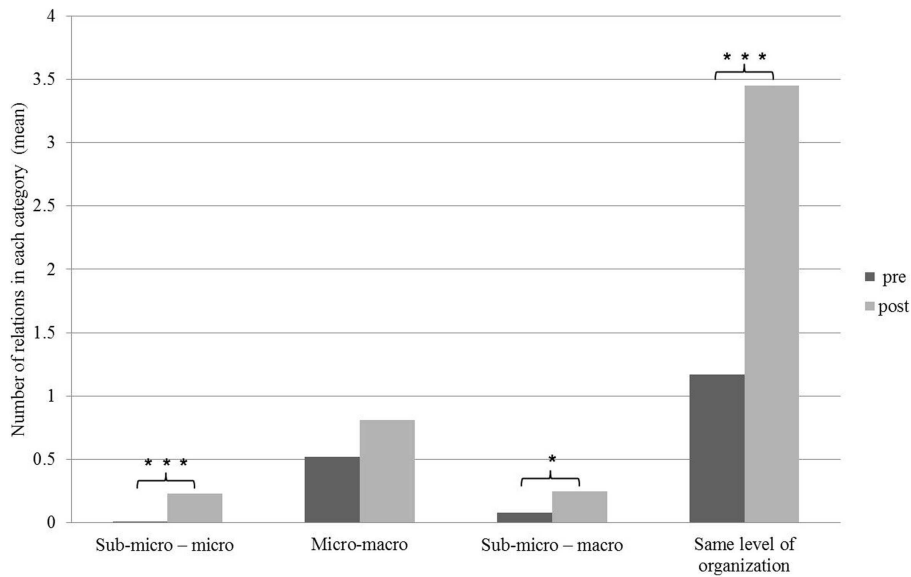
The relationships students formed between concepts were further classified according to the various organizational levels into four groups: (1) sub-micro – micro (relationships connecting between concepts at the sub-micro level to concepts at the micro level of organization), (2) micro–macro (relationships connecting between concepts at the micro level to concepts at the macro level of organization), (3) sub-micro–macro (relationships connecting concepts at the sub-micro level to concepts at the macro level of organization), (4) the same level of organization (relationships connecting between concepts at the same level of organization). Interestingly, despite a significant increase in the number of relationships at each organizational level (both in the simple



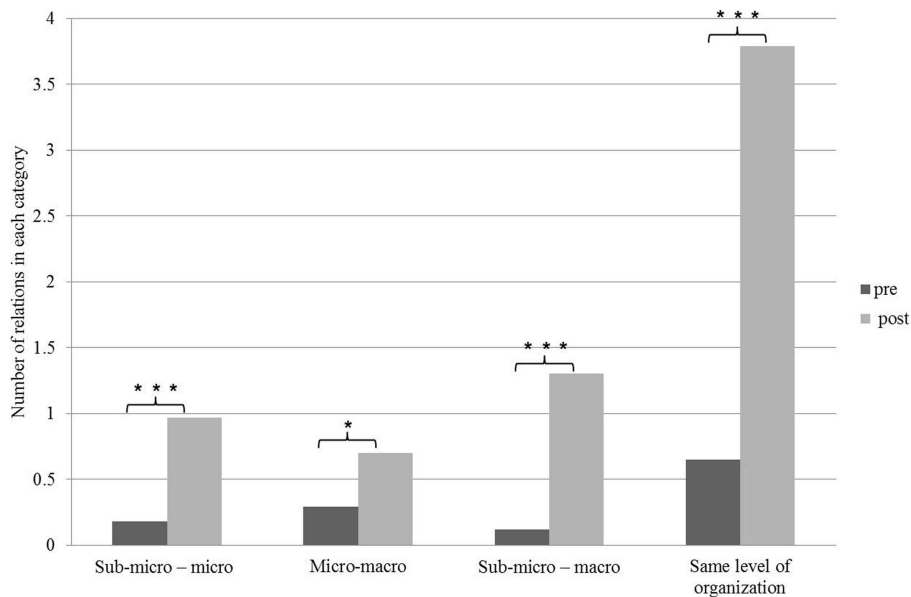
relationships as well as in the dynamic relationships, **Figures 5 and 6**), the most significant difference was identified in the relationships between concepts at the same organizational level, mostly between concepts at the macro level (**Figures 5 and 6**). This finding is in line with previous studies which showed that students

tend to connect components at the same level of organization and face difficulties in identifying relationships between the various levels of organization (12).

Examining the relationships between the different levels of organization raises an interesting conclusion; the observed



**FIGURE 5 | Distribution of simple relationships among students' concept maps before and following the learning process according to the level of organization.** Significant differences are indicated by asterisks ( $*p < 0.05$ ,  $**p < 0.01$ ,  $***p < 0.001$ ). Paired *t*-test.



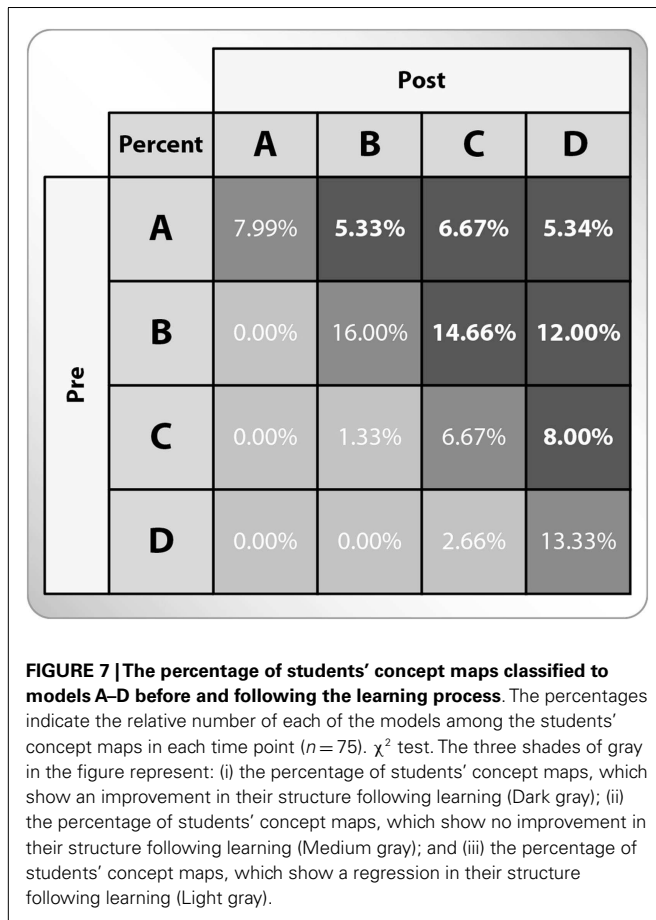
**FIGURE 6 | Distribution of dynamic relationships among students' concept maps before and following the learning process according to the level of organization.** Significant differences are indicated by asterisks ( $*p < 0.05$ ,  $**p < 0.01$ ,  $***p < 0.001$ ). Paired *t*-test.

improvement in students' ability to identify relationships between the different levels of organization is more significantly pronounced in dynamic relationships than in simple relationships. It may be assumed that identifying dynamic relationships encourages the formation of associations between various levels of organization and thus, a more profound understanding of the system.

**THE ABILITY TO ORGANIZE THE SYSTEM COMPONENTS WITHIN A FRAMEWORK OF INTERACTIONS**

Interaction framework analysis was carried out using the four models distribution (A–D, see Figure 2) among the entirety of students' concept maps, composed before and following the learning process. An increase in the complexity of the concept maps was observed following the learning process (see Figure 7). The





structure of 52% of students' concept maps show higher complexity following the learning process (see Dark gray in **Figure 7**), while the structure of 44% of students' concept maps show no change following the learning process (see Medium gray in **Figure 7**), and a smaller percentage (3.9%) of students' concept maps show lower complexity following the learning process (see Light gray in **Figure 7**). It is interesting to note that in the majority of these maps, the total number of concepts and relationships increased. An analysis of the concept map models indicates that the most dominant students' concept map model before the learning process was model B ("spoke," 43%), whereas the most dominant model following the learning process was model D ("net," 39%). Thus, indicating that a more branched knowledge structure and therefore, a probably more profound understanding of the system can be identified following learning. Likewise, model A, representing single, pairs or trios of concepts, appears among 25% of the students' concept maps before the learning process and in only 8% of the students' concept maps following the learning process.

Another interesting point to note is that 28% of the students' concept maps showed an improvement of "one step" (namely, advanced from model A to model B, or from model B to model C) following the learning process, while 19% of the students' concept maps showed an improvement of "two steps" (namely, advanced from model A to model C or from model B to model

D), and 5% of the students' concept maps showed an improvement of "three steps" (namely, advanced from A to D). Thus, many students enriched their knowledge constructs in terms of the number of concepts and the relationships between them. A difficulty in advancing from one model to a more advanced model was observed among the students, since only a very small percentage of students formed more complex concept maps following learning.

## DISCUSSION

In this study, we aimed to examine whether seventh grade students acquired systems thinking skills as well as the characteristics of those skills. We were able to show an improvement among the junior high school students' ability to identify the components of the human circulatory system, while addressing components at different organizational levels. Interestingly, despite the increase in the number of concepts at each of the organizational levels, the most significant increase was noted in the number of concepts at the macro level and the lowest increase was noted in the number of concepts at the micro level. In addition, an improvement was observed in students' ability to identify simple relationships and dynamic relationships in a given system. The largest difference was expressed in the number of dynamic relationships that were formed between the system components, thus indicating higher order systems thinking skills. Moreover, an improvement in students' ability to identify and describe the relationships between a given system's components can be recognized at all the levels of organization, despite the fact that the most significant increase was noted in the relationships connecting concepts at the same level of organization. Moreover, despite the significant improvement in the number of concepts and relationships in the students' concept maps, the structure of most students' concept maps did not advance to a more complex structure following learning.

The circulatory system is considered as one of the most significant five concepts studied in biology education in schools (25). We therefore chose to characterize systems thinking skills of seventh grade students in the context of this system. The unified model (**Table 1**), and the teaching and learning materials that were developed using this systems thinking model, emphasize the explicit differentiation between components, the processes, and the relationships between them at different levels of organization. This derives from the acknowledgment that the development of systems thinking skills in the context of the human circulatory system may influence students' perception of every complex biological system. Thus, this perception is essential both for cardiovascular health knowledge development as well as for health knowledge development and decision making skills in the medical field in general. In this way for instance, when teaching the students about the relationships between nutrition and the prevention of atherosclerosis, we can explicitly differentiate between the components at different levels of organization (the circulatory system, the digestive system, arteries, fats etc.), the phenomena related processes (blood vessel wall fat sedimentation, increased blood pressure, endothelial injury etc.), and the relationships between them at various levels of organization.

The unified model for characterizing systems thinking in biology education that was designed especially for this study,

is based on three principle theoretical models from the field of systems thinking: (1) systems thinking hierarchical model (3), (2) systems thinking competence for cell biology education (12), (3) structure-behavior-function theory (8). The unified model proved to be a useful tool for developing the teaching and learning materials, for analyzing the students' concept maps before and following the learning process, as well as in the characterization of the development of students systems thinking skills.

The results of this study suggest that learning based on this unified model, which was developed in the course of this study, may be considered as an efficient tool for the reorganization of knowledge. Knowledge organization is implemented through integrating new knowledge with existing knowledge and updating it. The study results show that at the end of the learning process the students' glossary regarding the circulatory system increased significantly. The new concepts refer to concepts and processes at all levels of organization. Moreover, students' knowledge became related and coherent, which indicates a profound understanding of the system. When discussing related knowledge from a system perception the emphasis is on the relations made between the system components and its processes at different levels of organization. Students' tendencies to attribute great importance to the structural components of a system on the expense of presenting the existing processes and interactions in the system is well known (15, 26). It appears that the unified model, which emphasizes the dynamic relationships between the components of the system, was fruitful and the students' ability to identify dynamic relationships within the system's components improved significantly following the learning process. In addition, the results indicate that the students' ability to connect between various levels of organization improved following the learning process, but following the learning process the majority of the relationships formed by the students remained at the macro level. This finding indicates the importance of placing a more significant and explicit emphasis on the relationships between various levels of organization when developing teaching and learning materials and suggests a concept for further research. In the following years in junior high school, namely at the eighth and ninth grades, these students will continue to study about other biological systems namely ecological systems, reproductive systems, and digestive systems in living organisms. It is therefore expected that their ability to analyze systems will further develop.

An additional reported difficulty which was raised in prior research is students' ability to connect between the circulatory system and the respiratory system (16, 27), thus impairing students' ability to comprehend the system and its function. This study results indicate that many students learned to associate between the two systems and chose to present these relationships in the concept maps summarizing their knowledge on the concept of the human circulatory system. It is important to mention that in this context the idea that the lungs are a crucial part of the circulatory system, is not appropriately mentioned in traditional textbooks (6). In continuation to this study, it would be interesting to examine the different factors bearing possible effect on students' systems thinking skills. In this way

for instance, we found that many students experienced difficulties making the expected transition from one thinking model to a more advanced thinking model. This difficulty calls for in-depth research that will be focusing on characterizing the students who easily make the transition to a more complex structural model and those who are fixated on a certain thinking model. It will be interesting to examine how the thinking model affects decision making skills regarding health concepts related to the human circulatory system. Furthermore, it will be interesting to examine the class discourse regarding the instruction of biological systems, whilst analyzing the discourse both at the student level and at the class level with regards to their systems thinking skills.

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