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Function before form: An alternative approach to learning about complex systems

Lei Liu, Surabhi Marathe, and Cindy E. Hmelo-Silver

Introduction

By definition, complex systems are difficult for learners to understand. Several features of complex systems make them hard to learn about, such as nonlinear and relational causality as well as invisible and dynamic mechanisms. Experts understand complex systems in various ways. The Structure-Behavior-Function (SBF) representation is an example of a conceptual representation that cuts across many complex systems. It is characteristic of expert knowledge. Research has shown that novices (pre-service teachers and middle school students) understand the human respiratory system with an extremely constrained focus on its constituent structures (Hmelo-Silver & Pfeffer, 2004; Hmelo-Silver, Marathe, & Liu, 2004). They fail to see the mechanisms and the causal relationships within the system and oversimplify the complex causal relations into simple linear causalities. Experts, however see the system as an interrelated web of behaviors and functions that are accomplished by structures. Thus, they hold a coherent understanding of the complicated causal relations within the system. In this paper we describe two different versions of hypermedia design based on SBF framework. One characterizes the expert understanding by foregrounding function (the function-centered); the other stresses the structural orientation instead, like traditional textbooks (the structure-centered). In addition, we present a comparative study of students working in these two versions of hypermedia. We hypothesize that the function-centered hypermedia should facilitate students understand the complex system better than the structure-centered hypermedia.

Theoretical Framework

Our theoretical framework has three main thrusts. First, we consider the nature of complex systems understanding and the barriers to such understanding. Next we consider how computer-based representational tools, such as hypermedia, can help overcome these barriers by embodying a conceptual representation. Finally, we present SBF theory as an appropriate representation to support learning about complex systems.

Complex Systems Understanding

Complex systems' understanding is very important in learning science. However students find it difficult to build up holistic understanding of complex systems, such as electricity (Grotzer & Subbury, 2000), force and motion (White & Frederiksen, 1995), the human respiratory system (Hmelo et al, 2004). Many features of complex systems make them hard to understand. For example, they are composed of multiple interacting levels and the functional aspects of a system are implicit and difficult for students to infer (Chi, et al., 1994; Wilensky & Resnick, 1998). They involve various abstract concepts and relations that are hard for students to represent in their schema. Grotzer and Perkins (2000) posited causal and epistemic complexity creates obstacles to learning. They believe the major difficulty stems from the students' inability to reason about systemic causality.

A large body of research shows that there is big difference between expert and novice understanding of complex systems. Chi, Feltovich, and Glaser (1981) found that learners tend to focus on superficial details and have difficulty seeing the underlying structure that is visible to experts, 1981). Our prior research (Hmelo-Silver & Pfeffer, 2004; Hmelo-Silver et al., 2004) indicates that experts focus more on behaviors, and functions than the novices across two complex systems - the human respiratory system and the aquarium system. Furthermore, novices concentrate on structures, whereas experts tend to talk about interactions between functions and behaviors. Structures are often the most concrete and superficially salient aspects of a complex system, thus they are relatively easy for novices to grasp. For instance, novices only talked about the surface components of the respiratory system, such as lungs, airways, ribs, and seldom mentioned the deep underlying mechanisms, such as how oxygen gets into our body and how diffusion occurs in the lungs. In comparison, experts explained a lot about the underlying mechanisms, such as how the cellular respiration and the diffusion happen, which actually connected most of the components within the system. In other words, expert understanding of such systems is characterized by an emphasis on functions and behaviors and the interactions within systems whereas novices focus on structures. Furthermore, in our baseline study, we found that pre-service teachers and middle school students rarely mentioned those nonsalient elements that are either invisible or involved in the complex causal mechanisms, such as the cellular respiration. Hence, to promote deeper understanding, we need to provide opportunities, such as conceptual models for students to reflect, reorganize and to broaden their repertoire of the causal understanding.

Computer-based Representational Tools

Computer-based tools, such as hypermedia, can use representations that embody conceptual representations to guide the learning process and help promote conceptual change in understanding complex phenomenon. Computers afford visualization and imagery that play a key role in developing students' scientific thinking (Roschelle, Kaput, & Stroup, 2000). The flexibility of going back and forth through links on computers can help students to build up the nonlinear understanding model. In addition, computers can characterize expert understanding of a domain (Pea, 1993) by presenting the information in the way experts tend to organize. For example, according to our previous research, experts tend to focus on the functional-behavioral perspectives of complex systems. We may design hypermedia systems to present the target systems with a functional-behavioral orientation by making the functions and behaviors salient.

Structure-Behavior-Function Theory

To help students overcome the difficulties in understanding complex systems, researchers build various effective computer-based conceptual representations to facilitate students understanding thus leading to eventual conceptual changes. Behind each tool, there is a theoretical frame to support the design of the tool. In this paper, we present a hypermedia representational tool that is effective in prompting students' deep understanding of complex systems, the design of which is based on the Structure-Behavior-Function theory.

The Structure-Behavior-Function (SBF) theory sheds light on causal understanding of systems because of its focus on the dynamic nature and multi-level organization of the system, and relationships between structures, functions and behaviors (Goel et al., 1996). Structures refer to the elements of a system. Behaviors refer to the mechanisms within a system. Finally functions refer to outcomes or roles in a system. For example, the diaphragm would be one of the structures of the human respiratory system. The contracting and relaxing mechanism is an example of the behavior of the diaphragm. The function of the movement of the diaphragm is to create an air pressure differential inside the thoracic cavity so that air can move in and out. The interrelations among structures are often embedded in the execution of behaviors and functions. In complex systems, several structures might be involved in the same function. For example, the diaphragm, intercostal muscles, and ribs are all involved in the same function of moving air into and out of the body. Thus to accomplish this function these structures are coordinated with each other. Similarly, the behavior of one particular structure often has impact on the behavior of other structures. For example, the capillaries transport oxygen and other nutrition throughout the body. However for this behavior to occur, the heart must pump the blood within the capillaries to move. This suggests that instruction that emphasizes behaviors and the functions of a system will help students construct a more coherent understanding of the system. Our previous research demonstrated the differences between expert and novice understanding in terms of SBF theory. In current study, we hypothesize that instruction focused on functions and behaviors should facilitate student complex system understanding more than one focused on structures. To test this hypothesis, we conducted an experiment to compare the effects of two versions of hypermedia systems.

Design of the Hypermedia

To test the value of using SBF theory as an explicit representational tool that embodies conceptual organization, we conducted an experiment using SBF framework to design hypermedia. We designed two hypermedia systems, a function-centered and a structure-centered. The content of the two versions of hypermedia is controlled. The information provided is identical except for different conceptual representations of hypermedia. The essential difference lies in the distinctively embodied conceptual representations.

In the function-centered hypermedia (F-hypermedia), we intended to make the functional and behavioral aspects of the human respiratory system salient. Thus student learning revolves around functions of the system. Specifically, the F-hypermedia starts with two big functional-behavioral questions, to which the answers require a holistic understanding of the human respiratory system (see Figure 1): "Why do we need oxygen?" and "How does oxygen get into the body?" In addition, the F-hypermedia is also designed to help scaffold students in answering the above two questions. For example, to scaffold answering the first question, we provided model answers such as "cells need oxygen to burn food to produce energy", "blood carried oxygen and food to the cell", "Breathing air from outside provides cells with oxygen" (see Figure 2). Thus, by clicking the first question, the students will be led to questions that help the students make connections between external respiration (moving air into and out of the lungs) and internal respiration (occurring at the cellular level). Research has shown that regardless of the interrelationships that exist between elements within a system, novices usually represent systems as isolated structures (Hmelo-Silver & Pfeffer, 2004). Furthermore, re-analysis of our earlier data demonstrated that novices rarely mentioned cellular respiration despite its essential importance in the respiratory system (Hmelo-Silver et al, 2004). By foregrounding function, we provide an alternative conceptual representation that should guide students to connect the salient aspects of air movement with the nonsalient aspects that are easily overlooked.

In contrast, the structure-centered hypermedia (S-hypermedia) presents information in much the same way as a traditional textbook. In S-hypermedia, students move from isolated elements of the system to their respective behaviors and functions. Learners start with a diagram of the human respiratory system with links to each component in the system (see Figure 3) and then from the structure they study respective behavior and function.

Figure 1. Opening screen of the function-oriented hypermedia.

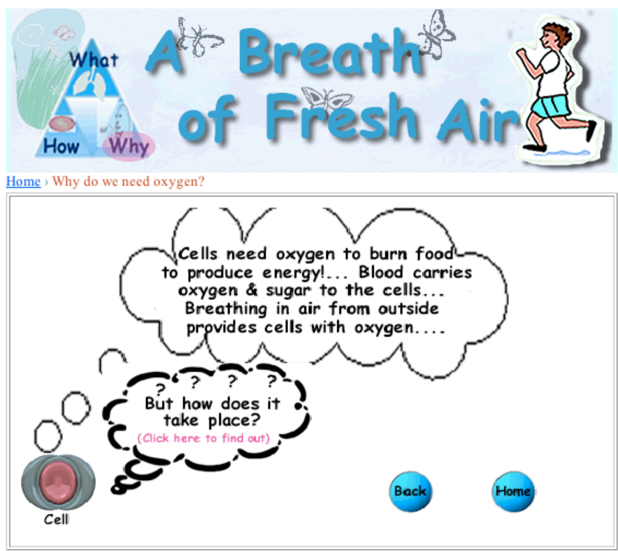

Figure 2. Scaffolding through modeling behavior questions.

In this study, we contrast the effects of learning with the two hypermedia systems. Based on our previous findings that experts tend to focus on functions and behaviors while novices stress on surface structures (Hmelo-Silver & Pfeffer, 2004; Hmelo-Silver et al., 2004), we hypothesized that students who explored the function-centered hypermedia should have better understanding than those students who use the structure-centered hypermedia. That is, after learning with the function-centered hypermedia, students' understanding will be closer to expert mental models which are grounded in the coherent understanding of functions and behaviors. In particular, the students in F-condition should identify more behaviors and functions in their posttests than students in the other condition and develop a more coherent understanding of the system.

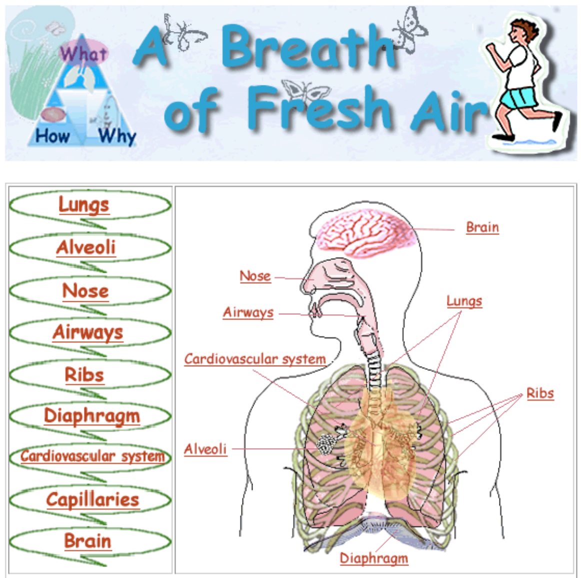

Figure 3. Opening screen of the structure-oriented hypermedia.

Method

Participants

82 undergraduates enrolled in the Educational Psychology t received research credits for their participation. They were randomly assigned to the two hypermedia conditions, namely the function condition (F-condition) and the structure condition (S-condition), working individually to explore the hypermedia. The numbers of students in both conditions were equal.

Materials

The participants used two different versions of hypermedia on the human respiratory system – the functional-behavioral and the structural version. Subjects in F-condition used the functional-behavioral version whereas subjects in the S-condition used the structural version. The two versions of hypermedia shared identical content regarding the human respiratory system, differing only in the organization and the introductory screens. As introduced above the functional-behavioral version of hypermedia had the systematic information organized around functions and behaviors of the components in the human respiratory system. Thus subjects in F-condition started with two major functional-behavioral questions leading them to all the functional-behavioral information. That is, the subjects learned the structural information only after they had viewed the function and behavior of the structures. Alternatively, the structure-oriented version of hypermedia organized the information around the components. Subjects in the S-condition explored structures which led them to behaviors and finally function. Participants received a post-test that was a written version of the clinical interview used in Hmelo-Silver et al., 2004. This instrument asked participants to draw the respiratory system, explain how breathing occurs, the role of various element in the system, and finally, they were asked to solve a problem about a hiker adapted from Rea-Ramirez (1998).

Procedures

All sessions were run in the same computer lab. Before the students entered the lab, all computers showed the opening screen of either F-condition or S-condition. The numbers of computers in both conditions were equal. When the students came in, the experimenter randomly assigned them to individual computers. Before exploring the hypermedia, students were oriented to the hypermedia. They were informed that s they needed to explore the hypermedia system and completing a post-test that measure their mental models based on the measures developed by Hmelo-Silver et al. (2004). To ensure the participants explored the whole system, the experimenter emphasized that they should explore the system for a minimum of 40-min. Approximately 40 minutes later, after the participants completed their exploration of the hypermedia, the experimenter handed out the post-test.

Coding and Analysis

All the answers to the post-test questions were coded using an SBF-based coding scheme (Hmelo-Silver, Holton, & Kolodner, 2000). We coded the whole post-test for the presence of each S, B, or F. In the first column of the coding sheet, we created an exhaustive list of all the structures of the human respiratory system, such as airways, alveoli, blood, brain, capillaries, cellular respiration, diaphragm, heart, lungs, muscles, red blood cells, ribs, vascular system. In the first row, all the coding variables were listed, such as S, B, F. For example, the mention of the lungs was coded as a structure, the mechanisms of gas exchange as a behavior, and the need to provide oxygen as a function. A target S, B, or F could only be coded once. In addition we also coded whether it was correct or incorrect. For example, one learner wrote, "the lungs are to hold air" when talking about the properties of the lungs. We coded it as an incorrect function since the lungs are places where the exchange of oxygen and carbon dioxide takes place. All protocols were coded blind to condition. To check reliability, an independent coder analyzed 20% of the data. The overall agreement was greater than 90%.

The general analysis strategy involved the use of a two-way mixed analysis of variance (ANOVA) to compare the difference in S, B, F between the two conditions as well as to compare the effects on salience SBF vs, Non-salient SBF as a within subjects factor. Because previous research indicates that novices tend to focus on superficially perceptible knowledge of a complex system (Chi et al, 1981), we divided the components of the human respiratory system into the salient and nonsalient variables. The salient components include macrolevel phenomena involved with external respiration, such as airways, brain, diaphragm, heart, lungs, muscles, ribs. On the other hand, the nonsalient components include microlevel phenomena related to gas exchange, transport, and internal respiration, such as alveoli, blood, capillaries, cellular respiration, red blood cells, vascular system.

Results

Because hypermedia systems may embody different conceptual representations so that they provide different conceptual models of understanding to learners, such the F- and the S-hypermedia we designed for current study. We hypothesized that there would be difference between the two conditions in terms of mentioning functions and behaviors in their answers. More specifically, we expected that students in the F-condition should mention more functions and behaviors than students in the S-condition. In addition, we also expected that students in the F-condition should pay more attention to the nonsalient phenomena in the system than those in the S-condition.

As can be seen in Table 1, even though students mentioned more SBF in F-condition, there were no statistically significant differences between the total SBF. However, there was a significant interaction between the degree of salience within the system and the hypermedia condition for structures, behaviors, and functions (*F=13.885,* p*<.000, F=17.863x,* p*<.000, F=8.973x,* p*<.004, respectively)*. The interaction effects are shown in Figures 4, 5, and 6. Simple effects tests demonstrate that there were no differences between the two conditions for salient structure, behaviors, and functions but the F-hypermedia group demonstrated more understanding of nonsalient structures, behaviors, and functions (as indicated in Table 1). This suggests that the more the hypermedia focuses on functions and behaviors, the more emphasis the students put on the nonsalient phenomena.

Table 1. Summary of Means and Standard Deviations.

		Function-centered	Structure-centered
Salient	Structure	6.22 (0.82)	6.41 (0.67)
	Behavior	2.98 (1.92)	3.44 (1.75)
	Function	4.56 (1.43)	4.68 (1.54)
Nonsalient	Structure	4.10 (1.55) *	3.24 (1.16) *
	Behavior	2.15 (1.53) *	1.00(1.16) *
	Function	2.83 (1.43) *	1.88 (1.27) *
Total	Structure	10.32 (1.97)	9.66 (1.61)
	Behavior	5.12 (2.92)	4.43 (2.51)
	Function	7.93 (2.37)	6.56 (2.30)

*Significant differences at p ≤ .05

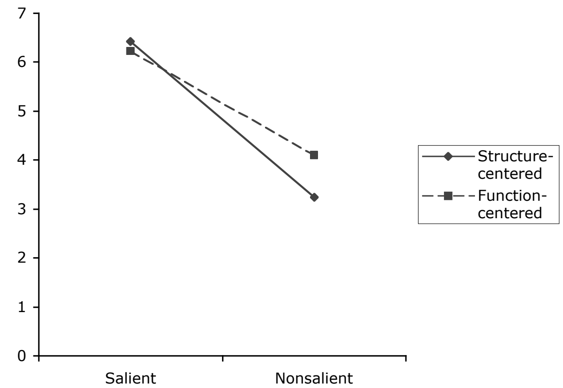

Figure 4. Interaction between the hypermedia type and the degree of salience (structure).

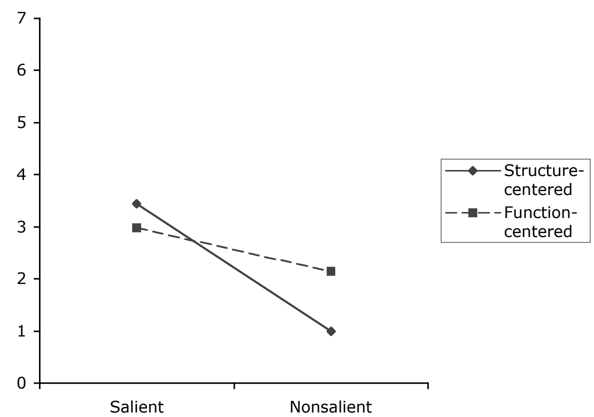

Figure 5. Interaction between the hypermedia type and the degree of salience (behavior).

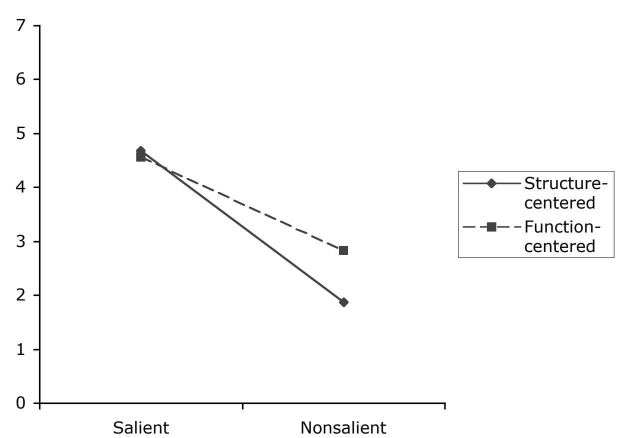

Figure 6. Interaction between the hypermedia type and the degree of salience (function).

In summary, our data analysis supported our hypotheses regarding the effects of the F-centered conceptual representations on students' improvement in nonsalient phenomena understanding within a complex system but not on the salient phenomena. This indicated an interesting focus transfer in student learning produced by different conceptual organization of hypermedia instructions. Specifically, as supported by our previous expert-novice research, students always focused on superficially perceptible phenomena (salient) in a system thus ignored the microlevel but essentially important phenomena (nonsalient). The conceptual representation that characterized expert mental models helped students change their focus from superficial on to deep level of understanding.

Discussion

In current study, we compared the effects of two different versions of hypermedia systems with the SBF theory as the underlying framework. The positive effects of modeling expert conceptual organization in the F-hypermedia (by making functions and behaviors salient) on improved understanding of nonsalient phenomena in the human respiratory system is the primary finding of this study. The results of the study suggest that different organization of computer-based conceptual representations had different influences on student complex system understanding. More importantly, the significant interactive effect of the embodied conceptual representations within hypermedia and the degree of salience of phenomena within the system shows that function-oriented instruction helps students focus on the coherent relationships of functions and behaviors of various. Although there were no difference in understanding salient phenomena, such as airways, ribs, brain, intercostal muscles, students in the F-hypermedia condition did make significant improvement in understanding those nonsalient phenomena, such as the cellular respiration, transporting, which are generally ignored by novices. Understanding these nonsalient phenomena are critical for a deep and coherent understanding of the system. For example, to understand the transporting function of blood, one needs to understand how oxygen gets through the lungs and alveoli, the behaviors that allow diffusion to occur across the alveoli into the capillary, the role of the heart in the process, and how oxygen is released at the cellular level. Hence, the transporting function exemplifies the interconnectedness in the system. In other words, starting learning from functional-behavioral aspects, students thought about on the relationships among different aspects of the system. In contrast, the S-hypermedia presented structures in isolation and did not support to the learners in understanding the interrelationships within the system, thus impeding them in constructing a coherent understanding.

As mentioned earlier, the F-hypermedia was organized to help students answer the two original global questions essential for understanding the human respiratory system (i.e., “Why do we need oxygen?” and “How does oxygen get into the body?”). It also provided scaffolding by modeling responses (“cells need oxygen to burn food to produce energy”) and breaking them down into smaller functional-behavioral questions (“But how does it take place?”). These questions stimulated students to think and reason; these hints provided scaffolding for their trying to answer the two questions. All these features made students’ navigation purposeful and triggered learners knowledge construction. For example, the questions would help students avoid mindless navigation. Such a design is consistent with Goldman and Maxwell’s proposition of designing and building technology-based tools as *thinking tool* that enables students to integrate old and new knowledge (2002). In contrast, the S-hypermedia did not provide such opportunities. Students might have been less purposeful when they navigated the hypermedia.

It is not surprising to see that the S-hypermedia did not work as well as the F-hypermedia in facilitating students’ understanding of the human respiratory system. Grozter and Basca (2003) pointed out that there is a need to provide students the structural knowledge which refers to “the way that experts in a domain deal with foundational concepts, such as causality or categorization, that impact how we frame experience or information” (p. 27). Our results indicate that the functional-behavioral orientation of hypermedia design should help students establish better understanding of the human respiratory system by helping them to organize the old and new information and to notice the essential nonsalient phenomena within the system.

To extend the results to other complex systems, we are currently investigating another complex system – the aquarium ecosystem. We expect to continue to see the differences in the effects of the two versions of hypermedia systems based on the underlying SBF theory. We will also extend our study to middle school populations to see whether these results are replicated with younger learners. In addition, we are investigating whether the SBF conceptual representation of hypermedia affects knowledge co-construction in collaborative learning environments.

Conclusion

In conclusion, the technology-based tool, such as hypermedia, can be used not only as a concrete representation but it can also embody a conceptual representation to facilitate student understanding. We agree with Grozter and Basca's proposition that in order to understand complex systems it is not enough to just provide students the information such as the structure-centered hypermedia and traditional textbooks (Grozter & Basca, 2003). Students also need to learn how to organize the information. The functional-behavioral oriented hypermedia can afford such opportunities. The research presented in this paper indicated that hypermedia systems organized in the expert way by making the functions and behaviors salient should help students understand the human respiratory systems better. In particular, students were driven to focus on nonsalient phenomena as well as the coherent understanding rather than separated pieces of knowledge. In addition, the results also suggest that the functional-behavioral representation should augment student cognitive thinking thus make the hypermedia a mindful tool and students' navigation purposeful.

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