Title

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Designing Better Scaffolding in Simulation-Based Learning Environments Teaching Science Systems: A Pilot Study Report

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Abstract

Systems are an important part in today's science education. Computer simulations have many advantages in teaching science systems. Our research goal is to test whether a hierarchical instructional scaffolding framework embedded in simulation-based learning environments and retrospective mental modeling task could facilitate mental model construction in learning science systems. This pilot study was conducted with a sample of adult learners who didn't have strong science background. They were asked to learn a chemical system in a simulation-based environment. The results show that participants in the hierarchical scaffolding condition performed better than the non-hierarchical scaffolding condition. The retrospective mental modeling task could enhance learning only within the hierarchical scaffolding condition; while in the non-hierarchical scaffolding condition, the task was detrimental to learning. Based on the results from the pilot study, an 8 session curriculum teaching ideal gas laws to middle school students has been designed for our future study.

Keywords: Science systems; simulation-based learning environments; scaffolding.

Research Background

Systems thinking skills have become increasingly important in today's science education. Scientific explanation of mechanism is usually difficult in learning a system (Jacobson & Wilensky, 2006). Studies have demonstrated that learning systems thinking skills go through several sequential stages before learners are able to grasp a network of mechanics-function relations (Assaraf & Orion, 2005); for example, studies on the reasoning processes of complex systems show that novices focus more on the structure of the system, while experts tend to reason around mechanism and functions of the system (Jacobson, 2001).

Structure-Behavior-Function framework (SBF) provides a language to describe experts' and novices' conceptual representations of systemic knowledge (Hmelo-Silver, Marathe& Liu, 2007). Structure refers to the elements of the system, behavior refers the mechanism of how the elements act and interact leading to certain outcomes; and function refers to the roles of the elements or the outcomes caused by the elements' behaviors (Hmelo-Silver, Marathe& Liu, 2007). Explaining mechanism and causality is usually difficult for learners especially when the systems have hierarchical levels (Duncan & Reiser, 2007). One important pedagogical implication from these studies is to provide hierarchical instructional scaffolding based on the SBF framework to help learners iteratively modify their conceptual representations (Liu & Hmelo, 2009).

Mental Models of Science Systems

Mental models are internalized representations of the structural and functional relations of the reality (Johnson-Laird, 1983). The constructivist perspectives imply that mental model construction goes through trajectories, and iterative mental model modification could be very effective (Vosniadou & Brewer, 1992). Learning science systems usually require learners to construct mental models with various entities and a network function relations among the entities, well scaffolded step-wise learning could produce better structured conceptual representations (Clement & Steinberg, 2002).

Active mental modeling, or active rule-driven visualization, involves cognitive processes such as mentally manipulate the visual information to solve a problem (Briggs & Bodner, 2005). Learners' knowledge of a system could still be fragmented after initial learning, retrospective mental modeling around system functions with "what" and "how" questions could facilitate internal information organization, and enhance reflective thinking.

Using Computer Simulations to Teach Science Systems

Deep understanding of a system involves constructing a mental perceptual simulation for information retrieval and reasoning (Black, 2010). Computational modeling and visualizing technology makes it possible to show the otherwise invisible mechanism of systems (Wilensky& Resnick, 1999), which could provide rich perceptual information to ground the abstract concepts (Barsalou, 2008). Multiple dynamic representations at different abstract levels could provide complimentary information, constraining interpretation of any singular representation, and support deep understanding (Ainsworth & VanLabeke, 2004). Active integration of multiple structurally and conceptually mapped representations can potentially facilitate deep learning (van der Meij & de Jong, 2006; Plass, Homer & Hayward, 2009). At different learning stage, different representation could be used for different learning purposes. For example, a concrete graphical representation can be used to depict system phenomena, and an abstract flowchart representation can be used to model symbolic systemic mechanism after sufficient perceptual information has been delivered.

Although multiple dynamic representations in simulation-based environments have the potential to facilitate mental model construction in learning difficult science systems, the instructional scaffolding should be well designed to help learners make full use of the learning environments. Our research question in this pilot study and future studies is: How to design better scaffolding in simulation-based environments teaching science systems? Pedagogical research implies that mental model construction has a hierarchical nature and goes through stages, thus the scaffolding should support sequential and step-wise learning. Additionally, retrospective mental modeling around system function might facilitate internal organization of systemic knowledge.

Hypotheses

H1: Hierarchical scaffolding based on the Structure-Behavior-Function framework produces better learning performance.

H2: Retrospective mental modeling task facilitates internal reconstruction of the system knowledge.

Method

Participants

Participants for this pilot study were 36 adult learners (Mean age: 29.7, SD=7.61) from a graduate school of Education with a diversity of ethnicity. 29 of them were females and 7 were males. Most of them majored in social sciences and humanities fields, and didn't have strong background in science. One case was dropped because the participant totally misunderstood the learning goals and didn't complete the posttest. Another pilot study earlier showed that reasoning across different levels of a complex system and scientific reasoning about causality was difficult even for this population, and that was why we conducted a pilot study in this population before designing the curriculum for the junior high population.

Instrument

Two computer-based simulations teaching three Ideal Gas Laws were used in this study. Participants were asked to learn how Temperature, Volume and Pressure of a certain amount of ideal gas interact and reason about the relationship between lower-level molecular activity and the emergent function. One simulation was a realistic model (see Figure 1) and the other was a conceptual flowchart model (see lower part of Figure 2). These two dynamic representations are structurally and conceptually mapped, depicting and describing the system knowledge at different abstract levels. The realistic model provides rich visual information of the system phenomena while the flowchart model emphasizes the mechanism and causality in the system. The function of a realistic graphic simulation is to provide rich perceptual information grounding the abstract symbolic concepts, and the function of a conceptual model simulation is to constrain the processing of the visual information, reinforce the symbolic level of understanding.

Design

This study employed a 2x2 factorial design testing the effect of hierarchical scaffolding based on SBF conceptual framework (HS), the effect of the retrospective mental modeling task (RMM) and their interaction effect. Regarding the procedure of the experiment, the manipulation of "RMM vs. N-RMM" came after the manipulation of "HS vs. N-HS".

Procedure

1. Participants signed the consent form
2. Participants read through powerpoint slides which gave them an introduction to what they were going to learn
3. Participants interacted with the simulations for a couple of minutes to get familiar with the interface
4. Learning stage: participants were randomly assigned to a condition, given the worksheet which guided them through the whole learning process. They were asked to think aloud as they were learning. Eight sessions were randomly selected to be videotaped and the verbal protocols transcribed.
5. Posttest

The whole session lasted around 70-80 minutes in total for each participant.

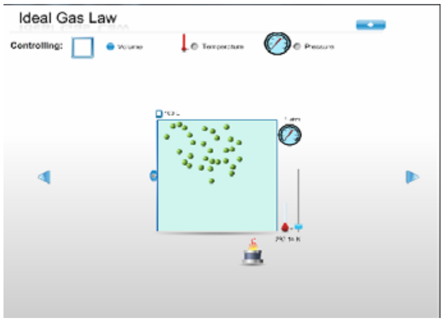

Figure 1: The realistic model simulation-an experiment

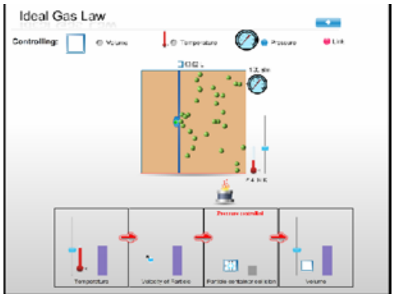

Figure 2: Two simulations displayed on the same page, and dynamically linked

Manipulation

Hierarchical Scaffolding. The instruction was divided into three steps:

Step 1. Learners observed the higher level system function;

Step 2. Learners Described system lower level behaviors;

Step 3. Learners modeled the system causality around the system function.

In step 1, participants played with only the concrete graphic simulation (see Figure 1), and were asked to describe higher level phenomena for each ideal gas law (e.g.: how temperature and volume interact when pressure is constant). In step 2, they were asked to observe and describe lower level element behaviors (gas particle velocity, particle-container collision). In step 3, the instruction is function-centered with questions such as "when pressure is constant, why increasing temperature will lead to increased volume?" With both the concrete graphic simulation and the conceptual flowchart simulation (see Figure 2), participants were required to explain the lower level mechanism in a coherent matter for each ideal gas law. Simply speaking, in the HS condition, participants observed and described system structure and function, integrated fragmented behavior information, then connected the molecular behavior and the emergent T-V-P relationship, and explained the mechanism or causality in a coherent manner.

Non-Hierarchical Scaffolding. Indicated in a previous pilot study, when two simulations were displayed on the same page at the very beginning, participants tended to regard the flowchart concept model as complimentary fragmented behavior information, thus described each bar diagram separately, rather than using it as a modeling tool to explain the system causality. So for the no hierarchical scaffolding condition (N-HS), participants were given the combined simulations interface at the very beginning (see Figure 2); given the worksheet including all the questions asking about the system function and lower-level behaviors for each ideal gas law. The participants were asked to describe the structure, function and behavior knowledge for each ideal gas law, and were not guided to iteratively interrogate with the system. It was ensured that participants in the N-HS condition had same amount of questions asking about the system functions and behaviors compared to the HS condition, while there were no structured progressive learning steps in this condition.

Retrospective Mental Modeling & Control Condition. There were three ideal gas laws for the participants to learn in this experiment. After a participant completed learning one ideal gas law, the other experimental variable (Retrospective mental modeling task) was manipulated. For the retrospective mental modeling condition (RMM), after learning each ideal gas law by interacting with the simulations, the participants were asked to close their eyes, describe the processes of how the phenomenon happens. For the no-retrospective mental modeling condition (N-RMM), there was simply no such a step.

Measures

The posttest included four sections:

1. Comprehension task: participants were given three questions asking them to explain the mechanism for each ideal gas law phenomenon.
2. Four multiple-choice questions on problem solving
3. Explaining new diagrams: participants were given three new line diagrams representing the events happening from time A to time B, and they were required to visualize and describe the what happened in the system
4. Transfer task: participants were asked to explain everyday gas law problems

Results

The posttest results indicate that the groups differ in their understanding of the lower-level molecular activity (the mechanism and processes of the system) but not higher-level structure and function of the system.

Task 1 (Comprehension task) and Task 3 (Explaining diagrams task) measured the understanding of lower-level behaviors and their functions (molecular activity). The answers for Task 1 (Comprehension task) were coded on the presence and absence of lower-level mechanism knowledge units (highest possible score: 7), by two raters blinded to the condition of the participants. The agreement was 93.2%, and the rest was resolved through discussion. The results of Task 1 are displayed in Table 1 and Figure 3.

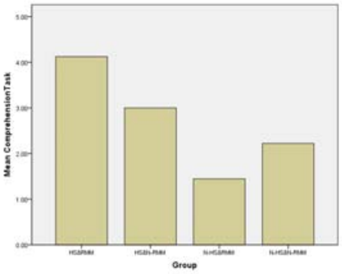

Figure 3. Comprehension task mean scores

Table 1. Comprehension task mean scores

Group	Mean	N	Std. Deviation
HS&RMM	4.1250	8	1.72689
HS&N-RMM	3.0000	9	1.00000
N-HS&RMM	1.4444	9	1.13039
N-HS&N-RMM	2.2222	9	1.09291
Total	2.6571	35	1.55190

Significance tests show that HS has significant effect on learning lower-level element behaviors and their functions, F(1, 31)=16.63, p< .001, no main effect is found for RMM, F(1, 31)=.168, n.s., while the interaction of HS and RMM is significant, F(1, 31)=5.03, p=.032<.05. Post-hoc tests show that HS&RMM performed significantly better than the N-HS&RMM and N-HS&N-RMM group, and the N-HS& RMM performed the worst, which indicates that without hierarchical scaffolding, the retrospective mental modeling will do no good but interfere with the learning.

Task 3 was also coded on the presence and absence of lower-level behavior and function knowledge units (possible highest score 8) by two raters blinded to the condition. The agreement is 95.9%. Participants who described more molecular activity in explaining the abstract line diagrams were believed to notice and appreciate the importance of behavior-function interdependence. The results of Task 3 (see Figure 4 and Table 2) show a similar pattern as in Task 1.

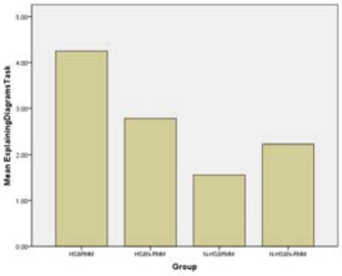

Figure 4. Explaining diagrams mean scores

Table 2. Explaining diagrams task mean scores

Group	Mean	N	Std. Deviation
HS&RMM	4.2500	8	2.81577
HS&N-RMM	2.7778	9	2.86259
N-HS&RMM	1.5556	9	1.50923
N-HS&N-RMM	2.2222	9	2.04803
Total	2.6571	35	2.46078

The main effect of HS is marginally significant, F(1, 31)=4.13, p=.051; although the interaction of HS and RMM is not statistically significant, it is mostly due to a small sample size.

No difference was found in Task 2 (multiple choice questions, highest possible score 4, see Table 3). It might be because the participants tended to do abstract rule-based reasoning rather than applying their mental models in solving the problems, as indicated in the interviews with some of the participants. e.g., one question is “If you want to maintain pressure at a constant level, which of the following combination would work?” Participants will tend to draw abstract rules (e.g., Pressure constant, Temperature increases, Volume increases) and then make the judgment for each choice, without visualizing the molecular activity and the processes of the system.

Table 3. Multiple choices task mean scores

Group	Mean	N	Std. Deviation
HS&RMM	2.7500	8	1.16496
HS&N-RMM	2.6667	9	.86603
N-HS&RMM	2.7778	9	1.09291
N-HS&N-RMM	2.8889	9	1.26930
Total	2.7714	35	1.05957

In task 4, although participants were originally expected to describe lower-level system behaviors to explain the everyday ideal gas law phenomena, many of them focused only on the higher-level structure and function of the system, so the answers were coded on the important system behavior and function knowledge units (both higher-level and lower-level, highest score: 8, see Table 4) The agreement between the two raters was 85.2%. In this task, the participants were only asked to explain the phenomena without explicit questions asking about the molecular activity. The data also imply that in order to help the learners to integrate the invisible lower-level system behaviors into their explanation, another level of scaffolding for transfer might be needed.

Table 4. Transfer task mean scores

Group	Mean	N	Std. Deviation
HS&RMM	4.2500	8	2.81577
HS&N-RMM	4.2222	9	2.10819
N-HS&RMM	4.2222	9	1.30171
N-HS&N-RMM	4.1111	9	2.42097
Total	4.2000	35	2.11159

Some Qualitative Analysis

For better understanding of the effect of hierarchical scaffolding, eight verbal protocols (4 from HS condition, 4 from N-HS condition) were transcribed and analyzed. It was hypothesized that more clear and efficient trajectories of mental model construction could be found in the HS condition. The qualitative data does indicate that the participants in the HS condition were more likely to progressively modify their mental models.

Below are parts of a participant’s verbal transcript (HS condition) which demonstrate how he gradually construct scientific causal model of the system.

When the participant was learning the structure and fragmented behavior knowledge (step 1):

“As the temperature goes down, the volume decreases, the volume goes down, the temperature decreases I guess… yeah…ha…I’ve no idea how that works…but that’s what the simulation tells me. Why would that happen? ‘cause the Temperature goes up, the Pressure goes up, the volume goes down, the pressure goes up…when pressure is constant…when the temperature goes down, volume goes down…hum…”

Here the participant was dealing with the higher-level system function (when pressure is constant, temperature changes cause volume to change), he was curious about how that happens, which prepared him to actively integrate and connect the lower-level molecular behaviors knowledge. This also supports the idea of function-centered scaffolding.

The second part of the transcript indicates the participant was now trying to connect the two levels of information. He was trying to clarify the causal relationship among all the lower level and higher level elements.

“so the temperature and velocity are clearly related, because as I bring the Temperature down, the velocity of particles move. If we wanna keep the pressure the same…So I am guessing, if I move this back, the pressure is probably gonna go…oh the pressure stays the same, the temperature will have to go up…yeah…so as volume increases…the temperature has to go up because…how can I explain that…so we have a constant pressure here, so that means… all of these have to collide at the same rate, that means when there is less space, they have to move a lot slower to maintain the same pressure…yeah……now they have to move a lot faster, the temperature has to go up”

After successfully integrating the information, when the participant was asked to answer the question “why temperature increases, volume increases” in the retrospective mental modeling stage, the participant was able to provide a very sophisticated answer while visualizing the system processes.

“so if the pressure is constant, then as volume decreases, the temperature also has to decrease because the particles have to move at a slower rate in order to maintain the pressure in a smaller volume.”

Below are parts of a participant’s verbal transcript (N-HS condition):

“*so pressure is gonna be controlled…and…temperature and volume…temperature affects volume…so…when you increase the temperature, you increase the volume, you decrease the temperature, you decrease the volume…the velocity also corresponds…and now container-collision is gonna go up…*(confused)”

Here the participant was trying to learn the Temperature-Volume relationship when pressure is controlled. She was given the combined simulations interface at the very beginning (see Figure 2.) and had to construct a hierarchical mental model without the progressive scaffolding. It could be seen that she was trying to integrate all the functional and behavior knowledge, but she struggled in trying to give a coherent explanation.

When she was asked to answer the question “why temperature increases, volume increases” in the retrospective mental modeling task, she failed in integrating lower-lever behavior knowledge in her explanation, as can be seen in the following transcript:

“The temperature increased, the volume increased. When the temperature decreased, volume decreased…Why? I have no idea.”

The qualitative data implies that learners might need to interrogate with the system progressively and iteratively in order to form deep understanding. Experiencing the system function and integrate the system behavior knowledge based on the system function could be very effective. Another implication is that modeling causality after learners have observed all the system behaviors lead to more compact and sophisticated mental models.

Discussion

This pilot study demonstrates that hierarchical scaffolding (HS) could help learners better integrate the lower-level system behavior knowledge and learn the causality. The interaction between hierarchical scaffolding and retrospective mental modeling is interesting. It seems retrospective mental modeling could enhance learning only when the learning process itself is well scaffolded. One explanation is that learners need to internalize the knowledge in a well structured way before they can mentally reorganize the information in a coherent manner.

Without such a structure, mentally reorganizing the information might counter learning.

Limitations and Future Study

This pilot study only included three-step scaffolding because we assumed the adult learners should be already familiar with the everyday ideal gas law phenomena. The total learning time was very short since this system was not too challenging to the adult learners. Based on the implications from this pilot, we have designed an 8 session curriculum teaching ideal gas laws for 7th and 8th graders. The hierarchical scaffolding is now operationalized into 5 steps, which help the junior high students gradually construct better mental models of the systems. Everyday ideal gas law problems are also incorporated into the simulation environment (e.g., students are able to manipulate the fire icon to make a soda can explode, etc). In our future study, learners' learning trajectory will also be recorded and analyzed to better answer our research question. To reduce the cognitive load in integrating the system behaviors and modeling system causality , two techniques are used in designing the simulations: a. the everyday ideal gas law simulation and the gas molecules simulation are dynamically linked for students to compare and analyze the different levels of the system (example, see Figure 5). b. Concrete icons instead of bar diagrams are used in the flowchart simulation which helps learners to model system causality (see Figure 6).

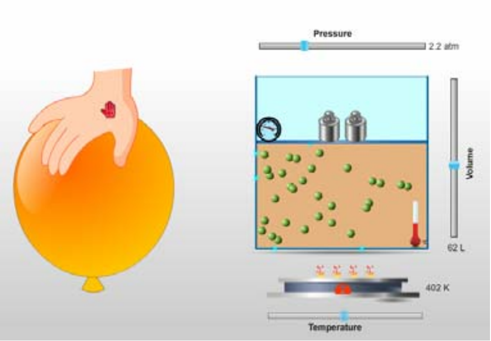

Figure 5. The everyday gas law problem and the molecule simulation dynamically linked

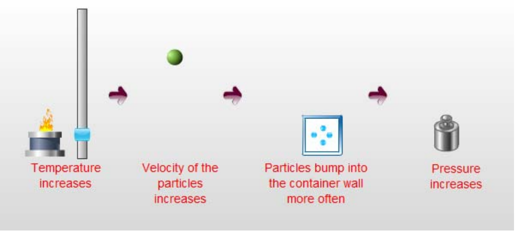

Figure 6. The flowchart simulation with concrete dynamic icons

References

Ainsworth, S. & van Labeke, N. (2004) Multiple forms of dynamic representation. *Learning and Instruction, 14,* 241–255.

Assaraf, O. B., & Orion, N. (2005). Development of system thinking skills in the context of earth system education. *Journal of Research in Science Teaching, 42*(5), 518-560.

Black, J. B. (2010). An embodied/grounded cognition perspective on educational Technology. In Issa Saleh (Ed.) *New science of learning: Cognition computers and collaboration in education*. Springer Publishing.

Barsalou, L.W. (2008). Grounded cognition. *Annual Review of Psychology, 59,* 617-645.

Briggs, M., & Bodner, G (2005): A Model of Molecular visualization. In J. K. Gilbert (Ed.): Visualization in Science Education, pp. 61-72. Springer.

Clement, J., & Steinberg, M. (2002). Step-wise Evolution of Mental Models of Electric Circuits: A "Learning-Aloud" Case Study. *Journal of the Learning Sciences, 11*(4), 389-452.

Duncan, R. G., & Reiser, B. J. (2007). Reasoning across ntologically distinct levels: Students' understandings of molecular genetics. *Journal of Research in Science Teaching, 44*(7), 938-959.

Hmelo-Silver, C. E., Marathe, S., & Liu, L. (2007). Fish swim, rocks sit, and lungs breathe: Expert-novice understanding of complex systems. *Journal of the Learning Sciences, 16*(3), 307-331.

Jacobson, M. J. (2001). Problem solving, cognition, and complex systems: Differences between experts and novices. *Complexity, 6*(3), 41-49.

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

Johnson-Laird, P. N. (1983). *Mental models: Towards a cognitive science of language, interferences and consciousness.* Cambridge, England: Cambridge University Press.

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

Plass J., Homer B., & Hayward E. (2009). Design factors for educationally effective animations and simulations. *Journal of Computing and Higher Education, 21,* 31-61.

van der Meij, J., & de Jong, T. (2006). Supporting students' learning with multiple representations in a dynamic simulation-based learning environment. Learning and Instruction, 16, 199–212.

Vosniadou, S., & Brewer, W. F. (1992). Mental models of the earth: A study of Conceptual Change in Childhood. *Cognitive Psychology, 24,* 535-585.

Wilensky, U., & Resnick, M. (1999). Thinking in levels: A dynamic systems perspective to making sense of the world. *Journal of Science Education and Technology, 8*(1), 3-19.