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Effect of Cognitive Regulation in Understanding Complex Science Systems During Simulation-based Inquiry Learning

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Understanding complex systems is fundamental to understanding science. The complexity of science systems makes them very difficult to understand because they are composed of large number of variables with dynamic interdependencies that determines the behavior of the systems. Hence, understanding complex system requires students to build an accurate mental model of the system components depicting the causal interrelationships among them. Proponents of the inquiry-based science education argue that through the scientific method learner scan effectively build accurate mental models of the complex science systems and learn the deep principles that govern them. However, the literature on the effectiveness of inquiry learning has mixed results. Prior studies suggest that inquiry learning of complex systems calls for multivariate analysis, which requires high-level cognitive regulation skills to be effective. The goal of this study was to investigate the effect of learners' cognitive regulation skills on their understanding of complex systems during inquiry learning. Ninety ninth-grade students were provided with a complex problem task that called for their understanding of a complex lake ecology system in the context of a simulation-based inquiry-learning environment. Findings confirmed the crucial importance of cognitive regulation during inquiry learning. In addition, results suggested that task complexity was an important factor affecting cognitive regulation of inquiry processes, which may have implications for designing cognitive regulation scaffolds.

Keywords: Cognitive regulation; complex systems; complex problem solving; simulation; inquiry learning; science education.

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INTRODUCTION

Understanding science calls for understanding complex systems. Self-organizing and adaptive biological systems such as cell biology; physiological systems such as those based on various multifunction organs including the brain and the immune system; ecological systems such as a lake ecosystem are all examples of complex systems.

Complex systems include many components that dynamically interact with each other. Hence, a complex system dynamically changes over time. These interactions between system components are fairly rich. For instance, any component of the system influences, and is influenced by, quite a few other components. The interactions themselves have a number of important characteristics. Firstly, the interactions are *non-linear*. Non-linearity means that small causes can have large effects, and vice versa. There are loops in the interactions. The effect of any activity can feed back onto itself, sometimes directly, sometimes after a number of intervening stages. This feedback can be positive (a.k.a. reinforcing or amplifying) or negative (a.k.a. balancing or stabilizing). An example of a positive feedback loop in human physiology can be observed in the process of blood clotting. The positive feedback loop is initiated when injured tissue releases signal chemicals that activate platelets in the blood. An activated platelet releases chemicals to activate more platelets, causing a rapid cascade and the formation of a blood clot. Examples of negative feedback loops can be observed in many of the biological processes in humans, from regulation of body temperature to the regulation of blood glucose levels. The disruption of such negative feedback loops leads to serious health problems. For instance, in the case of blood glucose levels, if negative feedback loop fails, the glucose levels in the blood begin to rise dramatically, which lead to diabetes. Complex systems operate under conditions far from equilibrium. There has to be a constant flow of energy to maintain the organization of the system and to ensure its survival. Therefore, complex systems seek to remain at a *dynamic equilibrium* through the use of self-correcting feedback loops. The interactions among different levels are dynamic as the system constantly recalibrates itself to remain at a dynamic equilibrium. This can result in novel features, usually referred to in terms of emergent properties.

All of these properties of complex systems make it unideal for humans to understand them through the *analytical method*, which has been one of the most important scientific tools. In the analytical method, if something is too complex to be grasped as a whole, it is divided into manageable units, which can be analyzed separately and then put together again. In a complex system, the interactions among components of the system and its environment are of such a nature that the system cannot be fully understood simply by analyzing its components. A complex system is not constituted merely by the sum of its components, but also by the intricate relationships between these components. In 'cutting up' a system, the analytical method destroys what it seeks to understand. Hence, learning about the *components* of a complex system does not result in students' actual understanding of the complex system.

Understanding complex systems require students to build an accurate mental model of the complex system depicting the causal interrelationships among system components. Proponents of the inquiry-based science education strongly argue that through the *scientific method* in an inquiry-based learning environment, students can effectively build accurate mental models of the complex science systems and learn the deep principles that govern them (Bransford, Brown, & Cocking, 2000; Cavalli-Sforza, Weiner, & Lesgold, 1994; Eisenhart, Finkel, & Marion, 1996; McGinn & Roth, 1999; Palincsar & Magnusson, 2001). During inquiry learning, students:

> Design studies, collect information, analyze data and construct evidence. ... They then debate the conclusion that *they* derive from their evidence. In effect the students build and argue about theories. ... Question posing, theorizing, and argumentation form the structure of the students' scientific activity. ... The process as a whole provide[s] a richer, more scientifically grounded experience than the conventional focus on text- books or laboratory demonstrations (Bransford Brown, & Cocking, 2000, pp. 171–172).

Is inquiry-based science education capable of delivering on its promise of supporting students' in their construction of accurate mental models of complex science systems? The arguments supporting its merits rest on a critical assumption. The assumption is that students possess the cognitive regulation skills, which refer to how individuals engage in a recursive process utilizing feedback mechanisms to direct and adjust their learning and problem-solving activities (Azevedo, Cromley, & Seibert, 2004; Manlove, Lazonder, & de Jong, 2009). Cognitive regulation enables students to engage in the scientific method in a way that allows them to infer from their investigations of a complex system: (1) which variables are responsible for an outcome; (2) how a change in the level of one variable causes a change in one or more other variables; (3) which variables are not responsible, thus, should be eliminated as sources of influence in understanding how the complex system functions. To further complicate matters, the characteristics of the complex system may change over the course of investigation due to some unexpected time-delayed effects of the in transparent interrelationships among system components. Correspondingly, it is argued that inquiry learning of a complex system calls for *multivariable analysis*, which requires high-level cognitive regulation skills (Azevedo, Cromley, et al., 2004; Eseryel & Law, 2010; Kuhn, Black, Keselman, & Kaplan, 2000). However, there exists little educational research on students engaged in inquiry learning that would answer this question directly (Hmelo-Silver & Azevedo, 2006).

The purpose of this study is to address this gap in the literature by investigating the effect of cognitive regulation in students' understanding of complex systems in the context of simulation-based inquiry learning of a complex lake ecology system. In the following section, we first review the requirements for the mental model transition targeted in inquiry learning of complex systems. Next, we review the literature on how to scaffold students' cognitive regulation in order to support desired mental model transition during inquiry learning. Following the presentation of the study, we discuss the interpretation of the findings and implications for future studies.

Mental Models Underlying Inquiry Learning of Complex Systems

In Rumelhart, Smolensky, McClelland, & Hinton's (1986) terms, inquiry learning of a complex system calls for the interplay between schemata and mental models, which fulfills the basic cognitive functions of *assimilation* and *accommodation* as described in Piaget's epistemology. Schemata assimilate new information into cognitive structures and constitute the fundamental basis for constructing mental models that aid in the process of accommodation (Seel, 2001). Consequently, the construction of a mental model in the course of learning often necessitates both a restructuring of the underlying representations and a reconceptualization of the related concepts (Seel, 2006).

Evidence that is available from the literature on scientific reasoning suggests significant strategic weaknesses that have implications for inquiry learning of complex systems. Based on a series of studies Kuhn and colleagues found that students start inquiry learning with an incorrect mental model, which impedes their learning from the inquiry processes because their incorrect mental models are resistant to revision (Kuhn, Amsel, & O'Loughlin, 1988; Kuhn, et al., 2000; Kuhn, Garcia-Mila, Zohar, & Andersen, 1995; Kuhn, Schauble, & Garcia-Mila, 1992). These findings underline the importance of cognitive regulation skills in order for the students to benefit from inquiry learning.

The incomplete or incorrect mental model, with which the students start their inquiry learning process, dictates the construction of their very first hypothesis to test the causality between the variables. If the students successfully engage in the scientific method, following a number of inquiry experiments, it is expected that they will discover the dynamic causal interrelationships among the components of a complex system and revise their mental model (Figure 1). During inquiry

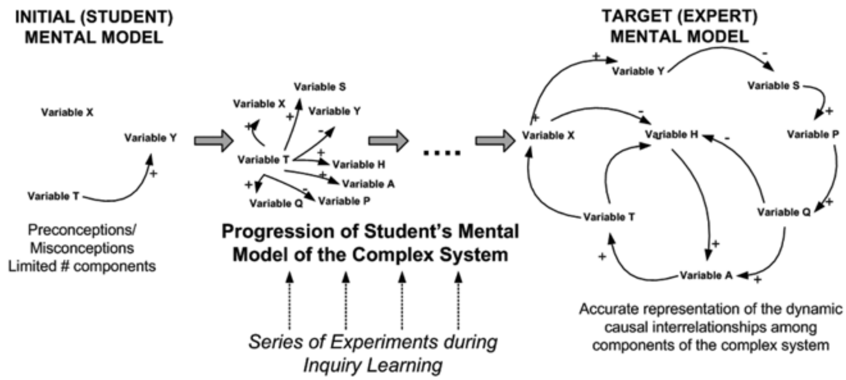

FIGURE 1
Hypothetical student's mental model progression of a complex system during inquiry learning.

learning, students are taught to engage in a *controlled comparison* investigation strategy, which is intended to support their cognitive regulation (DeLoache, Miller, & Pierroutsakos, 1988; Klahr, 2000; Kuhn, et al., 1988; Zimmerman, 2000). Controlled comparison strategy requires the students to recognize that to conduct a sound test of the effect of one variable, all other variables must be held constant, so that the effects of these other variables do not affect the outcome. For instance, the hypothetical student in Figure 1 starts with the assumption that Variable T affects Variable Y in the complex system under investigation. In order to test this hypothesis, she would manipulate Variable T keeping everything else constant. As a result, she would find that Variable Y changes as hypothesized; but so do a number of other variables. Even though there is no direct causal relationship between Variable T and Variable Y; Variable T affects Variable X, which affects variables Y, which then affects Variable S, and so on (see the targeted mental model in Figure 1). How could a student interpret these changes in multiple variables but transition to a second mental model that has more misconceptions? The controlled comparison strategy dictates that students form another hypothesis in an effort to isolate compounding factors. In this way, the strategy supports students' regulation of their cognition during the interpretation of the findings so they form a follow-up hypothesis to uncover piece-by-piece the characteristics of the complex system under investigation. However, this is not a very easy task since the system under investigation is a complex system, in which the relationships are dynamic, non-linear, and unbounded as seen in Figure 1.

In the research presented in this article, we first examine the extent to which cognitive regulation due to inquiry processes impact students' understanding of complex systems and facilitate a successful mental model transition (from an incorrect to correct mental model). There is evidence to suggest that the controlled comparison strategy underlying inquiry learning may not be sufficient, by itself, in supporting students' cognitive regulation when the object of the inquiry is a complex system (Eseryel & Law, 2010; Kuhn, et al., 2000). Thus, a related question is how additional cognitive regulation scaffolding strategies could be effectively integrated in inquiry learning to support students' mental model transition.

Scaffolding Cognitive Regulation via Dynamic Question Prompts During Inquiry Learning

One way to scaffold students' cognitive regulation during inquiry learning of a complex system is by providing them with question prompts at the end of each inquiry cycle (Davis & Linn, 2000; Ge & Land, 2004). During inquiry learning, it is important for the students to elaborate on what they have observed and integrate these observations into their understanding of the complex systems. However, seeking relevant information to understand complex systems can be very challenging due to the multivariable causal analysis required during inquiry learning. However, the literature on the effectiveness of questions prompts during inquiry learning points to mixed results (e.g., Choi, Land, & Turgeon, 2005; Greene & Land, 2000).

One possible factor that affects the effectiveness of the question prompts is the content of the scaffold. Greene and Land (2000) found that questions prompts needed to be dynamically provided to be effective. They suggested that learners were stubborn with their own understandings. As a result, learners tended to ignore static resources or procedural scaffolds, which did not directly confront learners' misconceptions. Azevedo and his colleagues (Azevedo, Cromley, et al., 2004; Azevedo, Cromley, Winters, Moos, & Greene, 2005) also had very similar findings. They compared two groups of students: one were provided with question prompts, and the other had the help of a tutor that scaffolded their self-regulation skills. Although both groups enhanced their declarative knowledge, students who had the help of a tutor gained deeper conceptual understanding. Thus, the content of the scaffold is important, and the effect of the scaffold can be enhanced if the scaffold can dynamically be adapted to students' understanding of the problem.

During the inquiry learning of a complex system, students are expected to construct and reconstruct a series of mental models, depicting the complex system in their "mind's eye" (Seel, 2001, pp. 407) as a causal network of system components and their dynamic interrelationships. The characteristics of complex systems make this task particularly challenging because they comprise multiple levels of organization that often depend on local interactions (Ferrari & Chi, 1998; Wilensky &

Resnick, 1999). The relationships across these levels may not always be intuitively obvious. Studies of complex systems suggest that invisible, dynamic phenomena pose considerable barriers to students' understanding (Feltovich, Coulson, Spiro, & Dawson-Saunders, 1992). One reason for this difficulty is that processing all the simultaneous events and interactions pose a substantial load on working memory due to the mental simulation process and rule-based inferences needed to construct a complete mental model (Graesser, 1999; Kirschner, Sweller, & Clark, 2006; Narayanan & Hegarty, 1998).

However, despite the emergent nature of complex systems, there are deep principles that explain behaviors in complex systems and account for the relationships across levels. Prior studies on expertise have demonstrated that experts are efficient problem solvers because they organize their knowledge around deep principles of a domain, which reduces their cognitive load during complex problem solving (Chi, Feltovich, & Glaser, 1981; Eseryel, 2006; Larkin, McDermott, Simon, & Simon, 1980; Norman, Trott, Brooks, & Smith, 1994; Wineburg, 1991). For example, in the study presented in this article, the students investigate the complex ecosystem of Lake Mirabile in a simulation-based inquiry learning environment. Lake Mirabile contains eight different species and other components such as detritus, nutrients, oxygen, carbon dioxide, and the sun. Hence, during their inquiry learning, students enter in a multivariable analysis of thirteen variables trying to identify the dynamic interrelationships among them. As Miller (1956) stated, human information processing capability is limited so humans can effectively manipulate $5 +/- 2$ variables; hence trying to make sense of the interrelationships among thirteen variables lead to significant cognitive load for students. Experts, on the other hand, who have access to deeper domain principles, would collapse these variables into four higher-level categories as: carnivores, herbivores, plants, and decomposers. Furthermore, experts can foresee the complex relationship among the variables. For instance, they would know that plants produce oxygen to supply for the carnivores, herbivores, and decomposer to survive; and carnivores, herbivores, and decomposers produce carbon dioxide to supply plants for the photosynthesis. In this way, experts would solve the problems presented by the inquiry learning system much more efficiently and with considerably lower levels of cognitive load than novices.

Thus, an important question is whether, at the end of each inquiry cycle, prompting students with dynamic questions, which aims at directing their attention to these deeper domain principles, would effectively scaffold their cognitive regulation resulting with improved understanding of a complex system. We hypothesized that scaffolding students' cognitive regulation by dynamic question prompts during inquiry learning would support the multivariable analysis required for their effective inquiry learning, and thus positively affect their understanding of the complex system.

THE PRESENT STUDY

Based on prior research reviewed earlier, we also hypothesized that when students' cognitive regulation is scaffolded with dynamic question prompts, which aim at directing their attention to deeper domain principles, they would be able to successfully engage in a multivariate analysis during inquiry learning and improve their understanding of a complex system. Thus, the first research question was posed in this study as:

> Research Question #1. Does cognitive regulation due to dynamic question prompts (CR_{QP}) have an impact on students' understanding of a complex system?

The goal of the inquiry learning is for the students to discover deep principles themselves by investigating, analyzing, and accurately representing a dynamic, multivariable complex system. During the inquiry learning process, the *controlled comparison* investigation strategy is intended to scaffold student's regulation of their cognition so they can interpret the findings of one inquiry learning cycle to reformulate a new hypothesis and start a new cycle of inquiry. We argued that when the object of inquiry is a complex system the inquiry process calls for multivariable analysis. Thus, we hypothesized that the controlled comparison strategy underlying inquiry learning would be insufficient to scaffold students' inquiry processes. Unless students' posses high levels of cognitive regulation skills they would not be able to interpret the results of their experiments to formulate effective hypothesis and achieve the intended mental model transition during inquiry learning. Hence, the following research question was posed in this research study:

> Research Question #2. Does cognitive regulation due to inquiry processes (CR_{IP}) have an impact on students' understanding of a complex system?

Although we hypothesize that students' cognitive regulation may have an impact on students' understanding of a complex system, it may not be easy for students to reflect on both the inquiry supports and question prompts. Previous studies suggest that when the system in question is highly complex or when students do not have the mental model structure to accommodate the question prompts, they would not be able to relate to the question prompts (Eseryel & Law, 2010; Kuhn et al., 2000). In these situations, the question prompts would be ineffective as a cognitive regulation scaffold; may even add to the cognitive load of students and further inhibit their learning. Moreover, prior research suggest that if students already possess high cognitive regulation skills that enable them to engage in an effective inquiry learning process, they may ignore questions prompts all together, in which case, it would not add to their cognitive regulation above and beyond that is afforded by the inquiry process (Eseryel & Law, 2010). Alternatively, students with high cognitive regulation skills may be confused by the additional question prompts, which may then add to their cognitive load (Eseryel & Law, 2010). Either scenario may inhibit students' mental model progression during inquiry learning, thus, negatively impact their understanding of the complex system. Hence, we posed two more research questions:

> <u>Research Question#3</u>. Does cognitive regulation due to dynamic question prompts (CR_{QP}) enhance students' understanding of a complex system above and beyond what is afforded by cognitive regulation due to inquiry processes (CR_{IP})?

> <u>Research Question#4</u>. Are there any interaction effects between cognitive regulation due to dynamic question prompts (CR_{QP}) and cognitive regulation due to inquiry processes (CR_{IP}) that impact students' understanding of a complex system?

METHOD

Participants

159 ninth grade students from a rural high school in Midwest participated in this study. The data presented in this paper is from 90 students, from whom we received both parental consent and student assent forms. Demographics of the participants were as follows: 74 (47%) males and 85 (52.87%) females; 17 (11%) African Americans, 3 (1%)Asian Americans, 62 (39%) Caucasian, 4 (3%) Hispanic, and 73 (46%) Native Americans. 78 (49%) of the students were on free and reduced lunch (F/R); 3 (2%) were English language learners (ELL). 14 (9%) of the students were *main streamed* special education students, i.e., they were integrated in regular classrooms and they did not require special educators to sit with them during classes and to support them during classroom learning. None of the students had received any prior instruction on lake ecosystems, which was the topic of the inquiry learning.

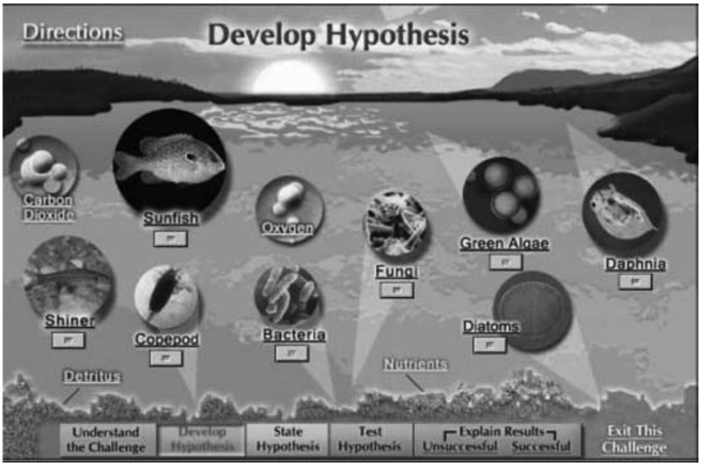

FIGURE 2
The hypothetical Lake Mirabile in the *Food Chain* simulation.

Instructional Materials

Food Chain is a simulation-based inquiry learning environment developed by the ISEE Systems built on the STELLA system modeling software. The simulation engine of *Food Chain* is a system dynamics model (i.e., stock-and-flow diagram), which depicts the interrelationships among the various entities that make up the ecosystem of Lake Mirabile (see Figure 2), an hypothetical lake that contain eight species, two from each of the four trophic levels: sunfish and shiners (the carnivores); copepods and daphnia (herbivores); green algae and diatoms (the primary producers); bacteria and fungi (the decomposers).

The inquiry challenge in *Food Chain* asks students to find two species out of eight that can live together in a lake for 90 days. Hence, the main task of the learners is to infer the characteristics of the model underlying the simulation in Figure 2 by first *discovering* that a higher-order categorization of the species is possible as carnivores, herbivores, primary producers, and the decomposers; and then *discovering* the inter-dependencies among these categories within the lake ecosystem.

The challenge is organized around the steps in the scientific method. After *understanding the challenge*, the students are guided to, in sequence, *develop hypothesis*; *state hypothesis*; *test hypothesis*; and e*xplain the results*. In each step, *Food Chain* scaffolds the students. For instance, in the *develop hypothesis* step, when the students click on any species a hypertext card opens up that provides requisite domain knowledge about that species such as the properties of its preferred location, its physical characteristics, nutritional requirements, and the

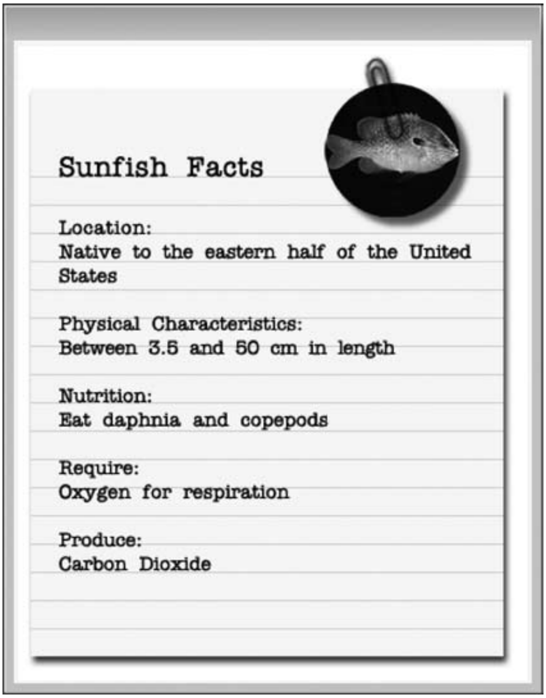

FIGURE 3
Sample hypertext information card in *Food Chain*.

atmospheric gases (i.e., carbon dioxide and oxygen) that it produces and requires (Figure 3). In the *state hypothesis* step, worksheets are provided for the students to write their formal hypothesis in the correct form along with their justification explaining the rationale behind their hypothesis. Hypotheses of the form, “We hypothesize that sunfish and daphnia will be able to survive in the lake for 90 days because....” are expected.

During the *test hypothesis* step, students test their hypotheses via simulating. Only the species that have been clicked on in the *develop hypothesis* step are considered to be in the lake in the ensuing simulation. When the students click on the *Run* button they start to visualize the changes in the lake ecosystem as *Food Chain* simulates what happens during the 90 days when the selected two species are put in the lake together. Status indicator lamps for each species in the lake will initially glow green to indicate that they are being included in the simulation, and that their initial number is within the normal bounds. As the simulation progresses, these lamps may begin to glow yellow, indicating that the associated

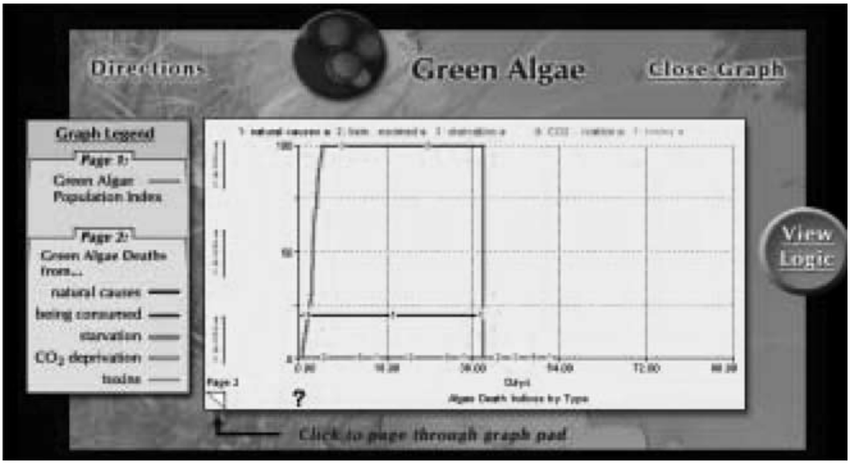

FIGURE 4
Sample graph provided to students depicting their findings following hypothesis testing.

population has either grown large or small enough to be considered at risk. Should a lamp begin to go red and flash that species and/or carrying capacity variable is either at peril of disappearing from the ecosystem or has achieved unsustainable proportions.

At the end of the simulation, changes in the population indices of the species and in carrying capacity indices of oxygen, carbondioxide, nutrients, and detritus are provided by various graphs and charts, which show the causes of death of the species, such as natural causes, starvation, and asphyxiation (see Figure 4). Interactions with these charts and graphs help students regulate their cognition and discover the interrelationships among the different species. During the *explain the results* step, the students are provided with a worksheet to explain their findings, articulate their understanding of what had happened during the experiment, and state which hypothesis should be tested next.

Finally, *Food Chain* scaffold students' inquiry process by dynamic question prompts. At the end of an inquiry cycle following the *test hypothesis* step, Food Chain prompts the students with question to further support their cognitive regulation. For example, if a student included a plant and an herbivore in their hypothesis, a question prompt is dynamically generated by *Food Chain* to reinforce the requirement of having a primary producer in the lake ecosystem and guide the students further to think about what was needed for the plants to survive. An example of a dynamic question prompt is shown in Figure 5.

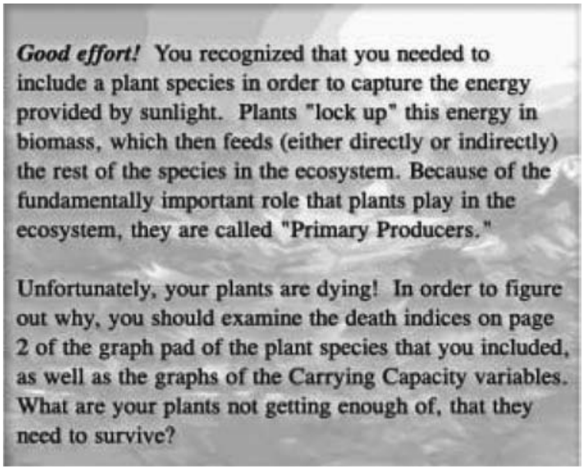

FIGURE 5
Sample dynamic question prompt provided by *Food Chain*.

Procedure

The experiment was conducted in a classroom equipped with desktop computers with the *Food Chain* simulation-based inquiry-learning environment. After a brief introduction of *Food Chain*, participants were asked to complete the inquiry challenge of finding two species (out of eight) that survive together in Lake Mirabile for 90 days. Participants were instructed to complete as many inquiry cycles as possible during the 50-minute session and find at least two sets of solutions. In that way, students had to go through the inquiry processes multiple times, which provided us the data to examine their cognitive regulation.

Measures

The measures included: (1) Understanding of a complex system; (2) Cognitive Regulation due to question prompts (CR_{QP}); (3) Cognitive regulation due to inquiry processes (CR_{IP}).

Understanding of a Complex System

We assessed students' understanding of a complex system by comparing their understanding of *Food Chain* with the expert's understanding of Food Chain, which were derived from the manual of *Food Chain*. During the inquiry process, students were required to write the hypotheses that they tested, the justification of their hypotheses, the results that they observed, and their own explanation of the

TABLE 1
The coding rubric for understanding of a complex system.

Cycle Identification	Number of points given
Energy cycle	1 point: if students suggested that plants (producers) harnessed energy from the sun; ½ point: if student suggested that plants can be sustained without mentioning the sun; 0 point: otherwise.
CO_2/ O_2 cycle	2 points: if students suggested that plants gave O_2 and consumed CO_2 & decomposers gave CO_2 and consumed O_2; 1 point: if students identified only 1 part of the cycle; ½ point: if students identified CO_2 or O_2 in the ecosystem; 0 point otherwise.
Food cycle	2 points: if students suggested that plants took in nutrients and decomposers decomposed dead plants to give nutrient to the plant; 1 point if students identified only 1 part of the cycle; 0 point: otherwise.

TABLE 2
The coding rubric for cognitive regulation due to question prompts.

Coding categories	Number of points given
Quality of hypothesis	1 point: some evidences of using the question prompts to develop the subsequence hypothesis; 0 point otherwise.
Quality of justification	2 points: evidences of good justification for new hypothesis, which based on question prompts; 1 point: some justification for new hypothesis, which based on question prompts; 0 point otherwise.

results. We examined all of students' writings throughout the whole inquiry process to assess their understanding of the complex system. In other words, if a student conducted four hypotheses, we examined all of her work to determine her understanding towards the complex system by looking for evidences of students understanding of the relationships among all the variables. Then, we gave them points for every correctly identified relationship to the maximum of five points. The coding rubric is shown in Table 1.

Cognitive Regulation due to Question Prompts (CR_{QP})

Food Chain provided a question prompt at the end of each inquiry cycle (see Figure 5 above). The content of the question prompts responded dynamically to students' hypotheses. For each hypothesis (other than the first hypothesis generated by students), we evaluated how well the students responded to the question prompts (both in terms of the new hypothesis they developed, and the justification of the hypothesis). The coding rubric is shown in Table 2.

Cognitive Regulation Due to Inquiry Processes (CR_{IP})

At the end of *test hypothesis* step, *Food Chain* provided participants with various charts and graphs depicting the states of different variables in the lake ecosystem (see Figure 4 above). These were intended to help participants regulate their cognition and discover the interrelationships among the variables affecting the lake ecosystem. When students regulated their cognition, they would utilize the feedback from these graphs and charts to formulate new hypotheses. At the end of each hypothesis, students were required to write their understanding of their inquiry. For each hypothesis (other than the first hypothesis generated by students), we examined students' explanation of inquiry processes and evaluated how well the students had responded to the feedback from the inquiry processes (both in terms of the new hypothesis they developed, and their justification of the hypothesis). The coding rubric is depicted in Table 3.

Because cognitive regulation was about students' recursive reflection, but not the quality of the reflection, we did not measure the correctness of new hypotheses. Instead, we only measured how well students responded to their own findings in previous hypothesis. So, it was possible that a student might score well in CR_{IP} even when they formulated a wrong hypothesis as long as they justified it based on the findings of her previous inquiry cycle. Whereas, another student might score low in CR_{IP} even if they formulated a correct hypothesis but could not provide any justification.

RESULTS

Two raters scored all students' responses with an interrater reliability of 0.9. Table 4 summarizes the descriptive statistics including mean and standard

TABLE 3
The coding rubric for cognitive regulation due to inquiry processes.

Coding categories	Number of points given
Quality of hypothesis	1 point: some evidences that the students used what they learned in previous hypothesis to develop the subsequent hypothesis; 0 point otherwise.
Quality of justification	2 points: evidences of good justification for new hypothesis, which based on the results of previous hypothesis; 1 point: some justification for new hypothesis, which based on previous hypothesis; 0 point otherwise.

TABLE 4
Mean, standard deviation and correlation.

	CR_{IP}	CR_{QP}	$CR_{IP} \times CR_{QP}$	Understanding of a Complex System
CR_{IP}	1.000			
CR_{QP}	.752**	1.000		
Understanding of a Complex System	.410**	.325**	.363**	1.000
Mean	.91	1.14	1.569	1.74
Standard Deviation	.955	.749	2.150	1.329

n = 90; **p < 0.01

deviations, and bi-variate correlation. Because the variables were ordinal in nature, caution is required when interpreting the results of descriptive statistics.

Hierarchical linear regression models were run to examine the four research questions. The assumptions of multiple linear regressions were tested. First, all the models were tested for multicollinearity using variance inflation factors (VIF's). All the VIF's were below 10, indicating that multicollinearity was not a problem (Hair, Black, Babin, Anderson, & Tatham, 2006). Second, the scatter plots also showed linearity between all the independent variables and the dependent variable. Finally, the distributions of the variables were reasonably normal in shape, in which the skewness statistics were below 2 (Hair, et al., 2006). The results from the OLS regression of the four models are summarized in Table 5.

Relationships Between Cognitive Regulation and Students' Understanding of a Complex System

OLS regression analyses were conducted to answer the first two research questions regarding the main effects of cognitive regulation on students' understanding of a complex system. In model 1, we ran a simple regression to examine the effect of cognitive regulation due to inquiry processes on students' understanding of a complex system. The OLS regression results confirmed that cognitive regulation due to inquiry processes had a significant impact on students' understanding of a complex system ($p < .05$). The more students regulated their cognition due to the inquiry processes the better their understanding of the complex system got.

The second OLS regression model examined the relationship between cognitive regulation due to question prompts and students' understanding of a complex system. The results of model 2 suggested that cognitive regulation

TABLE 5
The results of regression analyses.

Variables	Model 1 CR_{IP} only	Model 2 CR_{QP} only	Model 3 CR_{IP} and CR_{QP}	Model 4 Full Model with interaction
	β (t-value)	β (t-value)	β (t-value)	β (t-value)
Cognitive regulation due to dynamic question prompts (CR_{QP})	.58 (.18*)		.529 (2.57*)	.529 (2.57*)
Cognitive regulation due to inquiry processes (CR_{IP})		.57 (4.22*)	.068 (.258)	.160 (.438)
(CR_{IP}) × (CR_{QP})				−.068 (−.364)
F	10.41*	17.82*	8.85*	5.866*
Δ F			.067	.133
R^2	.106	.168	.169	.170
Δ R^2			.001	.001

$n = 90$; $*p < 0.05$

due to dynamic question prompts also had a significant positive impact on the understanding of a complex system ($p < .05$). Similar to the effect of cognitive regulation due to inquiry processes, the more a student regulated her cognition due to question prompts the better her understanding on the complex systems got.

Unique Contribution of Cognitive Regulation Due to Question Prompts to the Understanding of a Complex System

To answer the third research question, hierarchical regression modeling technique was employed to examine whether cognitive regulation due to question prompts explained students' understanding of the complex system above and beyond the effect of cognitive regulation due to inquiry processes did. In model 3, we entered CR_{IP} in step 1 and CR_{QP} in step 2 of the regression analysis. The F-test determined whether the addition of CR_{QP} contributed any significant effect on the students' understand of complex learning, which was afforded by CR_{IP}. The hierarchical regression results indicated that CR_{QP}, which we entered in the second step of the regression, only accounted for additional 0.1% of the variance of students' understanding of a complex system above and beyond what the CR_{IP} did. Indeed, cognitive regulation due to dynamic question prompts did not have a significant effect on students understanding of a complex system above and beyond that was afforded by cognitive regulation due to inquiry processes ($p > 0.05$).

Interaction of Cognitive Regulation Due to Question Prompts and Cognitive Regulation Due to Inquiry Processes

We added the interaction term in the final model to examine whether CR_{QP} interact with CR_{IP} in explaining understanding of a complex system. The result of the hierarchical regression suggested that the interaction term did not have a significant effect on students' understanding of a complex system ($p > 0.05$). In other words, there was also no interaction effect of cognitive regulation due to dynamic question prompts and cognitive regulation due to inquiry processes in explaining students' understanding of a complex system. The addition of the interaction term only accounted for additional 0.1% of the variance of students' understanding of a complex system above and beyond what the main effects did.

DISCUSSION

Our previous investigations showed that the level of complexity of a system under investigation was an important factor that explained why some studies found inquiry learning as effective while others did not (Eseryel & Law, 2010). In simpler systems, the analytical method underlying inquiry learning is sufficient in facilitating students' investigations. However, as the systems under investigation increase in their complexity (characterized by many variables dynamically affecting each other) previous studies showed that inquiry learning is not effective. Based on a series of studies, Kuhn and colleagues (2000) contend that the ineffectiveness of inquiry learning of complex systems is due to the insufficiency of the analytical method underlying inquiry learning to support the type of multivariate analysis required to interpret the findings from one inquiry cycle to design the next. Others argue that students' cognitive regulation skills is an important determinant of whether or not inquiry learning is effective when the system under investigation is complex see, for example, (Azevedo, Guthrie, & Seibert, 2004). However, there exists little educational research on students engaged in inquiry learning that would answer this question directly (Hmelo-Silver & Azevedo, 2006).

Thus, the main purpose of this study was to understand the effect of cognitive regulation in the context of simulation-based inquiry learning of a complex science system in order to address the mixed findings in the literature regarding the effectiveness of inquiry learning. The findings of the study confirm the important role cognitive regulation skills play during inquiry learning of complex systems. Students, who were able to regulate their cognition while utilizing the analytical method underlying inquiry learning, were able to conduct the type of multivariate analysis required to understand the complex system under investigation. Hence, inquiry learning supported their mental model transition as they piece-by-piece discovered the interdependencies among the different species in the complex lake ecosystem in *Food Chain*.

On the other hand, the students whom required further scaffolding on cognitive regulation benefited from the dynamic question prompts that were tailored to direct their attention to discover the deeper principles governing the complex lake ecology system. Such tailored dynamic prompts scaffolded their multivariate analysis required to understand the complex system under investigation. Hence, students, who utilized dynamic questions prompts to regulate their cognition, displayed desired mental model transitions.

Although we found positive effects of cognitive regulation due to dynamic question prompts, we were unable to observe significant effect of cognitive regulation due to dynamic question prompts above and beyond that afford by cognitive regulation due to inquiry processes. Indeed, in the hierarchical regression models, we found that cognitive regulation due to inquiry processes explained 16.8% of the variance of understanding of complex systems; adding cognitive regulation on dynamic question prompts to the model only explained additional 0.1% of the variance. In other words, if a student was able to regulate their learning due to the inquiry processes, the additional benefit of question prompts was small and insignificant.

Hmelo-Silver, Duncan & Chinn (2007) argued that scaffolding might reduce learners' cognitive load in inquiry-based learning by limiting the options for the learners. In our study, we provided dynamic question prompts, which were designed to direct students' attention to a certain principle depending on the hypothesis they were testing. Our results of the main effect of cognitive regulation due to question prompts echoed the relationship between scaffolding and learning, that cognitive regulation due to question prompts enhanced understanding of complex systems. Nevertheless, the additional benefit of question prompts, above and beyond the cognitive regulation due to inquiry process was not clear. Indeed, from the descriptive statistics in Table 4, we saw the cognitive regulation due to question prompts was not very high, 1.14 out of 3 with a standard deviation of .749. Those statistics reflected that many students did not really utilize the question prompts to develop their hypotheses. This finding suggest that if students already possess high cognitive regulation skills that enable them to engage in an effective inquiry learning process, they may ignore questions prompts all together to avoid cognitive overload.

In addition to the reported findings, we also investigated the effects of student characteristics such as gender, socioeconomic status, ethnicity, and different levels of intellectual functioning (i.e., mainstreamed special education students). However, there were no significant differences. The insignificant findings may be due to the small numbers of students represented in each category. Hence, for future studies, we recommend investigating the effect of student characteristics, especially the differences among students in different levels of academic achievement.

It should be noted that, in this study, the problem task given to the students was a relatively simple complex problem. For instance, a task calling for an environmental policy decision in Lake Mirabile would have introduced more variables, such as the impact of the number of housing being built across the shores of Lake Mirabile, hence increasing the complexity of the lake ecology system under investigation. One may argue that as the tasks increase in their complexity, scaffolding cognitive regulation would be more crucial and would significantly impact students' understanding of a complex system above and beyond what is afforded by cognitive regulation due to inquiry processes, even when students might have high cognitive regulation skills.

Hence, future studies should investigate additional benefits of dynamic question prompts in scaffolding students' mental model transition during inquiry learning as the task increase in their complexity to further explicate the interaction effects of cognitive regulation and various scaffolding methods during inquiry learning.

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