

**DYNAMIC MODELING AS A COGNITIVE REGULATION  
SCAFFOLD FOR DEVELOPING COMPLEX  
PROBLEM-SOLVING SKILLS IN AN EDUCATIONAL  
MASSIVELY MULTIPLAYER ONLINE GAME ENVIRONMENT**

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**ABSTRACT**

Following a design-based research framework, this article reports two empirical studies with an educational MMOG, called *McLarin's Adventures*, on facilitating 9th-grade students' complex problem-solving skill acquisition in interdisciplinary STEM education. The article discusses the nature of complex and ill-structured problem solving and, accordingly, how the game-based learning environment can facilitate complex problem-solving skill acquisition. The findings of the first study point to the importance of supporting cognitive regulation of students for successful complex problem-solving skill acquisition in digital game-based learning. The findings of the follow-up study show that when scaffolded by dynamic modeling, students made significant improvement in their complex problem-solving outcomes. Implications drawn from the findings of these two studies are discussed related to: (1) educational game design strategies to effectively facilitate complex problem-solving skill development; and (2) stealth or embedded assessment of progress in complex problem solving during digital game-based learning.

## INTRODUCTION

Recent years witnessed a plethora of task forces all around the world that were set out to identify the educational competencies for 21st-century workforce and the gaps in current educational systems that inhibit promotion of these competencies (e.g., Asia Pacific Economic Cooperation, 2008; International Commission on Education for the 21st Century, 1996). These efforts resulted with hundreds of descriptors of the skill set, including life skills, workforce skills, interpersonal skills, digital literacy skills, and noncognitive skills (Silva, 2008). However, complex problem solving is consistently identified as one of the most important 21st-century competencies according to the results of a recent survey (Asia Pacific Economic Cooperation, 2008). Furthermore, all of the respondent countries mentioned the importance of aligning classroom learning with the requirements of the real work environments, especially in science, technology, engineering, and mathematics (STEM) domains. These findings are consistent with the findings of similar international efforts (e.g., the 2008 report of the *Partnership for 21st Century Skills* and the 2010 report of the *Coalition of the Assessment & Teaching of 21st Century Skills*).

Associated with these efforts has been the discussion over the educative merits of digital game-based learning environments for effectively cultivating 21st-century skills. Proponents of game-based learning especially highlighted the unique affordances of massively multiplayer online games (MMOGs), arguing that these affordances can be leveraged to serve as a situated learning environment to effectively facilitate complex problem-solving skill acquisition (see Barab, Tomas, Dodge, Carteaux, & Tuzun, 2005; Gee, 2003; Prensky, 2001, 2006; Shaffer, 2006). However, there is a paucity of empirical evidence to support these claims (Schrader, Lawless, & McCreery, 2009). Based on their review of empirical literature, Eseryel, Ge, Ifenthaler, and Law (2011) conclude that the potential of digital game-based learning is unrealized due to lack of empirically-validated design frameworks that are built on students' cognitive and affective outcomes in relation to the 21st-century skills, especially in the area of complex problem-solving skills. Due to the unique affordances of the medium, little is known as to how to design effective educational MMOGs and how to effectively integrate digital game-based learning in K-12 curriculum to promote the 21st-century skill development.

In order to address this gap, for the last several years we were engaged in a comprehensive design-based research study that investigated high-school students' cognitive and affective learning outcomes related to 21st-century skills during digital game-based learning. More specifically, our investigations focused on complex problem solving, motivation, digital literacy, and interdisciplinary STEM-related learning outcomes in the context of an educational MMOGs, namely *McLarin's Adventures*, which was being developed by the K20 Center for Educational and Community Renewal at the University of Oklahoma with the funding by the U.S. Department of Education.

In this article, we report the findings of two back-to-back studies conducted in the 4th year of the design-based research cycle with the *McLarin's Adventures* MMOG as part of the small-scale testing stage. For the purposes of this article, we focus on complex problem-solving skill acquisition, which is one of the most crucial 21st-century skills. In the next section, we further elaborate on the nature of complex and ill-structured problem solving in STEM domains and discuss the challenges associated with designing learning environments to support this type of higher-order learning outcomes. Then, we introduce the design features of the *McLarin's Adventures* MMOG to address complex problem-solving skill development in interdisciplinary STEM education. Finally, we present the findings of the two studies and discuss their implications for educational game design and assessment.

### COMPLEX AND ILL-STRUCTURED PROBLEM SOLVING IN STEM DOMAINS

Recent research on problem solving in complex, ill-structured knowledge domains, such as STEM disciplines, illuminates a number of learning challenges due to the nature and structure of the real-life problems in these disciplines. First, real-life professional problems in STEM disciplines are complex. In other words, there are a large number of interrelated factors dynamically affecting the problem state. Second, real-life professional problems in STEM disciplines are typically ill-structured, with unknown elements or elements not known with any degree of confidence (Reitman, 1964; Wood, 1983). Problems in STEM disciplines typically possess multiple representations and understandings of the problems (e.g., Funke, 1991). Ill-structured problems seldom have a single, best solution; they typically possess multiple solutions, solution paths, or no solution at all (Kitchner, 1983).

The complex nature of real-life problems in STEM professions presents a challenge for novices, who may possess theoretical knowledge but lack applied experiences to be effective problem solvers in the workplace. In this regard, the unique affordances of learning environments based on massively multiplayer online games are exciting. These virtual worlds make it possible to develop situated learning environments replicating the full complexity of real-life problem-solving situations in a virtual practice world and, therefore, extend the boundaries of classroom-based learning (Schön, 1987). However, an important yet little understood research question remains whether immersing students in such an MMOG-based situated learning environment is sufficient for them to develop effective complex problem-solving abilities. If not, tracking the development of students' cognitive structures as they engage in simulated problem scenarios in an educational MMOG would be an important step in identifying students' requirements for further scaffolding. Our design-based research initiative with *McLarin's Adventures* MMOG was conceived as a step in this direction.

## DESIGN OF THE *McLARIN'S ADVENTURES* MMOG

*McLarin's Adventures* is an MMOG designed to support students' interdisciplinary STEM education. When students first enter the game-based learning environment, they are presented with the news reporting the eccentric trillionaire Jonathan McLarin's dream of interplanetary and interstellar travel. His company, McLarin International, finally produced a vehicle capable of traveling one light year in a single day. In this news video, McLarin announces the plans to send a team of experts to explore and survey Earth-like planets outside of our solar system. To select a team who will receive this great honor, McLarin International is holding a competition for mathematicians, scientists, and journalists. Each team will have to prove their abilities to survive while meeting the specified goals. Then, McLarin International's Chief Operating Officer appears and invites potential applicants to visit their corporate website and fill out the online form, which will be used to select viable applicants.

Following the news video, students in the game environment proceed to fill out an online evaluation form, which provides baseline information about their knowledge and skills in various subject matters. Accordingly, the system automatically groups three to five students to play the game as a team of researchers, who are sent to the island to explore an uninhabited, uncharted island to test their complex problem-solving and higher-order reasoning skills at finding necessary resources. Student teams have to work together and achieve the goals set for each complex task scenario by applying their learning in math, bioscience, geography, geology, social studies, and literacy.

The game divides the overall complex problem-solving task into several whole task scenarios including locating water resources, determining the quality of water supplies and purification, settlement planning and building of shelters, locating food sources for colonization, creating an inventory of supplies and requirements for additional supplies, building a sanitation system, and so on. In the game environment, whole task scenarios are presented through a communication kiosk. After student teams complete each task, they submit their reports to McLarin International through the system, receive automated confirmatory feedback from the system, and proceed to the next kiosk for the next task.

Each of these whole tasks includes a series of subtasks, some of which call for mastery of recurrent skills. For instance, the scenario of locating water resources calls for mapping the island, calculating the area of the island, mapping out the water resources, testing the quality and pH-levels of the water, recording the data in an spreadsheet built in the game-based learning environment, ranking bodies of water, conducting physical test of water, and writing a technical report to McLarin about water resources on the island. During these tasks, the game presents the players unexpected medical or emergency conditions. For instance, after finding a water resource, if a player drinks it without testing and sanitizing, that player will get very sick and requires medical treatment. Consequently, the

team has to deal with this medical event. On the other hand, emergencies like excessive rain require students to build appropriate shelters. Once players identify the location of the food and the density of the food source, a fire will begin and the players not only have to extinguish the fire but also have to investigate if potential food sources are in danger. Once they arrive at the fire, the players will see a grove of plants and trees burning. They have lost the food source. The players would struggle with a way to extinguish the fire due to lack of ability to transport large quantities of water. This would prompt them to seek modes of transporting large quantities of water and build it.

The recurrent tasks that are required to solve complex whole-task problem scenarios in the game are based on the State's Priority Academic Student Skills (PASS) for Grades 8 and 9. For example, one of the major concepts in geometry concerns the measurement of surface area. Related PASS Standard 4 requires students to estimate and find the surface area (and volume) in real world settings. In the game environment, Marcella Fermy, a non-play character, appears in a portal on the island and directs the students to establish a measurement standard by first discovering the length of the island. The students are guided to use a pedometer to measure the length of a grid cell on their map and then report the reading to Marcella Fermy, who would give them feedback and suggestions. After submitting the length of the island, they receive a new task that requires them to find the area of the island. When a student has submitted the final calculation, Jonathan McLarin appears on the portal and congratulates the students and then informs them of their next tasks.

Each complex problem-solving scenario in the game calls for a number of whole tasks to be mastered in addition to part tasks which call for the mastery of recurrent skills that are aligned with the PASS skills for Grades 8 and 9 as outlined by the State Department of Education. The goal of the game is to successfully complete these series of recurrent tasks situated within whole task scenarios that make up the complex problem scenario guiding the game and become the winning team. Directions and hints for completing the problem-solving tasks are embedded in the game.

## THE PRESENT STUDIES

Following a design-based research framework, two experimental impact studies were conducted to investigate the potential of the design features of the *McLarin's Adventures* MMOG in facilitating complex problem-solving skill acquisition in interdisciplinary STEM education.

### Study 1

Study 1 set out to examine the impact of immersing students in the MMOG-based situated learning environment while tracking the development of students'

cognitive structures as they engage in the simulated complex problem scenarios. The following research question was investigated in Study 1: Will students who played the interdisciplinary *McLarin's Adventures* MMOG exhibit significantly higher gains in their complex problem-solving skills than students in a comparable control group?

#### *Participants and Design*

A rural high school in the Midwest of the United States was used as a testbed for this experimental study: 349 9th-grade students were randomly assigned to 1 of the 19 classes, 10 were randomly assigned to treatment (game group) condition, and 9 were assigned to control (no game group) condition. The data reported here were from 251 students, from whom we received both parental consent and student assent forms. Of these 251 students, 156 were in the experimental group and 95 were in the control group. There were 47% males and 53% females.

#### *Procedure*

A week before and after the implementation of the game, pretest data were collected from the students in both groups. Following the pretest data collection, students in the experimental group played the *McLarin's Adventures* MMOG 2 days a week for 16 weeks during the 50-minute class period. At the same time, the students in the control group participated in a class that was specifically developed to facilitate students' interdisciplinary STEM learning and improving their leadership, management, and decision-making skills. In this sense, both the game-based learning environment and the traditional class curriculum attempted to facilitate, in their own ways, complex problem-solving skill acquisition in an interdisciplinary STEM curriculum.

At the end of the 16 weeks students in both groups took the posttest, which was the same as the pretest. In addition, class observations and focus group interviews with students and teachers were conducted.

#### *Game Procedure*

During both pretest and posttest, students in both experimental and control groups were provided with an account for the *McLarin's Adventures* game and an ultra mobile personal computer (UMPC). After the students logged in, they designed their avatars for the game and watched the opening news video. Pretest was administered at this point as if it was the first step in the game, during which the students had to take the evaluation test as part of the selection process by McLarin International. For the purposes of this evaluation test, the students were presented with the following scenario:

Suppose you are chosen as the lead scientist of a team of experts by Jonathan McLarin of McLarin International. Your team is sent to space to explore

Earth-like planets outside of our solar system. Your team has been traveling in space for about six months. Your ship's sensors have just identified a planet, which has sufficient oxygen levels in its atmosphere for humans to be able to breathe. You have decided to land on this planet and survey the area. Initial explorations show that the planet has similar characteristics to an island on earth. Your team decided to live on this planet and identify resources needed to survive. This will allow you to complete your mission. As the lead scientist, your task is to guide your team. Before you proceed, you must write a report to Jonathan McLarin to inform him of your team's discovery. The guidelines you received from Mr. McLarin suggest that your mission report must have certain information. Your first step is to report your observations of the planet. Further steps and additional information will be required. Use the space provided on the next page to complete your report and submit it to Jonathan McLarin.

The scenario represented a near-transfer problem-solving task compared with the complex problem task scenario in *McLarin's Adventures*. Afterwards, the students were provided with the outline of the report, which included four steps. Step 1 called the students to imagine that they were walking around on this new planet to explore its characteristics and asked them to write a report to Mr. McLarin of their initial observations of the planet. This first step was intended to provide us with information regarding students' background and assumptions related to the complex problem-solving task.

Step 2 reminded the students that their task as researchers included developing a successful settlement area, where humans could survive on this new planet. They were prompted to think about what humans needed to survive and were asked to make a list of each of these factors. When they finished identifying all the important factors, they were asked to develop an annotated causal representation by, first, arranging each of the related factors that are close to each other, then by drawing arrows between the factors they thought were related, and annotating their causal representation by writing on each arrow how the two factors were related. Students' annotated causal representation provided us with information related to their structural knowledge of the complex problem-solving task.

In Step 3, the students were asked to write a descriptive paragraph explaining why the factors they listed in Step 2 were important and how they were related to each other. The data collected from Step 3 provided us with additional information about students' problem space and helped us to check the alignment with the annotated causal representation developed in Step 2.

Finally, in Step 4, the students were asked to provide recommendations for solutions by listing the steps to be taken to allow their team to build a settlement area for humans to live on this new planet and ensure their survival. They were also asked to self-report to Mr. McLarin how confident they felt about their plan, including any concerns they might have or what they would do if problems

would arise. Data collected from Step 4 not only provided us with the solution strategies of the students for the complex problem task scenario but also data on whether the students were able to justify their solution approaches by providing plausible arguments.

#### *Data Analysis Framework*

Students' *problem-solving protocols* were analyzed by using problem-solving scoring rubrics to measure learning outcomes in (a) *problem representation* and (b) *generating solutions*, which served as two dependent variables (Chi & Glaser, 1985; Ericsson & Simon, 1980). Students' *annotated causal representations* were analyzed to measure learning outcomes in *structural knowledge*, which served as the third dependent variable (see Funke, 1985; Ifenthaler, 2010; Seel, 1999). All three dependent variables were crucial in understanding students' cognitive processes as they engaged in the problem scenarios in the game tracking their complex problem-solving development over time. Table 1 illustrates the data source and measures of the data analysis framework for Study 1.

*Analysis of problem-solving protocols using scoring rubrics*—In order to assess students' problem solving performance based on their problem-solving protocols, the research team went through an iterative process of developing, refining, and validating scoring rubrics for assessing complex problem-solving performance. Ten percent of the students' responses were rated by three researchers with 100% agreement, and the rest of the data were rated by two of the three researchers with 85% interrater reliability.

Scoring rubrics were developed to measure two variables: (a) *Problem Representation* and (b) *Generating Solutions*. For the *Problem Representation* variable, first we compared the critical factors for survival generated by the experts (e.g., habitability, terrain, vegetation, and animal life) with those generated by the students. A student would receive 1 point for each of the four critical factors identified, as well as an additional maximal point for an additional item identified outside those four factors. In other words, if a student identified three critical factors, that student would receive 3 points for identifying critical factors. Second, we also examined whether a student described or elaborated the factors that had been identified previously in relation to survival and how well the description or elaboration was done. A well-constructed description or elaboration of one identified factor would earn 1 point. For instance, if a student described three critical factors that had been previously identified, he/she would earn 3 points. Third, a score was assigned for each student on the overall depth of elaboration on the relationships among the factors influencing the problem state based on the number of factors identified and how well those factors were described or elaborated. For instance, if none of the identified factors was described or elaborated, the student would receive only 1 point. Yet, if one identified factor was described or elaborated, 2 points would be assigned. If all the



Table 1. Data Source and Measures for Study 1

Dependent variable	Data source	Measure
Problem representation	Problem-solving protocol	Problem representation rubric score
Generating solutions	Problem-solving protocol	Generating solutions rubric score
Structural knowledge	Annotated causal representation	Surface matching
Structural knowledge	Annotated causal representation	Graphical matching
Structural knowledge	Annotated causal representation	Structural matching
Structural knowledge	Annotated causal representation	Gamma matching
Structural knowledge	Annotated causal representation	Concept matching
Structural knowledge	Annotated causal representation	Propositional matching

factors identified were elaborated, 4 points are assigned. In summary, there were three scores for the *Problem Representation* variable: (i) number of factors identified; (ii) number of factors identified that have been described or elaborated; and (iii) overall depth of elaboration on the identified factors and their relationships influencing the problem state.

The rubrics for measuring the variable of *Generating Solutions* included four criteria: (i) Is a recommendation made by listing measures or actions? (ii) Are solutions aligned with their problem analysis and representation they had worked out in the previous step? (iii) Is a justification made about the recommendation? and (iv) How confident does a student feel about their recommendations? If each of the questions was answered satisfactorily with reasonable justifications, 1 point was awarded. The maximal points for *Generating Solutions* were 4, ranging from “0” (Unsatisfactory Performance) to “4” (Excellent Performance).

*Analysis of annotated causal representations*—In order to track the changes in students’ *Structural Knowledge* of the complex problem-solving domain as a result of game-play, each student’s annotated causal representation was compared with the expert causal representation on six measures as suggested by the Highly Integrated Model Assessment Technology and Tools (HIMATT). HIMATT is a combined toolset conveying the benefits of various methodological approaches in a single environment. The automated analysis generates measures on structural and semantic levels of causal representations (Ifenthaler, 2010; Pirnay-Dummer & Ifenthaler, 2010): (a) *surface matching*, which compares the number of propositions (concept – relation – concept) within two causal representation; (b) *graphical matching*, which compares the diameters of the spanning trees of the causal representation, which is an indicator for the range or complexity of conceptual knowledge; (c) *structural matching*, which compares the complete structures of two causal representations (expert and subject) without regard to their content; (d) *gamma matching*, which describes the quotient of terms per concept within a causal representation; (e) *concept matching*, which compares the sets of concepts within a causal representation to determine the use of terms (semantic correctness); and (f) *propositional matching*, which compares only fully semantically identical propositions between two causal representation. Surface, graphical, structural, and gamma matching refers to organizational structure of a causal representation, while concept and propositional matching indicates how semantically similar a student’s causal representation is to that of the experts’ in the respective category. Figure 1 shows the measures of HIMATT, which include the above-mentioned four structural and three semantic indicators.

### *Results and Discussion of Study 1*

*Impact on Problem Representation and Generation of Solution Approaches*—The analysis of the problem-solving protocols tracked students’ complex problem

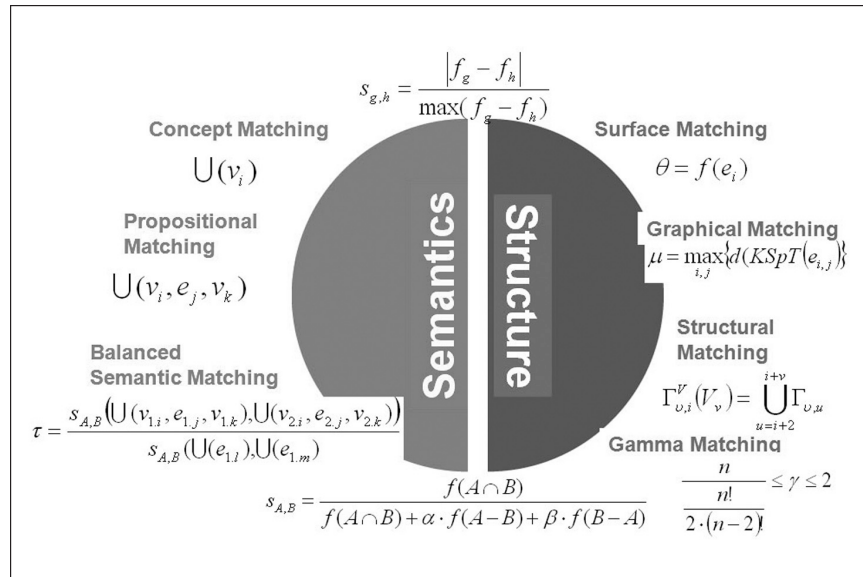


Figure 1. Structural and semantic HIMATT measures.

solving development related to two dependent variables: (i) *Problem Representation* and (b) *Generating Solutions* (see Table 1).

The repeated measures MANOVA conducted on the rubric scores of *Problem Representation* and *Generating Solutions* revealed a main time effect between the pretest and the posttest scores,  $F(2, 153) = 33.41, p < .01, Eta Sq. = .3$ . However, there was neither main effect for treatment nor interaction effect between group and time. The univariate tests showed that there were significant differences between pretest and posttest in both *Problem Representation* and *Generating Solutions* variables. These findings suggest that there were significant changes in students' complex problem-solving performance as a result of their engagement with *McLarin's Adventures* MMOG. A close look at the descriptive statistics for both measures (Table 2), however, reveals that the students' performance in both groups decreased significantly in the posttest as compared with pretest.

*Impact on Structural Knowledge*—In order to track the changes in students' structural knowledge related to the complex problem-solving domain, each student's annotated causal representation was compared with the expert model on six HIMATT measures: (i) *surface*; (ii) *graphical*; (iii) *structural*; (iv) *gamma*; (v) *concept*; and (vi) *propositional matching*.

ANOVA analyses on these six HIMATT measures revealed significant group effects on graphical matching,  $F(1, 321) = 13.823, p < .01, Eta Sq. = 0.041$ , on

Table 2. Descriptive Statistics for Study 1

	Game			Control		
	Pretest (SD)	Posttest (SD)	% Change	Pretest (SD)	Posttest (SD)	% Change
Problem representation	1.44 (0.72)	1.11 (0.47)	-30%	1.65 (0.88)	1.04 (0.57)	-59%
Generating solution	1.37 (1.030)	0.98 (0.594)	-40%	1.21 (0.84)	0.86 (0.622)	-41%
Surface	0.365 (0.159)	0.274 (0.138)	-33%	0.322 (0.154)	0.544 (.166)	-3%
Graphics	0.5 (0.180)	0.423 (0.160)	-18%	0.386 (0.181)	0.386 (0.172)	0%
Structure	0.643 (0.146)	0.589 (0.136)	-9%	0.559 (0.194)	0.558 (0.183)	0%
Gamma	0.698 (0.224)	0.662 (0.233)	-5%	0.575 (0.223)	0.602 (0.261)	4%
Concept	0.407 (0.130)	0.384 (0.106)	-6%	0.39 (0.115)	0.376 (0.144)	-4%
Propositional	0.043 (0.057)	0.026 (0.046)	-65%	0.011 (0.026)	0.021 (0.033)	48%

structural matching,  $F(1, 321) = 11.145, p < .01, \text{Eta Sq.} = 0.034$ , on gamma matching,  $F(1, 321) = 11.3, p < .01, \text{Eta Sq.} = 0.034$ , and on propositional matching,  $F(1, 321) = 13.735, p < .01, \text{Eta Sq.} = 0.041$ . The results also showed that there were main effects of time on surface matching,  $F(1, 321) = 8.664, p < .01, \text{Eta Sq.} = 0.026$ , and on graphical matching,  $F(1, 321) = 3.973, p < .05, \text{Eta Sq.} = 0.012$ . Finally, we found significant joint effects of group and time on surface matching,  $F(1, 321) = 5.527, p < .05, \text{Eta Sq.} = 0.017$ , on graphical matching,  $F(1, 321) = 3.973, p < .05, \text{Eta Sq.} = 0.012$ , and on propositional matching,  $F(1, 321) = 8.237, p < .01, \text{Eta Sq.} = 0.025$ . However, a close look of the descriptive statistics (Table 2) revealed that most of the HIMATT measures from the treatment group decreased over time.

The results suggest that the structural knowledge of the students' in the game group changed after the treatment both structurally and semantically. Yet, this change was not in the desired direction. While the complexity of students' representations in the treatment group increased over time, those changes did not involve the desired conceptual changes (highlighted by the measures concept and propositional matching), but rather newly-formed misconceptions, which could be attributed to cognitive overload during game play due to the interrelationships among the large number of variables affecting complex problems in the game and the ill-structured nature of the complex problems. These results were consistent with the results as measured by rubrics, which showed significant decrease in both *Problem Representation* and *Generating Solutions*.

The results of Study 1 suggested that immersing students in MMOG-based situated learning environment, which provided the opportunity for them to engage with real-life professional problem-solving situations in the safety of a virtual practice world, may not necessarily lead to improved conceptual learning and complex problem-solving performance. The study reported in this manuscript was part of a larger, longitudinal design-based research investigating other factors related to student characteristics (gender, socioeconomic status, prior game experience, etc.), student motivation, and classroom implementation (Eseryel & Ge, 2010; Eseryel & Swearingen, 2010; Eseryel, Miller, Ge, Ifenthaler, Law, & Guo, 2010) that may affect complex problem-solving performance in MMOGs. After eliminating all other possible explanations, the findings of Study 1 pointed to the requirement for supporting students' cognitive regulation to reduce their cognitive load so that they can successfully engage in a recursive process utilizing the feedback mechanisms afforded to them in the MMOG-based learning environments to direct and adjust their learning and complex problem-solving activities.

The feedback mechanisms embedded in game narrative and the collaborative problem-solving opportunities afforded by the MMOG-based learning environments were not sufficient in reducing the cognitive load of the students as they were trying to comprehend the dynamic interrelationships among the large number of variables affecting the problem-state. Thus, in complex learning situations, it is important for the students to elaborate what they have observed and

integrate their observations into their understanding of the complex systems. Therefore, an important question emerged: How can we properly embed design features to support students' cognitive regulation and decrease cognitive overload?

## Study 2

The purpose of the Study 2 was to follow up on Study 1 by further investigating how to effectively scaffold students' cognitive regulation in an MMOG-based learning environment that would lead to improved complex problem-solving development. We were compelled to explore the potential of dynamic modeling, which was successfully used in the field of system dynamics to model highly complex systems.

Study 2 was conducted during the following school year with the following research question: Will the students who received dynamic modeling instruction to support complex problem-solving strategies and played with the *McLarin's Adventures* MMOG exhibit have significantly higher gains in their complex problem-solving skills than students receiving only dynamic modeling instruction? As Study 2 was a replication of Study 1, with the exception of dynamic modeling instruction, we were also interested in comparing the results of both studies in order to investigate the potential of dynamic modeling as a cognitive regulation scaffold to support students' complex problem-solving performance during digital game-based learning.

### *Participants and Design*

Study 2 was conducted with the incoming 9th-grade students during the following school year at the same high school as in Study 1. Three hundred and forty-three 9th-grade students participated in Study 2. None of them had participated in Study 1. These students were randomly placed into 16 classes. Out of these 16 classes, 8 were randomly assigned to treatment (modeling + game group) condition and 8 were randomly assigned to control (modeling group) condition. The data reported here were from 280 students, from whom we received both parental consent and student assent forms. Out of these 280 students, 137 (48.9%) were in the treatment group and 143 (51.1%) were in the control group.

### *Procedure*

Students in both groups received a 3-week training on system dynamics modeling before receiving the pretest. During this period, students in both groups worked with complex problem scenarios in increasing complexity ranging from problems related to obesity epidemic to problems related to ecological phenomena; modeled each complex problem by using causal representations; and discussed possible solution paths.

Following the three-week dynamic modeling training, pretest data were collected from all the students and Study 2 began. Apart from the dynamic modeling training, Study 2 was a replication of Study 1. The same materials and procedure that were used in Study 1 were also used in Study 2. On the other hand, we only analyzed the students' causal representations along the six HIMATT measures due to the further findings of Study 1, which showed that students' structural knowledge, elicited by their causal representation of the complex problem, was reliable basis for tracking their complex problem-solving performance (see Eseryel et al., 2009 for further details of this validation study).

#### *Results and Discussion of Study 2*

Table 3 depicts the descriptive statistics of the HIMATT measures for complex problem solving based on causal representations. ANOVA analysis on the group and time effects related to the six HIMATT measures revealed significant joint effects of group and time on the following variables: *surface matching* ( $F(1, 317) = 4.442, p < .05, \text{Eta Sq.} = 0.013$ ), *graphical matching* ( $F(1, 317) = 4.442, p < .05, \text{Eta Sq.} = 0.012$ ), *gamma matching* ( $F(1, 317) = 4.442, p < .05, \text{Eta Sq.} = 0.013$ ), and *propositional matching* ( $F(1, 317) = 4.442, p < .05, \text{Eta Sq.} = 0.016$ ).

These results of Study 2 suggested that students in the modeling-only group exhibited significantly higher positive gains in their complex problem solving skills as suggested by the significant improvements on the *propositional matching*, and *graphical matching* measures. In contrast, students in the modeling + game group exhibited a slight decline.

However, when compared with Study 1, students in both groups in Study 2 showed significant improvement in all the six HIMATT measures. Table 4 summarizes the results of the ANOVA analyses, which compares the six HIMATT measures of Study 1 with those of Study 2. The means of the HIMATT measures of Study 2 were significantly higher than the means of Study 1, as depicted in Figure 2 (game group results) and Figure 3 (control group results). Therefore, the ANOVA results suggested that system dynamic modeling had positive effects on students' complex problem-solving skill acquisition.

## GENERAL DISCUSSION

Following a design-based research framework, we set out to address an important gap in the current literature and arrive at an empirically-tested design framework that can leverage the unique affordances of MMOGs to create much-needed situated learning environments that can effectively promote 21st-century competencies. In this article, we have reported the findings of two studies that specifically focus on complex problem-solving skill development as one of the

Table 3. Descriptive Statistics for Study 2

	Game			Modeling		
	Pretest (SD)	Posttest (SD)	% Change	Pretest (SD)	Posttest (SD)	% Change
Surface	0.563 (0.184)	0.519 (0.193)	-8%	0.502 (0.197)	0.544 (0.166)	8%
Graphics	0.735 (0.163)	0.731 (0.192)	-1%	0.673 (0.209)	0.749 (0.173)	10%
Structure	0.726 (0.160)	0.711 (0.155)	-2%	0.678 (0.163)	0.646 (0.191)	-5%
Gamma	0.755 (0.165)	0.719 (0.268)	-5%	0.728 (0.245)	0.795 (0.206)	8%
Concept	0.562 (0.145)	0.559 (0.177)	-1%	0.573 (0.140)	0.593 (0.161)	3%
Propositional	0.234 (0.160)	0.221 (0.147)	-6%	0.22 (0.160)	0.285 (0.153)	23%
Balance semantic	0.381 (0.228)	0.357 (0.189)	-7%	0.351 (0.213)	0.451 (0.212)	22%

Table 4. Comparison of Study 1 and Study 2 for Causal Representations

	Pretest			Posttest		
	F(1, 320)	p-Value	Eta-square	F(1, 320)	p-Value	Eta-square
Surface	96.342	0.000	0.231	152.620	0.000	0.323
Graphics	159.417	0.000	0.333	293.734	0.000	0.479
Structure	27.917	0.000	0.080	34.622	0.000	0.098
Gamma	17.936	0.000	0.053	21.981	0.000	0.064
Concept	124.823	0.000	0.281	137.728	0.000	0.301
Propositional	228.048	0.000	0.416	343.397	0.000	0.518



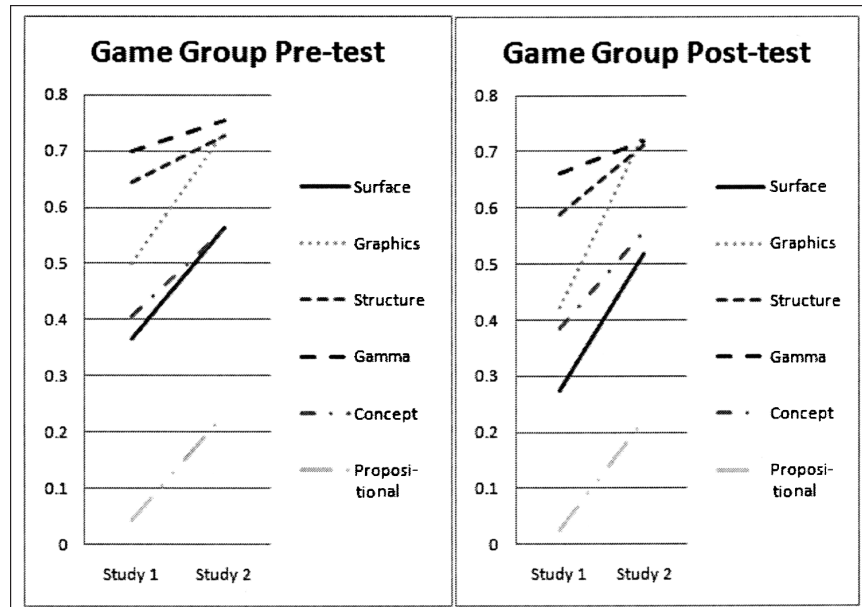


Figure 2. Comparison of the Study 1 and Study 2 on the mean scores of structural knowledge measures for the game group.

most important 21st-century skills. Study 1 sought to examine the impact of immersing students in the game-based situated learning environment of *McLarin's Adventures* MMOG while tracking the development of students' cognitive structures as they engage in the simulated complex problem scenarios.

One of the defining characteristics of MMOGs is that the players work individually or as a team to accomplish a complex task (whole task). Meanwhile the game environment requires the players to move through a series of subtasks or stages (part tasks). The players have to successfully complete the requirements in each subtask to be able to move to the next, earn points or some type or reward that give them the competitive edge. *McLarin's Adventures*, as an educational MMOG, was designed to take advantage of these affordances of the digital game-based learning. However, the findings of Study 1 suggested cognitive regulation scaffolds were needed in the game environment to help students construct a mental representation of the dynamic interrelationships among the constituents of the complex problem to be solved and to help them continually assess their internal mental representations of the problem. By means of such representations, an individual is able to simulate real actions in imagination (in the sense of thought experiments) in order to solve complex problems (Seel, Ifenthaler, & Pirnay-Dummer, 2009). This finding is consistent with the findings of similar

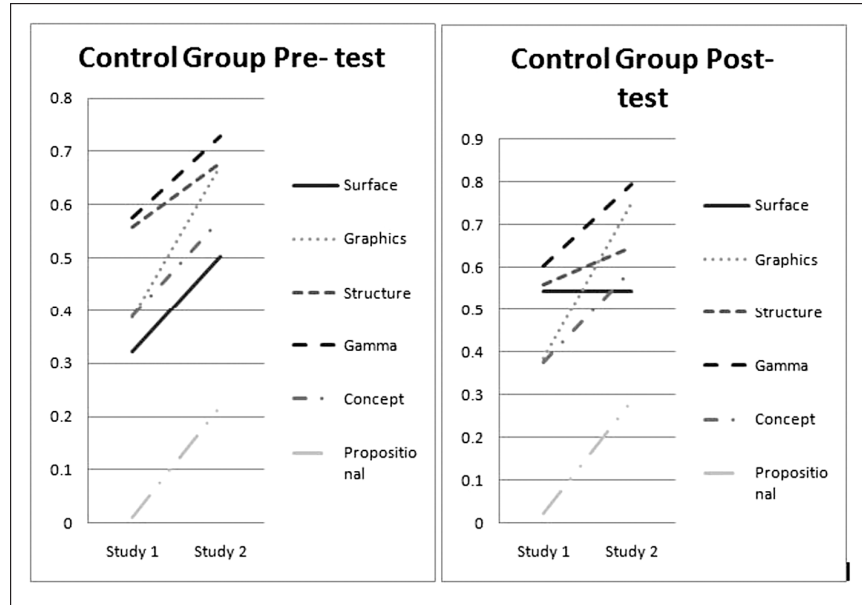


Figure 3. Comparison of the Study 1 and Study 2 on the mean scores of structural knowledge measures for the control group.

investigations with other computer-based interactive learning environments such as simulation-based inquiry learning environments on facilitating students' complex problem-solving skills (e.g., Azevedo, Guthrie, & Seibert, 2004; Eseryel & Law, 2010; Manlove, Lazonder, & de Jong, 2006).

The findings of Study 2 suggest that dynamic modeling adapted from the field of system dynamics is effective as a cognitive regulation scaffold to support complex problem solving during game play. An important research question is how to seamlessly integrate system dynamic modeling scaffolds in digital game design. This will be addressed in our follow-up studies in the future. Within an adaptive game environment, we will include dynamic modeling features as part of the game. Additionally, this newly designed game will include a dynamic and automated feedback function, which helps students during their problem-solving process (see Eseryel, Ifenthaler, & Ge, 2011).

Assessment is a curious driver in the 21st-century skills debate. Critics levy strong arguments against the push for these skills while arguing that these types of higher-order skills cannot be measured in reliable, cost-effective, or scalable ways. In order to leverage current discourse on 21st-century skills to drive fruitful educational reform, we argue that an important future direction

for educational research involves development of valid and reliable assessment methods to measure 21st-century skills that are scalable. Toward this direction, future generation of educational games should include embedded stealth assessment tools and provide instant analysis of a wide-variety of 21st-century skill acquisition and offer personalized feedback to learners (see Eseryel et al., 2011).

In order to understand the continuous progression of learning, thinking, reasoning, and complex problem solving during digital game-based learning, it is important that the underlying mental representations must be assessed carefully at various stages of the learning process. We used two different methods to assess student's progress of learning in complex problem solving. The first method was an established research methodology largely used in problem-solving studies, namely the adapted protocol analysis (Ericsson & Simon, 1980), to analyze students' responses to the given problem scenario within the framework of the problem-solving protocols. The second method was based on annotated causal representations to measure students' knowledge structures (i.e., structural knowledge) and utilized the HIMATT method (Pirnay-Dummer, Ifenthaler, & Spector, 2010) to analyze students' causal representations.

The findings of Study 1 demonstrated that both methodologies led to similar results. Further investigations confirmed the validity and reliability of both assessment measures (Eseryel et al., 2009). Coupled with HIMATT (Pirnay-Dummer & Ifenthaler, 2010), the assessment methodology based on causal representations and realized as web-based knowledge mapping methods, opens up unique possibilities for continuous stealth assessment and analysis in game-based learning (Eseryel et al., 2011). Such embedded assessment will include an in-game analysis architecture, which will automatically produce textual and graphical feedback for learners and teachers (see Pirnay-Dummer & Ifenthaler, 2011).

The assessment methodology based on causal representations also align well with dynamic modeling strategies; thus, it can complement dynamic modeling scaffolds to support cognitive regulation of complex problem-solving skill acquisition. In future research, we will redesign the game environment to include dynamic modeling scaffolds and stealth assessment based on causal representations coupled with embedded HIMATT to provide continuous feedback of students' progress in complex problem solving during game play (Ifenthaler, 2009).

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