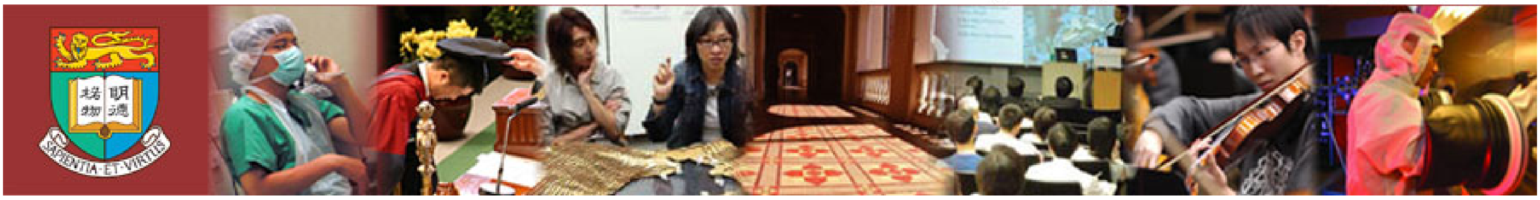

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Author(s)	CHEN, J; Wang, M; Dede, C; Grotzer, T
Citation	Journal of Educational Technology & Society, 2017, v. 20 n. 4, p. 191-204
Issued Date	2017
URL	http://hdl.handle.net/10722/242833
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Chen, J., Wang, M., Dede, C., & Grotzer, T. A. (2017). Design of a Three-Dimensional Cognitive Mapping Approach to Support Inquiry Learning. *Educational Technology & Society, 20* (4), 191–204.

Design of a Three-Dimensional Cognitive Mapping Approach to Support Inquiry Learning

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ABSTRACT

The use of external representations has the potential to facilitate inquiry learning, especially hypothesis generation and reasoning, which typically present difficulties for students. This study describes a novel three-dimensional cognitive mapping (3DCM) approach that supports inquiry learning by allowing learners to combine the information on a problem, the subject knowledge, and the hypothesizing and reasoning process involved in the exploration in a single image. The study also investigates the influences of the 3DCM approach on knowledge achievement and learner perceptions within an online inquiry-learning context. Forty-eight 11th-grade students used 3DCM to complete an inquiry task. Data were collected from multiple sources, including pre- and post-tests, questionnaires, and semi-structured interviews. The results revealed that the students showed high levels of academic achievement, positive attitudes toward inquiry learning, low levels of anxiety, and medium levels of confidence. A post-hoc test indicated that the students at a low academic level had acquired significantly more knowledge than either the high-level or medium-level students, thus narrowing the academic gap between low-level, medium-level, and high-level students. In addition, the participants' attitudes and degree of confidence were found to be positively related to their inquiry skills, such as hypothesis generation and reasoning. The implications of the study and directions for future work are also discussed.

Keywords

Inquiry learning, Reasoning, External representation, Cognitive mapping, Science education

Introduction

Education today emphasizes students' active involvement in learning, especially through inquiry and problem-solving experiences (Bransford, Brown, & Cocking, 1999). Originating in practices of scientific inquiry, inquiry learning engages students in exploring phenomena or problems by asking questions, collecting and interpreting data, constructing evidence-based arguments, and forming conclusions (Lazonder & Harmsen, 2016). Through inquiry activities, students acquire subject knowledge, develop discipline-related practical experience and reasoning skills (Hmelo-Silver, Duncan, & Chinn, 2007), and enhance motivation (Phielix, Prins, & Kirschner, 2010). The beneficial effects of inquiry learning have been reported on students at various ability levels, from low to high (Zohar & Dori, 2003).

In traditional inquiry-learning contexts, learners often interact with objects in the real world. For example, during physics experiments, they conduct physical hands-on investigations and interact directly with the material world. Information and communication technologies (ICT) are used increasingly in inquiry learning to present problem contexts in vivid and interactive formats. An important affordance of technology-supported inquiry learning is its capacity to highlight salient information and remove irrelevant details, facilitating the interpretation of the phenomena. Furthermore, such learning environments enable students to conduct experiments to investigate unobservable phenomena (e.g., the travelling of light rays). Technology-supported inquiry learning has been demonstrated to be more efficient than traditional inquiry because it provides simulated results instantaneously and enables students to gather more information in the same amount of time (De Jong, Linn, & Zacharia, 2013). Examples of technology-supported inquiry learning include the Web-based Inquiry Science Environment (WISE) (Linn & Slotta, 2000) and immersive learning environments (Dede, 2009).

However, whether working in traditional or technology-enabled contexts, students often experience difficulties in regulating the inquiry process and engaging in fruitful inquiry learning. The inquiry process often involves iterative cycles of gathering information through observation or experiments, generating hypotheses, reasoning based on the collected information, and drawing conclusions (Kuhn, Black, Keselman, & Kaplan, 2000). Generating hypotheses entails formulating ideas about the relationships between variables (Gijlers & de Jong, 2013). Scientific reasoning involves questioning initial premises, seeking evidence that confirms or contradicts the hypotheses, revising initial ideas, and considering alternative hypotheses (Zeineddin & Abd-El-Khalick, 2010). Many students do not know how to formulate hypotheses (de Jong & van Joolingen, 1998). In addition, students' reasoning ability may be inadequate (Zeineddin & Abd-El-Khalick, 2010). For example, some students find it difficult to connect evidence with claims or to reason using intertwined variables (Kamarainen, Metcalf, Grotzer, & Dede, 2014). Studies have also indicated that some students are unable to adapt or revise an initial hypothesis in the presence of conflicting evidence (Kuhn et al., 2000). Furthermore, some students rarely reflect on prior conceptions and readily dismiss contradictory information (Zeineddin & Abd-El-Khalick, 2010).

In light of these findings, it has been argued that it is urgently necessary to support inquiry learning by guiding students through the complex inquiry process and helping them to become accomplished problem-solvers (Kirschner, Sweller, & Clark, 2006). Hmelo-Silver et al. (2007) argued that effective problem-based learning involves significant, built-in supporting structure. More and more researchers are investigating a continuum of forms of support and guidance for inquiry learning. To facilitate the complex inquiry process, some strategies such as scripts, prompts, and hints (Kollar, Fischer, & Slotta, 2007) have been provided to facilitate the inquiry process (i.e., what to do next or how to do it). When developing supportive frameworks, however, it is important to avoid undermining the open-endedness of the task and individual endeavour. Accordingly, additional forms of cognitive supports based on cognitive maps have been explored and shown their promising effects, such as concept maps (Gijlers & de Jong, 2013), causal maps (Slof, Erkens, Kirschner, Janssen, & Jaspers, 2012), evidence maps (Suthers, Vatrapu, Medina, Joseph, & Dwyer, 2008), and integrated cognitive maps representing the problem-solving process and the underlying knowledge (Wang, Wu, Kinshuk, Chen, & Spector, 2013; Yuan, Wang, Kushniruk, & Peng, 2016). A cognitive map is an external representation of cognitive structures and processes. Cognitive maps are deemed to effectively engage students and to foster high-order thinking and meaningful learning in complex situations (Jonassen, 2005).

This study outlines a novel *three-dimensional cognitive mapping* (3DCM) approach that supports inquiry learning by allowing learners to combine, in a single image, *information on a problem, subject knowledge (key concepts and their relationships)*, and *the process of hypothesizing and reasoning involved in exploring the problem*. The premise that underlies the design is that externalizing the complex aspects of an inquiry task makes inquiry learning more accessible to learners (Janssen, Erkens, Kirschner, & Kanselaar, 2010).

The aim of this study was to explore the influences of the 3DCM approach on inquiry learning in an online environment. The benefits of constructing external representations to support inquiry learning can be explained on the cognitive (e.g., academic achievement), metacognitive, and social dimensions (Toth, Suthers, & Lesgold, 2002). In addition to their academic achievement, student motivational and emotional experiences were investigated with reference to their attitudes towards inquiry learning, perceived inquiry skills, anxiety level, and confidence level. These experiences have been shown to be significantly related to learning achievements (Pekrun, Goetz, Frenzel, Barchfeld, & Perry, 2011), although they have rarely been investigated thoroughly in technology-enhanced learning environments (Järvenoja & Järvelä, 2005).

In addition, the study examined the impacts of 3DCM approach on low-ability, medium-ability, and high-ability students, respectively, because it is critical to understand the differential effects of scaffolding or support on students of dissimilar academic levels (Veermans & Järvelä, 2004). It is logical to hypothesize that the impact of a specific instructional method and scaffolding/support will vary by academic level because high-level and low-level students differ in what they can and cannot do. However, few studies have investigated the impacts of scaffolding/support on students of different academic levels (Belland, Glazewski, & Richardson, 2011).

Literature review

External representation

External representations are graphical or diagrammatic representations of knowledge or information in the form of maps, diagrams, tables, or pictures (Cox, 1999; Toth et al., 2002). They can be constructed by the students themselves during learning sessions created beforehand by teachers, or taken from textbooks. Learners' active construction of maps related to the solution of a given problem has been found to promote learning in inquiry and problem-solving contexts in the dimensions of cognition, metacognition, and socio-emotional development (Janssen et al., 2010; Suthers et al., 2008; Wang et al., 2013). In the cognitive dimension, constructing external representations assists problem solving by clarifying learners' thinking, helping them to re-order information and draw inferences, sustaining their focus on the construction of knowledge, and helping to reduce their cognitive load (Cox, 1999). Metacognitively, the use of external representations tracks the progress of reasoning and directs attention to the unsolved part of the problem. In the social aspect, external representation serves as an discussion anchor that coordinates the discourse between peers by making one's thinking visible to others (Schwendimann & Linn, 2016).

Among various external representations, concept maps have been widely used in learning. Although most studies on concept mapping have used it as a conceptual learning tool (Schwendimann, 2015), several researchers have deployed this type of representation to facilitate inquiry learning and group tasks. For example, Gijlers and de Jong (2013) found that students who constructed concept maps performed better on knowledge tests in a simulation-based inquiry learning program. Collaborative concept mapping was found to be more effective in supporting group interaction in the situation of concept-oriented task than in that of design-oriented task (Wang, Cheng, Chen, Mercer, & Kirschner, 2017), and role assignment in concept mapping mediated small group learning improved socio-emotional experiences (Cheng, Wang, & Mercer, 2014).

Other popularly used external representations include causal maps, evidence maps, and integrated cognitive maps. Causal mapping is a form of concept mapping used to represent relationships of cause and effect. Slof et al. (2012) found that students who created causal maps offered better justification for their solutions than those who did not create causal maps. Evidence maps that link evidence with claims or hypotheses were found to support hypothetic reasoning (Suthers et al., 2008). Wu and Wang (2012) proposed a computer-based cognitive-mapping approach that enabled students to externalize the hypothetic reasoning process and the underlying knowledge in an integrated cognitive map when they work with diagnostic problems. This approach showed promising effects on diagnostic problem-solving (Wu, Wang, Grotzer, Liu, & Johnson, 2016).

External representations have been shown to promote student learning, especially with the potential to benefit low academic level students (Liu, Chen, & Chang, 2010; Schnotz, 2002). For example, O'Donnell, Dansereau, and Hall (2002) showed that low academic level students benefited the most from knowledge mapping and recalled more knowledge than students of other academic levels. Moreover, in the study on a graphical representation (i.e., proof tree), Wong, Yin, Yang, and Cheng (2011) found that medium-level students reported the most enjoyment.

Learners' motivation and emotion

Learners' motivation and emotion have been shown to significantly relate to their learning achievements (Pekrun et al., 2011). "Motivation" refers to the psychological characteristics that drive students to persist in working toward their learning goals (Muilenburg & Berge, 2005), mainly including beliefs and attitudes such as confidence, self-competence, and interest. Of these, confidence appears to be particularly salient to learning, especially self-regulated learning, because it influences the degree to which learners engage and persevere when facing challenging tasks (Jones & Issroff, 2005).

Emotion encompasses learners' positive and negative reactions to teachers, classmates, schools, and instructional methods (Fredricks, Blumenfeld, & Paris, 2004). Anxiety, boredom, and frustration are typical negative emotions; curiosity, enjoyment, and pride are common positive emotions. Negative academic emotions can impede cognitive processes, whereas positive ones can foster learning (Pekrun et al., 2011). If a learning task is too complex, students may feel frustrated and find it difficult to figure out what to do, which in turn increases their anxiety (Schutz & DeCuir, 2002). Various studies have suggested that the use of cognitive tools would be effective in promoting motivation and/or positive emotions. For example, the use of knowledge maps was shown to enhance motivation and positive attitudes (Sung & Hwang, 2013).

Design of a 3DCM-supported learning environment

Three-dimensional cognitive mapping

Because inquiry and problem-solving tasks usually combine various kinds of information, data, concepts, and relationships, many students find it cognitively demanding to integrate problem data with subject knowledge and to reason using intricately intertwined data. Therefore, more research is needed to investigate methods of externalizing complex cognitive processes to achieve the desired learning outcomes. We studied the use of a *Three-dimensional Cognitive Mapping* (3DCM) to support inquiry learning by allowing learners to combine in a single image problem information, subject knowledge (key concepts and their relationships), and the processes of hypothesizing and reasoning.

An example of 3DCM is illustrated in Figure 1. The figure shows an expressive representation of a problem with three parts: a concept map, a data table, and a reasoning map. The concept map illustrates the concepts underlying the problem and the relationships between these concepts. The data table records the problem information, reflected as a set of key variables and their changes over an observation period. The reasoning map represents the evidential relationships between the hypotheses and the data or subject knowledge. In the reasoning map, each hypothesis is supported ("for") or rejected ("against") by evidence from the data or subject knowledge. To examine the root cause of the problem, the hypothesis is further explained by other hypotheses that explicate deeper causes of the problem. Learners draw the reasoning map while observing the concept map and data table.

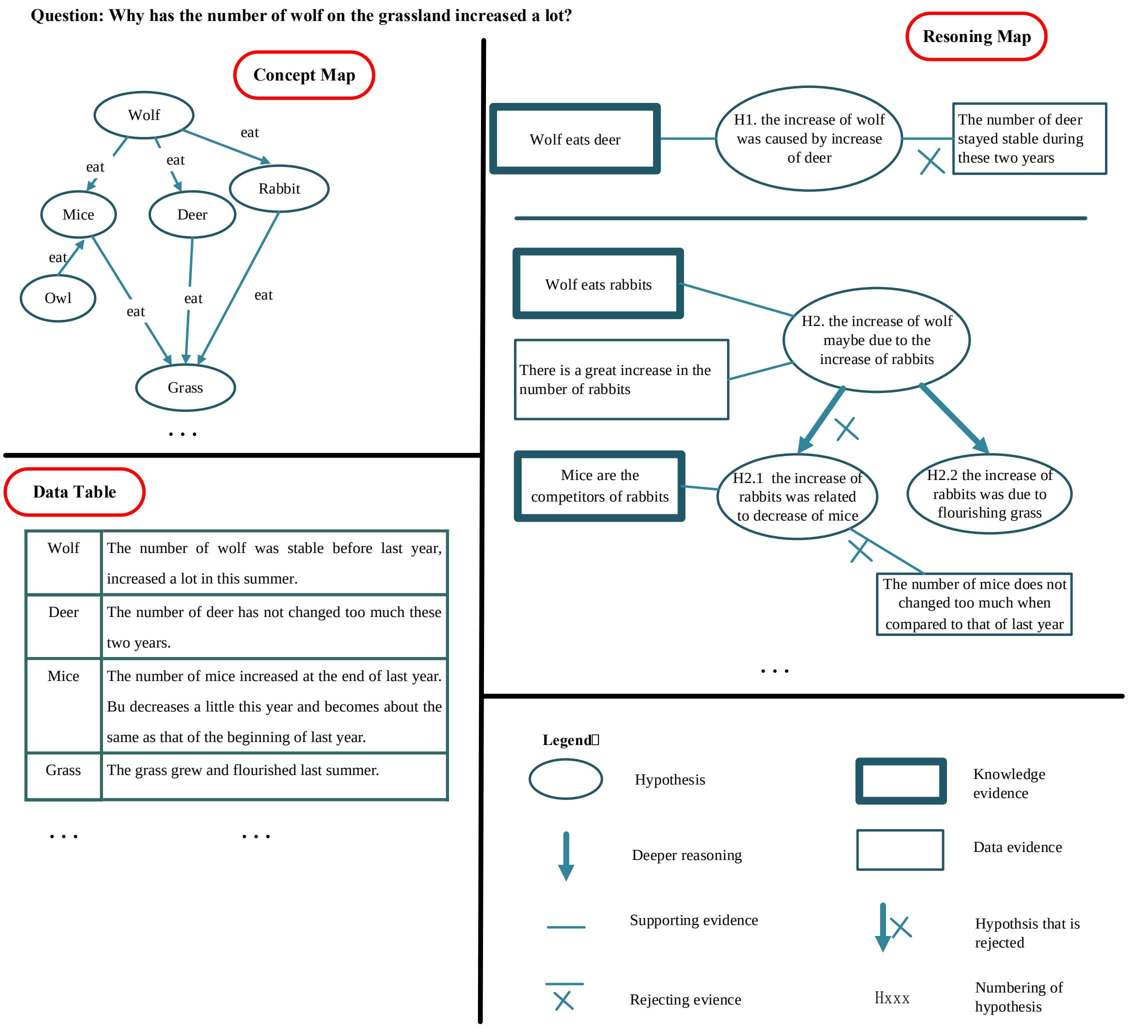

Figure 1. The Three-dimensional cognitive mapping

Learning environment and materials

To support situated learning, an online learning environment that presents a pollution problem within an ecosystem was designed and implemented. It consists of two major modules: *problem context* and *learning support*.

The *problem-context* module presents an authentic pollution problem in a pond ecosystem as a learning task that requires consideration of multiple perspectives and the use of evidence to reach an adequate solution. The problem-context was based on the EcoMUVE curriculum (Kamarainen, Metcalf, Grotzer, & Dede, 2015), in which students explore a virtual pond and the surrounding watershed, observe simulated organisms for a number of virtual "days," and collect relevant data in order to investigate why many of the fish had died overnight. The module contains *information-collection* and *data-observation* sub-modules. As shown in Figure 2, the sub-module of *information-collection* provides a rich context, such as descriptions and visualizations of the surroundings and background information on the pond ecosystem. Users select a specific date from a dropdown list of dates to observe and collect information that provides tacit clues or hints and guides students in observing the phenomena.

The sub-module of *data-observation* shown in Figure 3 facilitates problem exploration by presenting graphs of the data on the key variables and their changes over the observation period. For example, students could observe data on water conditions (e.g., water temperature, turbidity, dissolved oxygen), weather conditions (e.g., air temperature, wind speed), and the population of various organisms (e.g., bacteria, algae, bass) in the pond ecosystem. The module also enables learners to construct queries by selecting variables to facilitate the analysis and comparison of variables.

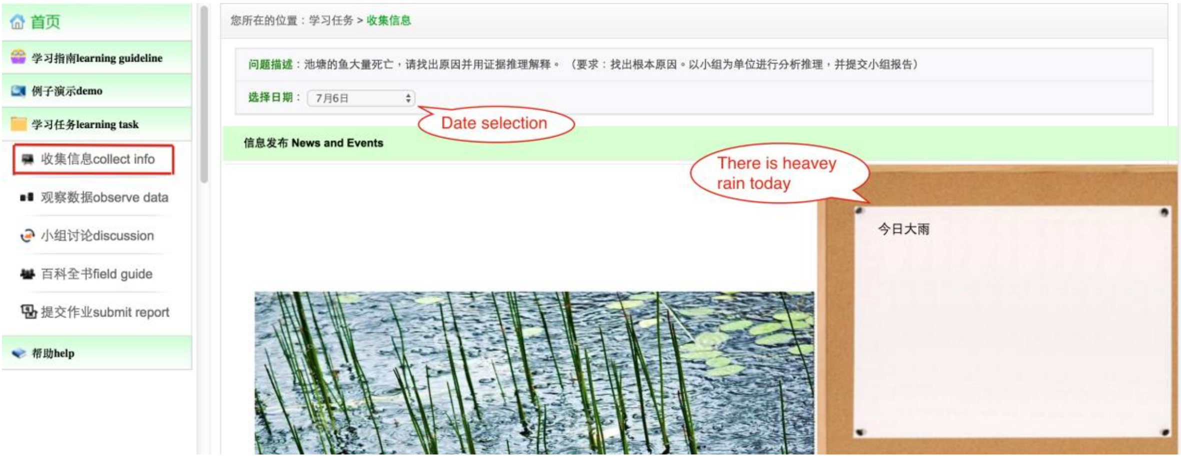

Figure 2. Information collection

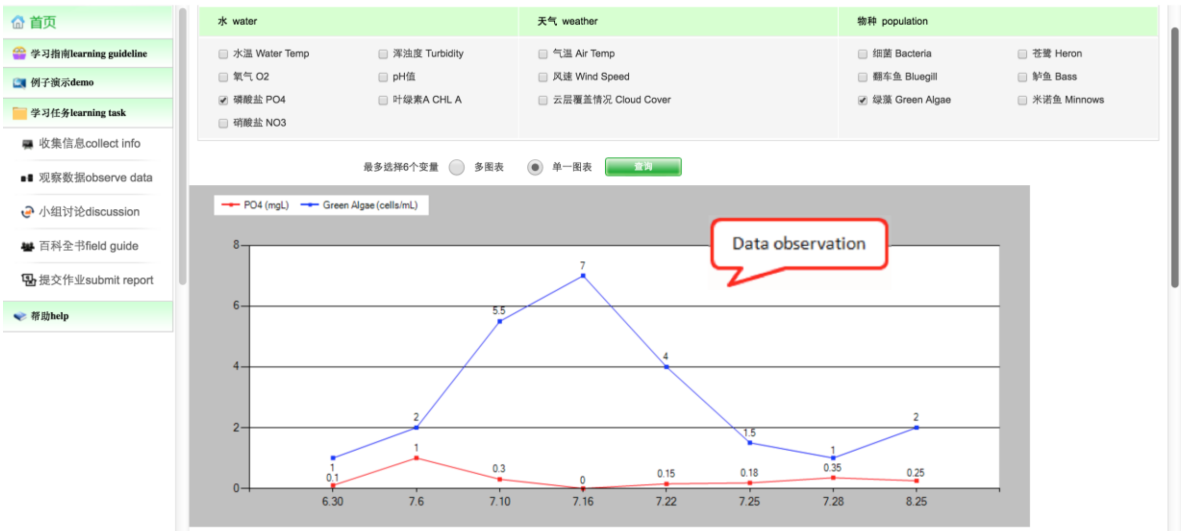

Figure 3. Data observation

The *learning support* module affords some useful learning guidelines. First, it provides domain-specific knowledge about ecosystems and ecological processes, such as the food web and photosynthesis. Second, the module introduces the basic skills required for scientific inquiry and the steps required for scientific inquiry and the fundamental steps involved, such as hypothesis formation and evidence-based reasoning. Third, the module provides general instructions on building a 3DCM, and conducting group discussions, along with an example to demonstrate how to use the learning system.

Research questions

This study's research questions are stated as follows:
RQ1. What are the influences of 3DCM on students' learning outcomes (i.e., knowledge achievement, inquiry skills, attitudes, anxiety level, and confidence level)?
RQ2. What are the influences of 3DCM on the performance of students of different academic levels?
RQ3. What are the relationships between different learning outcomes?

Methodology

Research design

A study was conducted to evaluate the feasibility and influences of the proposed 3DCM approach to support inquiry learning in an online learning environment. The students used the 3DCM to facilitate the inquiry process. They were required to work in small groups to complete the same learning task: exploring a fish die-off problem in a biology course. The students' learning outcomes were measured.

Participants

Forty-eight students from one 11th grade high school class were recruited to participate in the experiment. The sample comprised 24 male and 24 female students, with an average age of 17 (range: 16 to 18). They were classified into three categories of academic ability according to their pre-test scores: high, medium, and low, with each category having 16 students. Students were then randomly divided into 16 small groups of 3 (i.e., one high-level, one medium-level, and one low-level student), which is a typical method of heterogeneous ability grouping for group learning (e.g., Phielix et al., 2010) and has shown its effectiveness in fostering learning (Lou et al., 1996).

Learning task

The learning task required the students to perform causal reasoning and to construct logical and scientific explanations for a fish die-off problem; that is, why so many large fish in a pond ecosystem had suddenly died. The students could freely play with the online environment to collect relevant information and observe changes in each variable over time. They discussed and solved problem in small groups by evaluating and compiling the collected information, formulating hypotheses, and reasoning. They were also asked to create a 3DCM to assist their inquiry. Finally, every group was required to submit an inquiry report to present their solutions, which should include their hypotheses, reasoning, and conclusions.

Procedure

The experiment was conducted in six 45-minute sessions over 2 weeks. During the first session, consent forms were signed by the participants. A pre-test questionnaire was administered individually, and small groups were formed.

At the beginning of the second session, the researcher provided a 20-minute introduction and demonstration on how to perform inquiry learning using the online system in the school's computer laboratory. The principles of social interaction, the method of constructing a 3DCM, and the supporting materials were also briefly introduced.

After the demonstration, students embarked on the learning task in the computer laboratory at school, with group members sitting together and each member accessing a networked computer. After viewing the relevant information and data individually, each student might have developed some ideas or initial hypothesis about the problem. They then began group discussion and collaboration; each group member was encouraged to share personal ideas within the group and to respond to challenges from group mates. To support or reject their initial hypothesis, they collaboratively made observations, collected information, and formulated hypotheses from multiple perspectives by brainstorming ideas based on the compiled evidence (i.e., information and data). Finally, the group had to reach an agreement on the best explanations of the problem. At the end of the fifth session, each group was asked to submit an inquiry report. Next, a semi-structured written interview was conducted to investigate the students' perceptions of the 3DCM approach by asking them to write the responses on paper. Finally, in the sixth session, the participants were asked to individually complete a knowledge test and a questionnaire survey.

Measures and instruments

Pre-test questionnaire

The pre-test questionnaire elicited information on students' gender, age, and self-assessment of their computer skills ("Please describe your computer skills: 1 = Very poor; 2 = Poor; 3 = Neither poor nor good; 4 = Good; 5 = Very good.")

Knowledge test

Both pre- and post-knowledge tests were administered to assess the students' knowledge of the learning subject. Each test comprised multiple-choice questions, fill-in-the-blank questions, and short-answer essay questions to assess students' knowledge of ecosystems, photosynthesis, respiration, and decomposition. The post-test was directly related to the learning task (i.e., a problem within a pond ecosystem). The highest possible score on the knowledge test was 100. The pre- and post-test were at the same level of difficulty. Both tests were designed collaboratively by the teacher and the researcher together. The teacher and another biology instructor expert evaluated the two tests to determine their difficulty level and to confirm their content validity.

Post-test questionnaire

A post-test questionnaire was administered to measure students' attitudes toward inquiry learning, perceived inquiry skills, anxiety level, and confidence level. Responses were given on a 5-point Likert-scale ranging from 1 (strongly disagree) to 5 (strongly agree). Six items measuring attitudes were drawn from Chu, Hwang, Tsai, and Tseng (2010), such as, "I think inquiry learning is more interesting than traditional instruction." Four items measuring perceived inquiry skills used in the learning task were adapted from De Jong (1991), such as, "I can generate testable hypotheses from different perspectives." The inquiry skills measured were hypothesis generation, reasoning, and conclusion making. The students' self-reported anxiety and confidence during the learning task were also measured. To measure anxiety, three items were developed based on the work of Pekrun et al. (2011), such as, "I felt anxious while doing this task." Three items to measure confidence were developed from the work of Keller (2010), such as, "I felt confident during the processes of inquiry learning." Higher scores represented more positive attitudes, better inquiry skills, greater anxiety, and higher confidence, respectively.

Semi-structured written interview

The interview was conducted to get the students' perceptions of the 3DCM approach, using the following questions. "Did the 3DCM approach help you to solve the problem?" "If so, how did it help you?" Students were asked to write their responses to the questions on paper.

Data analysis methods

The following methods of data analysis were used.

- To answer RQ1, statistics were obtained for learning outcome measures, including means and standard deviations (SDs), and a paired-sample *t*-test was conducted to compare the difference between post- and pre-knowledge test scores.
- To answer RQ2, one-way analysis of variance (ANOVA) was performed to evaluate the statistical differences in learning outcomes between students of three different academic levels, with academic level as a between-subject independent variable. Since a statistical difference in knowledge gain was found between three levels of students, we then run Tukey's post-hoc test to compare each of the three levels to every other level to figure out which specific level of students differed from others.
- To answer RQ3, correlation analysis was run to gain a deeper understanding of the relationships between the measured learning outcomes.
- A thematic content analysis of the interview was performed to identify common themes in students' responses to the written interview question. It was performed by one of the researchers and a research assistant with expertise in content analysis. Cohen's Kappa value for inter-rater reliability was .78.

Results

Pre-test

The 48 students' mean score on the pre-test was 63.19 (*SD* = 8.49). As shown in Table 1, high-level students were those scoring the top third, with a mean score of 71.94 (*SD* = 2.77); medium-level students were those scoring the middle third, with a mean score of 64.25 (*SD* = 2.84); and low-level students were those scoring the bottom third, with a mean score of 53.37 (*SD* = 4.95). ANOVA result revealed significant differences in prior knowledge between students at the three levels (F (2, 45) = 103.75, $p < .001$). The mean score for the participants' self-perceived computer skills was 3.29 (SD = .51), and no significant differences were observed between the students at different academic levels (F (2, 45) = 1.16, $p > .05$).

RQ1. What are the influences of 3DCM on students' learning outcomes (i.e., knowledge achievement, inquiry skill, attitude, anxiety level, and confidence level)?

All 48 participants completed the post knowledge test. Yet, only 38 returned their completed questionnaires because the other 10 students were absent during the survey session. As shown in Table 1, the mean score on the post knowledge test (mean = 78.26, *SD* = 8.69) was higher than that on the pre-test (mean = 63.19, *SD* = 8.80); this difference was statistically significant (t_{47} = 9.576, $p < .001$), based on the paired-sample *t*-test result. This finding indicates a significant improvement in the students' domain knowledge.

Regarding the reliability of the questionnaire, the Cronbach's alpha values were .90 for attitude, .83 for inquiry skills, .74 for anxiety, and .72 for confidence, indicating credible internal consistency. The means were 4.15 (*SD* = .54) for attitude, 4.20 (*SD* = .49) for inquiry skills, 2.44 (*SD* = .77) for anxiety, and 3.82 (*SD* = .61) for confidence, indicating fairly high inquiry skills, positive attitude, low anxiety, and medium confidence. With respect to inquiry skills, the mean scores were 4.18 (*SD* = .61) for hypothesis generation, 4.13 (*SD* = .66) for scientific reasoning, and 4.32 (*SD* = .62) for making conclusions. All of these values were fairly high (exceeding 4 out of 5), suggesting that the students perceived themselves to have performed quite well in all aspects of inquiry processes.

Table 1. Descriptive statistics for learning outcomes and ANOVA results for students at different academic levels

Type of learning outcome		*N*	Mean	*SD*	ANOVA
Pre-knowledge test		48	63.19	8.49	F (2, 45) = 103.75 ($p < .001$)
	High	16	71.94	2.77	
	Medium	16	64.25	2.84	
	Low	16	53.37	4.95	
Post-knowledge test		48	78.26	8.69	F (2, 45) = .59 (p = .56)
	High	16	79.63	8.89	
	Medium	16	78.77	8.70	
	Low	16	76.38	8.72	
Attitude		38	4.15	.54	F (2, 35) = .70 (p = .51)
	High	12	4.03	.54	
	Medium	13	4.28	.66	
	Low	13	4.14	.38	
Inquiry skills		38	4.20	.49	F (2, 35) = .21 (p = .81)
	High	12	4.13	.56	
	Medium	13	4.24	.47	
	Low	13	4.23	.47	
Anxiety		38	2.44	.77	F (2, 35) = 2.03 (p = .15)
	High	12	2.42	.84	
	Medium	13	2.74	.87	
	Low	13	2.15	.46	
Confidence		38	3.82	.61	F (2, 35) = .15 (p = .86)
	High	12	3.81	.50	
	Medium	13	3.77	.79	
	Low	13	3.90	.53	

RQ2. What are the influences of 3DCM on the performance of students of different academic levels?

The mean scores on post-test obtained by the high, middle, and low academic level students (as defined by their pre-test scores) were 79.63 (*SD* = 8.89), 78.77 (*SD* = 8.70), and 76.38 (*SD* = 8.72), respectively, as shown in Table 1. ANOVA result revealed no significant differences in post knowledge test scores between the students of the three levels (F (2, 45) = .59, *SD* = .56). In terms of the knowledge gain (i.e., the difference between post-test and pre-test scores), the mean values were 7.69 (*SD* = 8.94) for the high-level students, 14.52 (*SD* = 9.35) for the medium-level students, and 23 (*SD* = 8.91) for the low-level students. This demonstrates the effectiveness of 3DCM in improving all students' knowledge regardless of their prior knowledge level. ANOVA result revealed significant difference between the students at the three levels in knowledge gain (F (2, 45) = 11.44, $p < .001$), indicating that academic level had a significant effect on knowledge gain. Post-hoc comparisons using the Tukey HSD test indicated that the low-level students acquired significantly more knowledge than the high- and medium-level students at the $p < .05$ level, respectively. However, no significant difference in knowledge gain was observed between the high- and medium-level students.

Regarding the students' perceived inquiry skills, attitudes, anxiety level, and confidence level, ANOVA results showed no significant differences between the three levels of students, as demonstrated in Table 1.

RQ3. What are the relationships between different learning outcomes?

As seen in Table 2, both the students' attitude and their confidence were positively related to their perceived inquiry skills; anxiety and confidence were statistically negatively correlated.

Table 2. Pearson's correlations between different learning outcomes

	Post-test	Attitude	Inquiry skill	Anxiety	Confidence
Post-test	1	.10	.03	-.03	-.12
Attitude		1	.65 **	-.18	.49
Inquiry skills			1	-.12	.61**
Anxiety level				1	-.42**
Confidence level					1

Note. $^{**}p < .01$.

Written interview

The students' responses to the interview question about the benefits of 3DCM are presented in Table 3. They made 45 different positive comments in total. Twenty-six of the students reported that the 3DCM approach had helped them to think in an organized and logical way. These responses indicate that 3DCM had fulfilled its intended functions.

Table 3. Students' responses to the semi-structured interview question

Did the 3DCM approach help you to solve the problem? If so, how did it help you?	
Students' comments	Count
Data and information collection	
Helping us to visualize the data.	1
Facilitating the integration and organization of information.	1
Systematic thinking	
Helping us to think in an organized and logical way.	26
Covering all relationships (e.g., causal relationship).	3
Helping us to find the right direction to solve the problem.	1
Hypothesizing	
Enabling us to conduct more in-depth and comprehensive analysis of the causes of fish death.	2
Helping us to revise previously formed incorrect hypotheses or ideas.	1
Reasoning	
Improving our reasoning abilities.	1
The reasoning map clarified the detailed reasoning process.	1
Reasoning map guided us step-by-step and helped develop a logical argument progressively.	1
Sufficient evidence was included to make the reasoning convincing.	1
Helping us to clearly see the relationships between pieces of information/evidence.	2

Enabling us to find disconfirming evidence and thus reject incorrect hypotheses.	1
Drawing a data table helped us notice the data that mighty be missed or omitted.	1
Communication	
Helping others to easily understand my ideas.	1
Recording the key viewpoints.	2

Note. Count = number of students who made similar comments.

Discussion

RQ1 addressed the influences of the 3DCM approach on learning outcomes. First, analysis of the pre- and post-knowledge test revealed that the students made significant knowledge gains (measured by the difference in scores between pre- and post-knowledge test), indicating the effectiveness of the approach. This large knowledge gain may be explained by the fact that the designed 3DCM approach effectively supported collaborative knowledge construction. Constructing 3DCM elicited students' ideas and made students elaborate on them, thus improving their knowledge understanding. The concept map in 3DCM integrated concepts and their relationships, promoting knowledge integration. Research has also suggested that reasoning activities help students to integrate new information with prior knowledge to develop deep, contextualized, and applicable knowledge (Keselman, Kaufman, Kramer, & Patel, 2007; Keys, 2000). Moreover, the 3DCM approach helped students to reflect on their existing knowledge and identify knowledge gaps. The benefits of external representations in facilitating these elaborative, integrative, and reflective processes have also been highlighted by Suthers et al. (2008).

Second, the high mean score obtained for perceived inquiry skills revealed that the students perceived the tool as useful in fostering their problem-solving skills. This was consistent with the findings of previous studies (Janssen et al., 2010; Sung & Hwang, 2013). More specifically, the students reported fairly high levels of skills for generating reasonable hypotheses, reasoning, and drawing conclusions. This result was validated by the interview data. Most of the interviewees reported that 3DCM had enabled them to develop a logical set of hypotheses, and to review and revise previously formed hypotheses or ideas. This confirmed the belief that well-designed external representation helps students to refine their ideas (Cox, 1999).

Regarding reasoning, the reasoning map focused the students' attention on developing logical justification by finding confirming and disconfirming evidence and linking evidence with their hypothesis. In addition, it helped the learners to clearly see the relationships between different pieces of information/evidence. Moreover, some students said that drawing a data table helped them to notice data that might be omitted. In addition, some students reported that constructing the maps helped them to draw conclusions.

Third, the students' attitudes toward inquiry learning were quite positive. This was also evident from their interview data. In addition, during the free discussion between the researcher and the participants after the experiment, most students revealed that this inquiry learning approach was very interesting, stimulated their passions in exploring the problem, and made them become active in learning. Sung and Hwang (2013) also showed that the use of external representations in inquiry learning led to a positive attitude.

Fourth, the students' confidence failed to reach a high level (i.e., > 4) in the inquiry process (mean = 3.82), due to several possible reasons. Participants rarely had prior experiences with such a learning approach. They had been accustomed to passive learning, while the proposed active learning approach was totally new to them. Unfamiliarity with creating 3DCM might reduce their confidence. Moreover, the open-ended task presented to them seemed difficult and challenging. Task is often a source of motivation and emotion (Wosnitza & Volet, 2005). As reflected by some participants, it was their first time solving this kind of problem. These factors may also explain the result for anxiety (mean = 2.44). In addition, technical problems may have contributed to the students' anxiety; for example, one student said that he needed more time to become familiar with the system. Unfamiliarity with technology was also reported as a cause of anxiety by Wosnitza and Volet (2005). A few students reported Internet connection problems, causing a lack of time in conducting the inquiry activities. Time pressure, also found in other research, may also trigger anxiety (Janssen et al., 2010).

RQ2 explored the influences of 3DCM on students of different academic levels. We found that the students of the three academic levels differed significantly in terms of knowledge gain. Specifically, the low-level students benefited significantly more from the 3DCM approach than the students at the other two levels. This result was consistent with the findings of previous studies, which have shown that cognitive tools or external representations are especially effective in improving the learning achievement of low-level students and narrowing the gap between low and high academic level students (Belland et al., 2011; Liu et al., 2010; O'Donnell et al., 2002). The students classified as low-level achievers based upon their pre-test scores scored higher than those classified as high achievers based upon their pre-test scores (Dori, Tal, & Tsaushu, 2003). Low-level students may be more susceptible to distraction (Armbruster & Anderson, 1980); building external representations can help focus their attentions on relevant learning content (Guastello, Beasley, & Sinatra, 2000). In addition, low-level students in comparison with their high-level peers might need extra support in constructing mental models, which suggests the usefulness of visual representations(Schnotz, 2002).

Additionally, there were no significant differences in learning attitudes, perceived inquiry skills, anxiety level, or confidence level among the students of different academic levels. Similar findings have been reported elsewhere (Liu, 2004). This indicated that all students displayed fairly high levels of learning confidence and perceived inquiry skills when using the 3DCM approach. Although many educators avoid teaching high-order thinking skills to low-level students because they believe that such students are incapable of performing tasks that require high-order thinking (Zohar & Dori, 2003), the findings of the current study suggest that, if taught properly, low-level students can acquire high-order thinking skills as well as high-level students, in line with the findings of Perkins and Grotzer (2005).

RQ3 examined the correlations between different learning outcomes. Both the students' attitudes and their confidence were positively related to their inquiry skills. Unsurprisingly, it is easy to understand that more positive attitudes toward learning and greater confidence yielded better inquiry performance (Eseryel, Law, Ifenthaler, Ge, & Miller, 2013). The negative correlation between confidence and anxiety was also consistent with previous findings (Dalgarno, Bishop, Adlong, & Bedgood, 2009).

Conclusions

In science learning, students often experience difficulties in engaging in fruitful inquiry learning, such as generating hypothesis and carrying out scientific reasoning. Despite the availability of various kinds of support or guidance (e.g., prompts), learners may still find it cognitively demanding to successfully complete inquiry tasks. This study proposed and investigated the influences of a 3DCM approach that allowed learners to articulate information about a problem, relevant concepts and their relationships, and the processes of hypothesizing and reasoning about the problem in a holistic picture to support inquiry learning.

The findings show that the students displayed high academic achievement, positive attitudes, low anxiety, and medium levels of confidence, indicating that the proposed approach is a promising means of supporting inquiry learning. Specifically, the 3DCM approach provided the learners with an overview of the inquiry task, and guided them in generating hypotheses step-by-step and developing evidence-based reasoning based on relevant data and knowledge. In addition, the students of high-, medium-, and low-levels showed significant improvements on the knowledge test. Particularly, students of a low academic level benefited the most from this approach, indicating the effectiveness of 3DCM in narrowing the gap between low and high academic level students. Moreover, both the participants' attitudes and their confidence were positively related to their inquiry skills (including hypothesis generation and reasoning).

Implications

This study has several implications for designing support/guidance for inquiry learning in computer-supported environments. First, it is important to scaffold students when they engage in a complex inquiry task. Visually representing diverse aspects of inquiry learning can facilitate students' inquiry. Second, narrowing the academic gaps between low and high level students is critically important (Yerrick, 2000; Zohar & Dori, 2003). Providing appropriate inquiry learning environments and external representations, such as cognitive mapping, seems a promising means of realizing the potential of low academic level students and narrowing the gap between low- and high-level students. Third, the impact of the proposed approach on emotions and motivations has implications for the design of learning support for inquiry learning. In particular, reducing learners' anxiety and improving their confidence is critical to enhance their inquiry skills and knowledge.

Limitations and future work

Some issues or limitations exist in the current study. First, comparison of groups with and without the use of 3DCM is needed to further verify the validity of this intervention. Second, this study investigated only the students' outcomes on knowledge test, and their perceptions of the inquiry process; it did not examine the quality of the maps constructed, group reports, the discussion process, and the relationship between the quality of the maps and the group reports. Investigation of these components may provide a deeper understanding of the mechanisms of the 3DCM approach. Third, inquiry skills were assessed with a questionnaire rather than a more authentic measure. These issues will need to be addressed in future work.

Acknowledgements

This research is supported by the General Research Fund (No. 17201415) from the Hong Kong SAR Government, and the Seeding Fund for Basic Research (No. 201611159071) from the University of Hong Kong. The EcoMUVE curriculum was supported by the Institute of Education Sciences, U.S. Department of Education, Grant No. R305A080514 to Chris Dede and Tina Grotzer.

References

Armbruster, B. B., & Anderson, T. H. (1980). *The Effect of mapping on the free recall of expository text* (Technical Report No. 160). Urbana, IL: University of Illinois, Center for the Study of Reading.

Belland, B. R., Glazewski, K. D., & Richardson, J. C. (2011). Problem-based learning and argumentation: Testing a scaffolding framework to support middle school students' creation of evidence-based arguments. *Instructional Science, 39*(5), 667-694.

Bransford, J., Brown, A. L., & Cocking, R. E. (Eds.) (1999). *How people learn: Brain, mind, experience, and school*. Washington, DC: National Academy Press.

Cheng, B., Wang, M., & Mercer, N. (2014). Effects of role assignment in concept mapping mediated small group learning. *The Internet and Higher Education, 23*, 27-38.

Chu, H. C., Hwang, G. J., Tsai, C. C., & Tseng, J. C. (2010). A Two-tier test approach to developing location-aware mobile learning systems for natural science courses. *Computers & Education, 55*(4), 1618-1627.

Cox, R. (1999). Representation construction, externalised cognition and individual differences. *Learning and Instruction, 9*(4), 343-363.

Dalgarno, B., Bishop, A. G., Adlong, W., & Bedgood, D. R. (2009). Effectiveness of a virtual laboratory as a preparatory resource for distance education chemistry students. *Computers & Education, 53*(3), 853-865.

De Jong, T. (1991). Learning and instruction with computer simulations. *Education and Computing, 6*(3/4), 217-229.

De Jong, T., Linn, M. C., & Zacharia, Z. C. (2013). Physical and virtual laboratories in science and engineering education. *Science, 340*(6130), 305-308.

De Jong, T., & van Joolingen, W. R. (1998). Scientific discovery learning with computer simulations of conceptual domains. *Review of Educational Research, 68*(2), 179-201.

Dede, C. (2009). Immersive interfaces for engagement and learning. *Science, 323*(5910), 66-69.

Dori, Y. J., Tal, R. T., & Tsaushu, M. (2003). Teaching biotechnology through case studies - Can we improve higher order thinking skills of nonscience majors? *Science Education, 87*(6), 767-793.

Eseryel, D., Law, V., Ifenthaler, D., Ge, X., & Miller, R. (2013). An Investigation of the interrelationships between motivation, engagement, and complex problem solving in game-based learning. *Educational Technology & Society, 17*(1), 42-53.

Fredricks, J. A., Blumenfeld, P. C., & Paris, A. H. (2004). School engagement: Potential of the concept, state of the evidence. *Review of Educational Research, 74*(1), 59-109.

Gijlers, H., & de Jong, T. (2013). Using concept maps to facilitate collaborative simulation-based inquiry learning. *Journal of the Learning Sciences, 22*(3), 340-374.

Guastello, E. F., Beasley, T. M., & Sinatra, R. C. (2000). Concept mapping effects on science content comprehension of low-achieving inner-city seventh graders. *Remedial and Special Education, 21*(6), 356-364.

Hmelo-Silver, C. E., Duncan, R. G., & Chinn, C. A. (2007). Scaffolding and achievement in problem-based and inquiry learning: A Response to Kirschner, Sweller, and Clark (2006). *Educational Psychologist, 42*(2), 99-107.

Janssen, J., Erkens, G., Kirschner, P. A., & Kanselaar, G. (2010). Effects of representational guidance during computer-supported collaborative learning. *Instructional Science, 38*(1), 59-88.

Järvenoja, H., & Järvelä, S. (2005). How students describe the sources of their emotional and motivational experiences during the learning process: A Qualitative approach. *Learning and Instruction, 15*(5), 465-480.

Jonassen, D. H. (2005). Tools for representing problems and the knowledge required to solve them. In S. O. Tergan & T. Keller (Eds.), *Knowledge and Information Visualization* (pp. 82-94). Berlin, Germany: Springer.

Jones, A., & Issroff, K. (2005). Learning technologies: Affective and social issues in computer-supported collaborative learning. *Computers & Education, 44*(4), 395-408.

Kamarainen, A., Metcalf, S., Grotzer, T., & Dede, C. (2014). Understanding data variability in ecosystems: Blending MUVE and mobile technologies to support reasoning with real world data. In *Proceedings of the International Conference of the Learning Sciences* (Vol. 3, pp. 1581-1582). Boulder, CO: International Society of the Learning Sciences.

Kamarainen, A. M., Metcalf, S., Grotzer, T., & Dede, C. (2015). Exploring ecosystems from the inside: How immersive multi-user virtual environments can support development of epistemologically grounded modeling practices in ecosystem science instruction. *Journal of Science Education and Technology, 24*(2/3), 148–167.

Keller, J. M. (2010). *Motivational design for learning and performance: The ARCS model approach*. Boston, MA: Springer.

Keselman, A., Kaufman, D. R., Kramer, S., & Patel, V. L. (2007). Fostering conceptual change and critical reasoning about HIV and AIDS. *Journal of Research in Science Teaching, 44*(6), 844-863.

Keys, C. W. (2000). Investigating the thinking processes of eighth grade writers during the composition of a scientific laboratory report. *Journal of Research in Science Teaching, 37*(7), 676-690.

Kirschner, P. A., Sweller, J., & Clark, R. E. (2006). Why minimal guidance during instruction does not work: An Analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educational Psychologist, 41*(2), 75-86.

Kollar, I., Fischer, F., & Slotta, J. D. (2007). Internal and external scripts in computer-supported collaborative inquiry learning. *Learning and Instruction, 17*(6), 708-721.

Kuhn, D., Black, J., Keselman, A., & Kaplan, D. (2000). The Development of cognitive skills to support inquiry learning. *Cognition and Instruction, 18*(4), 495-523.

Lazonder, A. W., & Harmsen, R. (2016). Meta-analysis of inquiry-based learning: Effects of guidance. *Review of Educational Research, 86*(3), 681-718.

Linn, M. C., & Slotta, J. D. (2000). WISE science. *Educational Leadership, 58*(2), 29-32.

Liu, M. (2004). Examining the performance and attitudes of sixth graders during their use of a problem-based hypermedia learning environment. *Computers in Human Behavior, 20*(3), 357-379.

Liu, P. L., Chen, C. J., & Chang, Y. J. (2010). Effects of a computer-assisted concept mapping learning strategy on EFL college students' English reading comprehension. *Computers & Education, 54*(2), 436-445.

Lou, Y., Abrami, P. C., Spence, J. C., Poulsen, C., Chambers, B., & D'Apollonia, S. (1996). Within-class grouping: A Meta-analysis. *Review of Educational Research, 66*(4), 423-458.

Muilenburg, L. Y., & Berge, Z. L. (2005). Students barriers to online learning: A Factor analytic study. *Distance Education, 26*(1), 29-48.

O'Donnell, A. M., Dansereau, D. F., & Hall, R. H. (2002). Knowledge maps as scaffolds for cognitive processing. *Educational Psychology Review, 14*(1), 71-86.

Pekrun, R., Goetz, T., Frenzel, A. C., Barchfeld, P., & Perry, R. P. (2011). Measuring emotions in students' learning and performance: The Achievement Emotions Questionnaire (AEQ). *Contemporary Educational Psychology, 36*(1), 36-48.

Perkins, D. N., & Grotzer, T. A. (2005). Dimensions of causal understanding: The Role of complex causal models in students' understanding of science. *Studies in Science Education, 41*, 117-165.

Phielix, C., Prins, F. J., & Kirschner, P. A. (2010). Awareness of group performance in a CSCL-environment: Effects of peer feedback and reflection. *Computers in Human Behavior, 26*(2), 151-161.

Schnotz, W. (2002). Commentary: Towards an integrated view of learning from text and visual displays. *Educational Psychology Review, 14*(1), 101-120.

Schutz, P. A., & DeCuir, J. T. (2002). Inquiry on emotions in education. *Educational Psychologist, 37*(2), 125-134.

Schwendimann, B. A. (2015). Concept maps as versatile tools to integrate complex ideas: From kindergarten to higher and professional education. *Knowledge Management & E-Learning, 7*(1), 73–99.

Schwendimann, B. A., & Linn, M. C. (2016). Comparing two forms of concept map critique activities to facilitate knowledge integration processes in evolution education. *Journal of Research in Science Teaching, 53*(1), 70-94.

Slof, B., Erkens, G., Kirschner, P. A., Janssen, J., & Jaspers, J. G. M. (2012). Successfully carrying out complex learning-tasks through guiding teams' qualitative and quantitative reasoning. *Instructional Science, 40*(3), 623-643.

Sung, H. Y., & Hwang, G. J. (2013). A Collaborative game-based learning approach to improving students' learning performance in science courses. *Computers & Education, 63*, 43-51.

Suthers, D. D., Vatrapu, R., Medina, R., Joseph, S., & Dwyer, N. (2008). Beyond threaded discussion: Representational guidance in asynchronous collaborative learning environments. *Computers & Education, 50*(4), 1103-1127.

Toth, E. E., Suthers, D. D., & Lesgold, A. M. (2002). "Mapping to know": The Effects of representational guidance and reflective assessment on scientific inquiry. *Science Education, 86*(2), 264-286.

Veermans, M., & Järvelä, S. (2004). Generalized achievement goals and situational coping in inquiry learning. *Instructional Science, 32*(4), 269-291.

Wang, M., Cheng, B., Chen, J., Mercer, N., & Kirschner, P. A. (2017). The Use of web-based collaborative concept mapping to support group learning and interaction in an online environment. *The Internet and Higher Education, 34,* 28–40.

Wang, M., Wu, B., Kinshuk, Chen, N. S., & Spector, J. M. (2013). Connecting problem-solving and knowledge-construction processes in a visualization-based learning environment. *Computers & Education, 68*, 293-306.

Wong, W. K., Yin, S. K., Yang, H. H., & Cheng, Y. H. (2011). Using computer-assisted multiple representations in learning geometry proofs. *Educational Technology & Society, 14*(3), 43-54.

Wosnitza, M., & Volet, S. (2005). Origin, direction and impact of emotions in social online learning. *Learning and Instruction, 15*(5), 449-464.

Wu, B., & Wang, M. (2012). Integrating problem solving and knowledge construction through dual mapping. *Knowledge Management & E-Learning (KM&EL), 4*(3), 248–257.

Wu, B., Wang, M., Grotzer, T. A., Liu, J., & Johnson, J. M. (2016). Visualizing complex processes using a cognitive-mapping tool to support the learning of clinical reasoning. *BMC Medical Education, 16*(1), 216. doi:10.1186/s12909-016-0734-x

Yerrick, R. K. (2000). Lower track science students' argumentation and open inquiry instruction. *Journal of Research in Science Teaching, 37*(8), 807-838.

Yuan, B., Wang, M., Kushniruk, A. W., & Peng, J. (2016). Design of a computer-based learning environment to support diagnostic problem solving towards expertise development. *Knowledge Management & E-Learning, 8*(4), 540–549.

Zeineddin, A., & Abd-El-Khalick, F. (2010). Scientific reasoning and epistemological commitments: Coordination of theory and evidence among college science students. *Journal of Research in Science Teaching, 47*(9), 1064-1093.

Zohar, A., & Dori, Y. J. (2003). Higher order thinking skills and low-achieving students: Are they mutually exclusive? *Journal of the Learning Sciences, 12*(2), 145-181.