Using cognitive mapping to foster deeper learning with complex problems in a computer-based environment

Computers in Human Behavior 87 (2018) 450–458

Contents lists available at ScienceDirect

Computers in Human Behavior

journal homepage: www.elsevier.com/locate/comphumbeh

Full Length Article

Using cognitive mapping to foster deeper learning with complex problems in a computer-based environment

Minhong Wang [a, b, *], Bian Wu [b], Paul A. Kirschner [c, d], J. Michael Spector [e]

[a] KM&EL Lab, Faculty of Education, The University of Hong Kong, Hong Kong
[b] Department of Educational Information Technology, East China Normal University, China
[c] Welten Institute, Open University of the Netherlands, Netherlands
[d] University of Oulu, Finland
[e] Department of Learning Technologies, University of North Texas, USA

A R T I C L E I N F O

Article history:
Available online 1 February 2018

Keywords:
Problem solving
Cognitive mapping
Concept map
Visualization
Scaffolding
Computer-based learning environment

A B S T R A C T

Concept mapping has been widely used to foster meaningful learning and support the communication of complex ideas. With a focus on conceptual understanding, traditional concept mapping is found to be inadequate in supporting problem solving particularly in eliciting and representing the complex process of applying knowledge to practice. In this study, a computer-based cognitive-mapping approach was used to extend traditional concept mapping by allowing learners to represent the problem-solving process and the underlying knowledge in a visual format. By representing ideas both verbally and pictorially, the cognitive mapping approach has a high potential to foster effective thinking and reflection in problem-solving contexts. This study examined the effects of the computer-based cognitive-mapping approach by comparing it to a note-taking approach that represents ideas in verbal text only. Forty-nine senior year medical students participated in the study. The experimental group used the cognitive-mapping approach, while the control group used a note-taking approach, to articulate complex thinking and actions when working with simulated clinical diagnostic problems in a computer-based learning environment. The results show the promising effects of the cognitive-mapping approach on improving students' problem-solving performance, subject-matter knowledge, and intrinsic motivation to learn with complex problems.

1. Introduction

Concept mapping, a way of representing knowledge as a set of concepts and the relationships between the concepts in graphical formats (Novak & Musonda, 1991; Cañas, Reiska, & Möllits, 2017), has been widely used as a teaching and learning strategy. Concept mapping supports the understanding and communication of complex ideas and enables effective cognitive processes by organizing pieces of knowledge into a schematic structure. Concept mapping is supported by Ausubel's (1963) theory of meaningful learning, which claims that meaningful learning occurs when learners deliberately seek to relate and assimilating new concepts with prior knowledge into a systematic structure.

Concept maps have been increasingly used in educational practice, where teachers present them to facilitate learning, learners create them to facilitate and demonstrate their understanding of complex issues, and teachers use them again to assess students' understanding. Nesbit and Adesope (2006) meta-analysis of the literature reported the effects of concept mapping in fostering in-depth understanding, knowledge construction, and higher-order thinking by enabling learners to construct communicate their understanding and manage cognitive processes. In particular, concept mapping activities were found to be effective in improving knowledge retention with effect sizes varying from small to large depending on how concept maps were used, the type of comparison treatment (such as reading text, writing summaries, participating in discussions), and learners' prior knowledge or verbal ability.

Concept mapping is mainly used to support conceptual learning. Its effects on learning in problem-solving contexts was investigated only in a few studies. Engelmann and Hesse (2010) reported that sharing individual concept maps within group members improved

* Corresponding author. Faculty of Education, University of Hong Kong, Pokfulam Road, Hong Kong.
E-mail addresses: magwang@hku.hk (M. Wang), bwu@deit.ecnu.edu.cn (B. Wu), Paul.Kirschner@ou.nl (P.A. Kirschner), Mike.Spector@unt.edu (J. Michael Spector).

https://doi.org/10.1016/j.chb.2018.01.024
0747-5632/

collaborative problem-solving performance. Gijlers and de Jong (2013) found that students who constructed concept maps performed better on knowledge tests in a simulation-based inquiry learning program. Hwang, Kuo, Chen, and Ho (2014) found that integrating concept mapping into problem-solving-based learning may improve students' problem-solving performance and subject knowledge. However, concept mapping alone is inadequate in supporting complex problem-solving tasks, particularly in eliciting and representing the process of applying knowledge to practice (Wang, Cheng, Chen, Mercer, & Kirschner, 2017; Stoyanov & Kommers, 2008). Learning in problem-solving contexts often involves a complex cognitive process such as searching for problem information in multiple aspects, integration of problem information and domain knowledge, and reasoning with intertwined elements. The complex and tacit nature of such processes place high cognitive demand for novices, making them unable to accomplish the task and achieve desired learning outcomes (Kirschner, Sweller, & Clark, 2006; Patel, Arocha, & Kaufman, 2001; Zeineddin & Abd-El-Khalick, 2010). The literature has discussed the importance of scaffolding or guiding students through the complex process and helping them to become accomplished problem-solvers (Hmelo-Silver, Duncan, & Chinn, 2007; Kim & Hannafin, 2010).

Recent research has highlighted the importance of making thinking visible in complex problem or task situations to foster deeper learning (Wang, Derry, & Ge, 2017; Wang, Kirschner, & Bridges, 2016). Meanwhile, computer-based cognitive mapping approaches have been increasingly promoted to facilitate thinking in complex situations. By representing cognitive structures and processes in visual formats, cognitive mapping approaches may amplify, extend, and enhance human cognitive functions and engage learners as they represent, manipulate, and reflect on what they know (Cox, 1999; Jonassen, 2005). Among various cognitive representations, concept mapping has been widely employed and shown its advantages in enhancing conceptual learning. There is however, inadequate knowledge of how the complex cognitive processes in problem-solving contexts can be externalized and facilitated in a way that leads to improved performance and learning outcomes.

This study examined the effects of a computer-based cognitive-mapping approach that extends traditional concept mapping by allowing learners to capture the essence of problem-solving experience in a visual format. Medical education was selected as the domain for the study, as problem-solving experience is regarded as crucial to learning and expertise development in this field. Students used the computer-based cognitive-mapping approach to elicit complex thinking and actions when working with simulated clinical diagnostic problems in a computer-based learning environment.

1.1. Problem-solving performance

In externalizing the complex problem-solving process for effective learning and practice, it is important to focus on the essential aspects of problem-solving performance. Research on problem solving and expert-novice difference reveals that problem-solving performance is mainly influenced by two factors: problem-solving strategy and subject-matter knowledge, in addition to self-regulation or metacognitive ability (Bransford, Brown, & Cocking, 1999; Mayer & Wittrock, 1996; Patel et al., 2001; van de Wiel, 2017).

The first factor "problem-solving strategy" concerns the cognitive process of applying subject matter-knowledge to solve a problem by using relevant methods. Among various problem-solving strategies, the hypothesis-driven method is most widely used to solve a problem by collecting relevant data, generating hypotheses, and using data to test hypotheses. In other words, the cognitive process of solving a problem in most situations consists of three key elements: (1) exploring problem information in multiple aspects which can be associated with problem representation, (2) generating solutions or hypotheses to solve or explain the problem, and (3) reasoning with intertwined variables/elements to analyze the problem and justify or reject solutions, in addition to follow-up activities such as evaluation of the solutions and reflection on the performance (Ge & Land, 2003; Jonassen, 1997; Kim & Hannafin, 2010).

The second factor "subject-matter knowledge" concerns domain-specific concepts or principles related to a problem or task to be solved. Research shows that experts' ability to solve problems heavily depends on their well-organized knowledge reflecting an in-depth understanding of the subject, while novices usually lack sufficient or systematic knowledge (Bransford et al., 1999). In addition to the acquisition of specific concepts and principles, it is even more important to organize knowledge into a systematic structure for meaningful understanding and flexible application as well as assimilate new ideas from practice to extend prior knowledge (Ausubel, 1963). In other words, the organization or construction of knowledge into systematic structures is crucial to learning in problem-solving contexts. The cognitive process of knowledge construction consists of two elements: (1) the acquisition of related concepts and (2) the connection of concepts based on their relationships. Organizing knowledge into a systematic structure is also supported by Mayer's (1996) Select, Organize, and Integrate (SOI) model, which describes the cognitive process of constructing knowledge by selecting relevant information, organizing information into a coherent representation, and integrating information with prior knowledge.

Based on the above discussion, the process of solving a problem in most situations involves the (1) capture of problem information, (2) generation of hypotheses, and (3) justifications of hypotheses, which reflects the most widely hypothesis-driven method for problem solving. In addition to the general method, one's problem-solving performance is heavily influenced by his/her subject knowledge, in particular knowledge-construction performance, which mainly involves the (4) acquisition of related concepts and (5) connection of concepts based on their relationships. Putting together, the five elements are crucial to problem-solving performance.

The above-mentioned elements are aligned with formative assessment of learning in problem-solving contexts. In addition to traditional knowledge tests, performance-based assessment (e.g., case-based examination and interaction with simulated problems) has been increasingly promoted in learning with problems (Kreiter & Bergus, 2009). These instruments focus on formative assessment of learners' problem-solving performance in multiple aspects such as collection of important information for analysis, the integration of problem information and subject knowledge in the reasoning process, coherent argument, and generation of plausible hypotheses. Moreover, the assessment of subject-matter knowledge acquired in problem-based contexts concerns not only specific concepts or principles, but also the organization of knowledge into a systematic structure (Gijbels, Dochy, van den Bossche, & Segers, 2005).

1.2. Representation of complex ideas

Externalizing problem-solving experience requires the use of language or other forms of representation for effective communication of complex ideas. Related work can be referred to thinking-aloud scripts that allow people to explain their thinking and actions when they work with tasks (Ericsson & Simon, 1980; Kuusela &

Paul, 2000) or learning journals that uses narrative as the natural framework for representing the world of action in a variety of forms (McDrury & Alterio, 2003; Schön, 1988). The literature shows that verbal text alone is limited in representing the understanding of complex issues, and a diagram is sometimes worth a thousand words (Larkin & Simon, 1987). Graphical formats and visual representations, if used appropriately, can reduce people's cognitive load by meaningful representation of complex ideas (e.g., grouping together relevant information, representing information verbally and spatially, and reduce ambiguous expression) and by virtue of the brain's capacity to process visual images rapidly (Scaife & Rogers, 1996).

Computer-based cognitive mapping approaches have been increasingly recommended to represent complex ideas in graphical formats and visual representations to support learning and cognition in complex situations (Jonassen, 2005; Kirschner & Wopereis, 2013; Shute, Jeong, Spector, Seel, & Johnson, 2009; Spector & Anderson, 2000). They can be referred to as a variety of applications such as concept maps, causal maps (Slof, Erkens, Kirschner, Janssen, & Jaspers, 2012), evidence maps (Suthers, Vatrapu, Medina, Joseph, & Dwyer, 2008; Toth, Suthers, & Lesgold, 2002), and integrated cognitive maps representing the problem-solving process and the underlying knowledge (Chen, Wang, Dede, & Grotzer, 2017; Wang, Wu, Kinshuk, Chen, & Spector, 2013).

Cognitive mapping approaches can foster high-order thinking and meaningful learning by externalizing complex cognitive structures and processes (Cox, 1999; Jonassen, 2005). They have a high potential to improve students' subject-matter knowledge by representing complex ideas for effective communication and in-depth thinking, as well by connecting separate pieces of knowledge into coherent structures for meaningful understanding and flexible application (Novak & Musonda, 1991). As mentioned, the meta-analysis of the literature has shown that concept mapping is more effective than traditional learning activities in improving knowledge retention (Nesbit and Adesope, 2006).

Meanwhile, external representations of complex cognitive processes may influence students' motivational experience. Motivation refers to the psychological characteristics that drive students to persist in working toward their learning goals, which have been shown to be significantly related to learning achievements (Pekrun, Goetz, Frenzel, Barchfeld, & Perry, 2011). Motivation mainly involves beliefs and attitudes such as interest, value, confidence, self-efficacy, enjoyment, and satisfaction (Pekrun et al., 2011; Ryan & Deci, 2000). Of these, confidence appears to be particularly salient to learning because it influences the degree to which learners engage and persevere when facing challenging tasks (Jones & Issroff, 2005). Also, the anxiety experienced by learners in the learning process may influence their motivation to learn. If a learning task is too complex, students may feel frustrated, which in turn increases their anxiety and reduces their motivation (Schutz & DeCuir, 2002). Cognitive mapping approaches were found to be able to increase students' motivation to learn (Bahr & Dansereau, 2001; Sung & Hwang, 2013) and lower learners' anxiety (Czerniak & Haney, 1998).

As mentioned, concept mapping has been mainly employed in conceptual learning contexts, and there are only a few studies reporting its effects in inquiry or problem-solving contexts (Engelmann & Hesse, 2010; Gijlers & de Jong, 2013; Hwang et al., 2014). While concept maps can support problem solving by helping students to organize important concepts related to a problem (Hwang et al., 2014), concept mapping alone is limited in eliciting and representing the complicated process of applying knowledge to solve a problem. Learners' construction of external representations related to a problem and its solution has received increased attention. For example, causal maps representing the relationship of cause and effect (Slof et al., 2012), evidence maps linking evidence with claims or hypotheses (Suthers et al., 2008; Toth et al., 2002), and integrated cognitive maps connecting the problem-solving and knowledge-construction processes (Wu, Wang, Grotzer, Liu, & Johnson, 2016) have shown their promising effects in improving knowledge and performance in problem-solving contexts. Moreover, causal loop diagrams were used to represent one's understanding of problems in a complex dynamic system (Spector, Christensen, Sioutine, & McCormakc, 2001). More research is needed to explore how concept mapping can be extended for example by the inclusion of heuristics and techniques (Stoyanov & Kommers, 2008) to make it more effective in supporting problem-solving.

1.3. The present study

The present study proposed a computer-based cognitive-mapping approach that extends traditional concept mapping by allowing learners to capture the essence of problem-solving experience in a visual format. The approach enables learners to visualize a set of key elements of cognition in problem-solving contexts: namely critical information, generated hypotheses, justifications of the hypotheses, identified concepts, and relationships between the concepts. The first three elements reflect the problem-solving performance and the latter two reflect the knowledge-construction performance. By eliciting a set of key cognitive elements of problem-solving experience and representing them in a computer-based cognitive map, this approach aims to foster deeper learning in problem-solving contexts via making complex cognitive processes accessible for effective thinking and practice.

The implementation of the proposed approach has been investigated in a pilot study, where a cognitive-mapping tool was developed and used by students for initial evaluation (Wang, Wu, Kinshuk, & Spector, 2013; Wu & Wang, 2012). The preliminary results showed that students found the computer-based cognitive-mapping tool useful and innovative. After using the tool for a four week's study, students made a moderate pre-post improvement in their problem-solving and knowledge-construction performances and in subject knowledge tests.

Built on the pilot study, this study aims to further examine the effects of the cognitive-mapping approach by comparing it to a note-taking approach. By representing ideas both verbally and pictorially, the cognitive mapping approach has a higher potential to foster effective thinking and practice in problem-solving contexts than the note-taking approach that represents ideas in verbal-text only. To examine the difference in the effects of the two approaches, a control group design was adopted in this study. The experimental group used the cognitive-mapping approach, while the control group used the note-taking approach, to capture the complex process of working with simulated clinical diagnostic problems in a computer-based learning environment. Students in both groups employed the same structure (i.e., the five key elements) to capture the essence of problem-solving experience. The study aimed to answer the following research questions (RQs).

- RQ1: Will learners using the cognitive-mapping approach and those using the note-taking approach differ in problem-solving performance? If so, how do they differ?
- RQ2: Is there a difference in subject-matter knowledge of learners using the cognitive-mapping approach as compared to those using the note-taking approach? If so, what's the difference?

- RQ3: Is there a difference in intrinsic motivation of learners using the cognitive-mapping approach as compared to those using the note-taking approach? If so, what's the difference?

2. Method

Nephrology, the study of kidney function and problems, was chosen as the learning subject. It concerns the diagnosis and treatment of kidney diseases, which is a complex task since many diseases affecting the kidney are systemic disorders not limited to the organ itself. The diagnostic analysis should consider various reasons such as acute kidney failure, chronic kidney disease, hematuria, proteinuria, kidney stones, hypertension, and disorders of acid/base or electrolytes. Two domain experts with more than ten years of clinical and academic experience in diagnosis and treatment of kidney disease participated in this study. They supported the preparation of clinical cases and the assessment of learning outcomes.

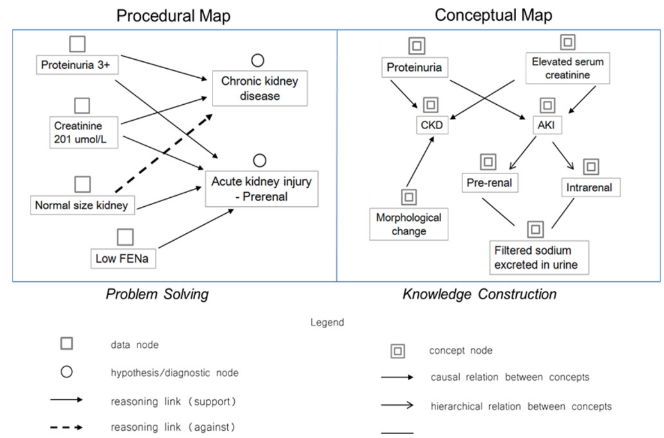

Fig. 1. The cognitive-mapping approach.

2.1. Participants

Forty-nine Year 3 medical students enrolled in a clinical internship course in a medical school signed an informed consent form to participate in the study. This study was a non-mandatory module of their internship course, and their participation was voluntary. The participants had fundamental medical knowledge and problem-based learning experience. They were randomly assigned to two conditions: 25 students to the experimental condition using the cognitive-mapping approach, and other 24 to the control condition using the note-taking approach.

2.2. Learning tasks

Students in both groups worked with simulated cases of kidney disease in a web-based learning environment. Five cases were used in the study. They were adapted from clinical practice and academic references, and were determined by the experts to be at the same level of difficulty. Among the five cases, one was used for a sample case for demonstration and pre-study practice. Other three were used for independent study, and the last one for assessing learners' problem-solving performance at the end of the study.

For each case, students could access its initial information and select clinical examinations or tests to obtain additional information of the case. Students had to go through several rounds of clinical examinations to collect sufficient data, and their initial analysis of existing data helped their selection of clinical examinations. Moreover, students were required to capture their problem-solving experience in five elements: critical information, generated hypotheses, reasoning with justifications (justifying or rejecting a hypothesis based on relevant reasoning), identified concepts, and concept relationships. Learners in the *experimental* group used the cognitive-mapping tool to represent their problem-solving experience in a cognitive map. Those in the *control* group used the note-taking tool to report their problem-solving process in five columns of text. Both representation tools were integrated in the learning system. A summative report on the case prepared by the domain experts could be accessed by the student after he or she had completed that case.

An example of using the cognitive-mapping approach to report the problem-solving experience is shown in Fig. 1. The patient was observed to have proteinuria and increased serum creatinine. Based on the two symptoms, the learner recalled relevant knowledge. The learner remembered that elevated serum creatinine might be caused by chronic kidney disease (CKD) or acute kidney injury (AKI) in general, as represented in the conceptual map as the organized/constructed subject knowledge. Accordingly, two hypotheses, chronic kidney disease and acute kidney injury, were generated. The former was rejected, and the latter was supported with further information about the normal size of the kidney. Such hypothesis generation and justification processes were informed by relevant knowledge about the diseases. During the process, the learner recalled other knowledge relevant to the diseases. As represented in the conceptual map, chronic kidney disease may cause morphological changes in the kidney; acute kidney injury may cause prerenal and intrarenal diseases, and fractional excretion of sodium (FENa) can be used for differentiation.

2.3. Procedure

The learning program lasted for 5 weeks. The procedure was the same for both groups. In the first week, a questionnaire survey was administered to collect the participants' demographic information, followed by a pre-test to assess their prior knowledge. A tutorial of how to work with a clinical case by capturing the essence of the problem-solving experience into five key elements was delivered to all the participants. Next, a demonstration was given to students regarding how to perform diagnostic problem-solving tasks in the learning environment including the use of the representation tool (cognitive-mapping tool for the experimental, and note-taking tool for the control group) to capture the problem-solving experience into five key elements. A sample case was used for demonstration and for students to practice and get familiar with the learning environment and the learning approach. A reference solution to the sample case was presented to learners along with a cognitive map to the experimental group or text-based notes to the control group at the end of the practice session.

The participants started their independent study in the second week. They were asked to complete 3 cases within 3 weeks. For the first and second cases, they were advised to pace themselves and spend about two hours per case. During the study, there was no teacher involvement or feedback to learners except for technical assistance.

In the fifth week, a survey was administered to collect learners' motivation to learn using the given approach and their comments on the learning program. Learners also completed a post-test to assess their subject-matter knowledge at the end of the study. Moreover, learners' problem-solving performance was assessed in a lab by using the given approach solve the last case on an individual basis and submitting a text-based problem-solving report involving five aspects: capture of critical information of the problem, formulation of hypotheses, justification by reasoning (justifying or rejecting hypotheses based on relevant reasoning), diagnostic conclusion, and identification of medical knowledge underlying the case.

2.4. Measures

Demographic questionnaire. The pre-test questionnaire was administered to collect students' gender information and self-assessment of computer skills (very poor, poor, intermediate, good, very good).

Problem-solving report. The problem-solving reports submitted by learners for the last case were analyzed to assess their problem-solving performance based on a set of predefined scales and rubrics adapted from Wu et al. (2016) and other prior studies (Anderson, Peterson, Tonkin, & Cleary, 2008; Gijbels et al., 2005; Srinivasan, McElvany, Shay, Shavelson, & West, 2008; West, Park, Pomeroy, & Sandoval, 2002). The rubrics consisted of five components: capture of critical information, formulation of hypotheses, justification by reasoning, diagnostic conclusion, and identification of knowledge from the case. As shown in Table 1, each component was scored on a five-level scale between 0 (lowest) and 1 (highest). The scores for capture of critical information, formulation of hypotheses, justification by reasoning, and diagnostic conclusion reflect the performance in the *problem-solving dimension*, while the score for identified medical knowledge from the case reflects the performance in the *knowledge-construction dimension*.

Subject-matter knowledge tests. Pre- and post-tests were used to assess learners' knowledge about kidney function and problems. Each test included 34 single choice questions and 4 short essay questions. All questions were adapted from relevant textbooks and the question bank of the medical school. The scores for each single choice question ranged from 0 (incorrect) to 2 (correct). The short essay questions were assessed based on a five-level scale including 0: little argument and evidence; 1: argument with irrelevant evidence; 2: argument supported by limited evidence; 3: argument supported by more evidence; and 4: argument supported by sufficient evidence. Accordingly, the scores for each essay question ranged from 0 to 8. The total possible scores on a test ranged from 0 to 100, which were rescaled to a range of 0–1. Two sets of test papers were prepared using different questions, which, however, were at the similar level of difficulty as validated by the domain experts.

Intrinsic motivation questionnaire and comments. The post-test questionnaire survey was administered to collect learners' motivation to learn using given approach (cognitive-mapping or note-taking). It used a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). The intrinsic motivation inventory model (Ryan & Deci, 2000) was adapted to measure learners' motivation in terms of usefulness, enjoyment, confidence, effort, and anxiety. Each scale involved three items. Examples of the items include, "This learning approach is very useful for me," "I enjoy the learning program very much," "I think I am pretty good at the learning tasks," "I put a lot of effort into this learning program," and "I get very nervous while working on the tasks." The survey also included two open-ended questions: (1) the strengths and weaknesses of the learning program; and (2) suggestions for improvement of the learning program.

The test papers and problem-solving reports were assessed by two domain experts, both of whom were blind to student identification (i.e., whether the test paper or problem-solving report was from the experimental of control group) and test information (i.e., whether the test was pre-test or post-test). Any differences in their grading results for test papers were resolved by referring to reference answers. When assessing the problem-solving reports, any disagreements on the score for each scale were resolved by discussion and by referring to an expert solution to the case. The inter-rater reliability computed using intra-class correlation coefficient (ICC) reflected a high degree of agreement in scoring the problem-solving reports on data capture (ICC = 0.91, 95% CI: 0.85–0.99), diagnostic hypothesis (ICC = 0.91, 95% CI: 0.85–0.95), justification by reasoning (ICC = 0.94, 95% CI: 0.90–0.97), diagnostic conclusion (ICC = 0.97, 95% CI: 0.95–0.99), and knowledge identification (ICC = 0.92, 95% CI: 0.86–0.96), as shown in Table 2.

Table 2
Inter-rater reliability on problem-solving performance.

Indicators	ICC	95% CI		*F*	*p*
		Lower	Upper		
Capture of critical information	.91	.85	.95	21.69	<.001
Formulation of hypotheses	.91	.85	.95	21.63	<.001
Justification by reasoning	.94	.90	.97	33.60	<.001
Diagnostic conclusion	.97	.95	.99	71.78	<.001
Identification of knowledge	.92	.86	.96	24.59	<.001

2.5. Data analysis

The collected data were analyzed using the following methods.

Table 1
Rubrics for assessing problem-solving performance.

Component	Description
Problem-solving dimension	
1) Capture of critical information	Identify critical information of the problem 0: no critical, well-described data 1: mostly critical, well-described data
2) Formulation of hypotheses	Formulate hypotheses 0: no plausible hypotheses 1: plenty of plausible, differential diagnostic hypotheses in a strategic sequence from general to more specific
3) Justification by reasoning	Perform reasoning to support or reject hypotheses 0: unjustified, incorrect reasoning 1: sufficient, well-justified reasoning
4) Diagnostic conclusion	Draw a diagnostic conclusion 0: incorrect diagnostic conclusion or no prognosis 1: completely correct diagnostic conclusion or plausible prognosis
Knowledge-construction dimension	
5) Identification of knowledge	Identification of subject knowledge underlying the problem 0: no relevant and sound knowledge 1: sufficient relevant and sound knowledge

Table 3
Comparisons of problem-solving performance between the two groups.

Indicators	Cognitive-mapping group		Note-taking group		Independent sample *t*-tests			
	Mean	*SD*	Mean	*SD*	*t*	*p*	*α*	Cohen's *d*
Data capture	2.94	.94	3.09	.84	-.53	.598	.021	N.A.
Hypotheses formulation	2.4	.68	1.72	1.02	2.58	.014[a]	.021	.78
Justification by reasoning	2.96	1.08	2.13	1.09	2.41	.021	.021	N.A.
Diagnostic conclusion	3.98	1.03	2.91	1.24	3.01	.005[a]	.021	.94
Identification of underlying knowledge	3.04	.98	2.88	1.07	.51	.615	.021	N.A.

[a] Significant at the .05 level.

1. Descriptive statistics were used to describe the basic features of the data in the study.
2 Independent sample *t*-tests were used to examine the difference in problem-solving performance and intrinsic motivation between the two groups. A one-way analysis of covariance (ANCOVA) was used to examine the group difference in subject-matter knowledge, whereby the pre-test score was used as covariate. Bonferroni-based corrections were made when using students' problem-solving reports to perform comparisons in multiple aspects. Cohen's effect size was calculated to judge the practical significance of the effects.
3. Learners' responses to the two open-ended questions were summarized.

3. Results

Among the 49 participants, 2 students in the control group were absent from the post-test due to their participation in internship activities. The data of the 47 students who completed the study were used for analysis. Among the 25 participants (10 males, 15 females) in the experimental group, most had intermediate (60.0%) or good (28.0%) computer skills. Among the 22 participants (11 males, 11 females) completing the study in the control group, most had intermediate (72.3%) or good (18.2%) computer skills.

3.1. Subject-matter knowledge

The independent sample *t*-tests showed that the experimental and control groups had equivalent subject-matter knowledge before the learning program (Cognitive-Mapping group: Mean = .44, $SD = .12$; Note-Taking group: Mean = .45, $SD = .16$). The ANCOVA results revealed that the experimental group outperformed the control group in subject knowledge after the study (Cognitive-Mapping group: Mean = .57, $SD = .15$; Note-Taking group: Mean = .46, $SD = .17$; $F\ (1,\ 45) = 2.45$, $p < .05$). The effect size (Cohen's $d = 0.69$) indicated a medium effect of the cognitive-mapping approach on subject-matter knowledge.

3.2. Problem-solving performance

The problem-solving reports generated by students in solving the last case were assessed to compare students' problem-solving performance between the two groups. Bonferroni-based corrections were made to adjust the significance levels when using students' problem-solving reports to perform comparisons in multiple aspects/constructs. The Bonferroni correction is often used to reduce the chances of obtaining false-positive results (type I errors) when multiple pair wise tests are performed on a single set of data. In this study, considering that the multiple constructs for comparisons (i.e., capture of critical information, formulation of hypotheses, justification by reasoning, and diagnostic conclusion, identification of knowledge) are highly correlated, we adopted Shi et al.'s (2012) ICC correlation factor method to adjust the value for the number of comparisons in the traditional Bonferroni approach. In this improved Bonferroni approach, the corrected α level is $\alpha^* = \alpha/g^*$, $g^* = (g{+}1){-}[1{+}(g{-}1)\widehat{ICC}]$, where g is the number of comparisons and $\widehat{ICC}$ is the sample-based estimate of the intra-class correlation. We calculated the corrected α level for multiple comparisons of problem-solving performance, $\widehat{ICC} = 0.651$, $g^* = 2.396$, $\alpha^* = .0209$.

Table 3 presents the comparison results after the corrections. Learners in the cognitive-mapping group outperformed those in the note-taking group in hypotheses formulation and diagnostic conclusion. The effect size indicated a medium to large effect of the cognitive-mapping approach on problem-solving performance, but not in knowledge-construction performance.

3.3. Intrinsic motivation and comments

An internal consistency analysis using Cronbach's alpha confirmed that all of the subscales used in the study were reliable (.87 for usefulness, .75 for enjoyment, .79 for confidence, .77 for effort, and .86 for anxiety).

The participants in both groups reported having higher levels of motivation to learn using the given learning approach. As shown in Table 4, both groups found the learning program useful. Moreover, they reported that they had made efforts in the learning tasks, and their confidence in their ability to complete the tasks was close to moderate. Their perceived anxiety during the learning program was slightly lower than neutral. Based on the *t*-test results, the cognitive-mapping group found the learning program much more *useful* and *enjoyable* and felt more *confident* during the study than the note-taking group. There were no significant differences between the two groups in perceived *effort* and *anxiety*.

Responses to the open-ended questions showed that learners in both groups found the learning program to be attractive and useful, especially in fostering their self-directed learning with authentic problems. Learners in the experimental group stated that the cognitive-mapping approach was innovative in that it offered a vivid picture for logical thinking and reasoning with intertwined

Table 4
Comparison of intrinsic motivation between the two groups.

	Cognitive-mapping group		Note-taking group		Independent sample *t*-tests		
	Mean	*SD*	Mean	*SD*	*t*	*df*	*p*
Usefulness	4.18	.55	3.50	.70	3.70	45	.001
Enjoyment	4.24	.60	3.37	.68	4.63	45	.000
Confidence	3.87	.73	3.34	.58	2.79	45	.008
Effort	3.71	.81	3.53	.64	.84	45	.403
Anxiety	2.45	1.00	2.75	.83	−1.09	45	.281

knowledge when solving a clinical problem. Learners in the note-taking group commented that the learning program enabled them to apply the abstract knowledge to real-world practice, which in turn stimulated them to reflect on their knowledge gaps. Finally, learners in both groups mentioned that more cases could be offered in the learning program. In addition, students in the experimental group requested simplified operations for the cognitive-mapping tool, and those in the control group suggested providing expert feedback on individual performance during the task period.

4. Discussion

Problem solving often involves complex processes that are inaccessible to novices. It is important to scaffold/support learners in such contexts or make them adequately empowered to achieve desired learning outcomes. To do so, it is crucial to externalize the "hidden" aspects of problem-solving processes (Collins, Brown, & Holum, 1991; Delany & Golding, 2014). In this study, a computer-based cognitive-mapping approach was used to foster deeper learning in problem-solving contexts by allowing learners to capture a set of key elements of cognition in solving a problem. By representing ideas both verbally and pictorially, the cognitive mapping approach has a high potential to foster effective thinking and practice in problem-solving contexts. After comparing it to a note-taking approach that represents ideas in verbal-text only, we summarized the promising effects of the cognitive mapping approach on improving learning through problem solving in several aspects.

Subject-matter knowledge. The cognitive-mapping approach was found to make a medium effect on improving learners' acquisition of subject-matter knowledge from problem-solving experience. Students who externalized their problem-solving experience in a graphics-based cognitive map developed better understanding of subject-matter knowledge than those externalizing their problem-solving experience in text-based notes. According to Nesbit and Adesope (2006) meta-analysis, concept mapping is slightly more effective in knowledge retention than other constructive activities such as writing summaries and outlines. By extending traditional concept mapping, the cognitive mapping in this study has shown its promising effects on improve knowledge retention with a medium effect size. The finding is supported by the study reporting the promising benefits of cognitive representations to knowledge achievement in an inquiry learning program (Gijlers & de Jong, 2013). Meanwhile, it is noted that learning outcomes in problem-solving contexts are mixed and not always fully reflected in traditional tests, and that traditional examinations lack sensitivity to learning in such contexts (Gijbels et al., 2005; Hartling, Spooner, Tjosvold, & Oswald, 2010; Nendaz & Tekian, 1999). Further studies are needed to examine how the learning outcomes in problem-solving contexts can be properly and adequately determined.

Problem-solving performance. The cognitive-mapping group outperformed the note-taking group in the problem-solving performance, showing a medium to large effect of the cognitive-mapping approach on problem-solving performance, particularly in hypotheses formulation and diagnostic conclusion. Externalizing the key elements of cognition in a graphics-based cognitive map made students achieve better problem-solving performance. The findings support the claimed advantages of graphics-based cognitive-mapping approaches in representing and manipulating cognition, clarifying thinking, re-ordering information, and drawing inferences in complex problem situations (Hwang et al., 2014; Jonassen, 2005; Suthers et al., 2008; Toth et al., 2002; Wang et al., 2013).

With regard to the result of no clear effect of the cognitive-mapping approach on improving the construction of organized knowledge from the problem-solving experience, further studies are needed to examine this issue. The findings from prior studies indicate that students in problem-solving contexts tend to focus on surface features of the problems rather than on developing an adequate understanding of the problem domain (Ericsson, 2009; van de Wiel, Boshuizen, & Schmidt, 2000). When knowledge is taught by tightly integrating it with a problem case, it is not easy for learners to separate the basic knowledge from the problem for transfer to new problems (Anderson, Reder, & Simon, 1996; Gick & Holyoak, 1983; Patel, Groen, & Norman, 1993).

Intrinsic motivation. Compared to the note-taking approach, the graphics-based cognitive-mapping approach was perceived to be more useful and enjoyable and made learners feel more confident in solving complex problems. The result is consistent with the findings of prior studies in that external representations of complex cognitive processes and structures may improve learners' motivation, positive attitudes and self-efficacy in addition to academic achievement (Sung & Hwang, 2013).

On the other hand, students in both groups were highly motivated to learn using either the cognitive-mapping or the note-taking approach. Students' learning with complex problems in this program was supported by enabling them to capture a set of key cognitive elements of problem-solving experience and represent them either in a computer-based cognitive map (in the experimental condition) or in text-based notes (in the control condition). Students in both groups found their learning approach to be attractive and useful, especially in fostering their self-directed learning with authentic problems, as reflected in their comments on the learning program. Students' perceived anxiety was slightly lower than neutral for both groups. While learners might feel frustrated and experienced anxiety when working with complex tasks (Schutz & DeCuir, 2002), allowing learners to capture the complex process in a set of key elements as proposed in this study may help reduce anxiety to some extent for both groups.

5. Conclusion

Learning through problem solving involves sophisticated processes that are inaccessible to learners but often ignored in conventional instruction. Research has highlighted the importance of scaffolding or guiding learning in such contexts with a view to realizing the full potential of learning with real-world problems or authentic tasks. However, there is limited knowledge regarding how complex problem-solving processes can be externalized or scaffolded for effective thinking and reflection throughout the practice. While concept mapping supports the understanding and communication of complex ideas, it is inadequate in eliciting and representing the process of applying knowledge to practice.

In this study, a computer-based cognitive-mapping approach was used to extend traditional concept mapping by allowing learners to capture the essence of problem-solving experience in a set of key elements of cognition in a visual format. The proposed approach has a high potential to foster effective thinking and reflection in problem-solving contexts by representing complex ideas both verbally and pictorially. By comparing it to a note-taking approach that represents ideas in verbal-text only, this study demonstrated the promising effects of the cognitive-mapping approach on improving problem-solving performance, subject-matter knowledge, and intrinsic motivation to learn.

The findings of the study have some implications. *First*, reflection, the process of making sense of an experience by thinking about what one has been doing, is crucial to experiential learning (Dewey, 1938; Moon, 1999). However, given the contextual and dynamic nature of actual problem-solving practice, it is difficult for novices to capture the essence of the problem-solving experience and elicit the complex ideas in a meaningful way. The difficulty is often underestimated by instructors or experts, for whom many of the requisite processes have become largely subconscious or automated. While scaffolding is regarded as crucial to learning with complex problems or tasks, cognitive mapping plays an important role in externalizing and scaffolding the complex cognitive process in such contexts.

Second, cognitive processes in problem-solving contexts concern not only applying knowledge to solve problems using relevant methods but also constructing knowledge from past and current practice. The integration of content learning and process learning has long been recognized as important in science education (Lawson, 1995), and is embodied by learning in problem contexts. Learners have to be equipped with procedural knowledge enabling them to apply content knowledge to solve problems, which in turn stimulates them to identify misconceptions or knowledge gaps and develop new understanding. The construction of conceptual knowledge should pay more attention to articulating new ideas acquired from problem-solving experience and integrating them with prior knowledge into a coherent whole.

Third, while learning through problem solving is increasingly being employed in educational practice, there is a concern about its weakness in assessment methods (Pirnay-Dummer, Ifenthaler, & Spector, 2010; Shute et al., 2009; Spector & Koszalka, 2004; Spector, 2008). The development of valid and reliable approaches to assess the outcomes congruent with the goals of problem-oriented learning is a prerequisite to improving learning in problem contexts.

Finally, cognitive mapping to support and assess learning can and should play a critical role in developing inquiry and critical thinking skills that so many believe are relevant for the future. Cognitive mapping can combine the power of words and visual representations to support the development of productive habits of mind in individuals and thoughtfulness and informed responsibility in citizens and workers.

Acknowledgments

This research is supported by the General Research Fund from the Research Grants Council of the Hong Kong SAR Government (Project No. 17201415), the Seeding Fund for Basic Research from The University of Hong Kong (Project No. 201611159071), the Humanity and Social Science Youth foundation from the Ministry of Education of China (Project No. 16YJC880085), and the Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institution of Higher Learning (2017).

References

Anderson, K., Peterson, R., Tonkin, A., & Cleary, A. (2008). The assessment of student reasoning in the context of a clinically oriented PBL program. *Medical Teacher, 30*, 787–794.
Anderson, J. R., Reder, L. M., & Simon, H. A. (1996). Situated learning and education. *Educational Researcher, 25*, 5–11.
Ausubel, D. P. (1963). *The psychology of meaningful verbal learning*. New York, NY: Grune & Stratton.
Bahr, G. S., & Dansereau, D. F. (2001). Bilingual knowledge maps (BiK-Maps) in second-language vocabulary learning. *The Journal of Experimental Education, 70*, 5–24.
Bransford, J. D., Brown, A. L., & Cocking, R. R. (1999). *How people learn: Brain, mind, experience, and school*. Washington, DC: National Academy Press.
Cañas, A. J., Reiska, P., & Möllits, A. (2017). Developing higher-order thinking skills with concept mapping: A case of pedagogic frailty. *Knowledge Management & E-Learning, 9*(3), 348–365.
Chen, J., Wang, M., Dede, C., & Grotzer, T. A. (2017). Design of a three-dimensional cognitive mapping approach to support inquiry learning. *Journal of Educational Technology & Society, 20*(4), 191–204.
Collins, A., Brown, J. S., & Holum, A. (1991). Cognitive apprenticeship: Making thinking visible. *American Educator, 15*(6–11), 38–46.
Cox, R. (1999). Representation construction, externalised cognition and individual differences. *Learning and Instruction, 9*, 343–363.
Czerniak, C. M., & Haney, J. J. (1998). The effect of collaborative concept mapping on elementary preservice teachers' anxiety, efficacy, and achievement in physical science. *Journal of Science Teacher Education, 9*, 303–320.
Delany, C., & Golding, C. (2014). Teaching clinical reasoning by making thinking visible: An action research project with allied health educators. *BMC Medical Education, 14*, 20.
Dewey, J. (1938). *Experience and education*. New York, NY: Simon & Schuster.
Engelmann, T., & Hesse, F. W. (2010). How digital concept maps about the collaborators' knowledge and information influence computer-supported collaborative problem solving. *International Journal of Computer-Supported Collaborative Learning, 5*(3), 299–319.
Ericsson, K. A. (2009). *Development of professional expertise: Toward measurement of expert performance and design of optimal learning environments*. New York, NY: Cambridge University Press.
Ericsson, K. A., & Simon, H. A. (1980). Verbal reports as data. *Psychological Review, 87*, 215–251.
Ge, X., & Land, S. (2003). Scaffolding students' problem-solving processes in an ill-structured task using question prompts and peer interactions. *Educational Technology Research & Development, 51*(1), 21–38.
Gick, M. L., & Holyoak, K. J. (1983). Schema induction and analogical transfer. *Cognitive Psychology, 15*, 1–38.
Gijbels, D., Dochy, F., van den Bossche, P., & Segers, M. (2005). Effects of problem-based learning: A meta-analysis from the angle of assessment. *Review of Educational Research, 75*, 27–61.
Gijlers, H., & de Jong, T. (2013). Using concept maps to facilitate collaborative simulation-based inquiry learning. *The Journal of the Learning Sciences, 22*, 340–374.
Hartling, L., Spooner, C., Tjosvold, L., & Oswald, A. (2010). Problem-based learning in pre-clinical medical education: 22 years of outcome research. *Medical Teacher, 32*, 28–35.
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*, 99–107.
Hwang, G. J., Kuo, F. R., Chen, N. S., & Ho, H. J. (2014). Effects of an integrated concept mapping and web-based problem-solving approach on students' learning achievements, perceptions and cognitive loads. *Computers & Education, 71*, 77–86.
Jonassen, D. H. (1997). Instructional design models for well-structured and III-structured problem-solving learning outcomes. *Educational Technology Research & Development, 45*(1), 65–94.
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: Springer.
Jones, A., & Issroff, K. (2005). Learning technologies: Affective and social issues in computer-supported collaborative learning. *Computers & Education, 44*(4), 395–408.
Kim, M. C., & Hannafin, M. J. (2010). Scaffolding problem solving in technology-enhanced learning environments (TELEs): Bridging research and theory with practice. *Computers & Education, 56*, 403–417.
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*, 75–86.
Kirschner, P. A., & Wopereis, I. G. J. H. (2013). Do you know the way to... Web 2.0? In J. M. Spector, B. B. Lockee, S. E. Smaldino, & M. C. Herring (Eds.), *Learning, problem solving, and mindtools: Essays in honor of David H. Jonassen* (pp. 88–104). New York, NY: Routledge.
Kreiter, C. D., & Bergus, G. (2009). The validity of performance-based measures of clinical reasoning and alternative approaches. *Medical Education, 43*, 320–325.
Kuusela, H., & Paul, P. (2000). A comparison of concurrent and retrospective verbal protocol analysis. *American Journal of Psychology, 113*, 387–404.
Larkin, J. H., & Simon, H. A. (1987). Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science, 11*, 65–99.
Lawson, A. E. (1995). *Science teaching and the development of thinking*. Belmont, CA: Wadsworth.
Mayer, R. E. (1996). Learning strategies for making sense out of expository text: The SOI model for guiding three cognitive processes in knowledge construction. *Educational Psychology Review, 8*(4), 357–371.
Mayer, R. E., & Wittrock, M. C. (1996). Problem-solving transfer. In D. C. Berliner, & R. C. Calfee (Eds.), *Handbook of educational psychology* (pp. 47–62). New York: Macmillan.
McDrury, J., & Alterio, M. (2003). *Learning through storytelling in higher education: Using reflection and experience to improve learning*. London: Kogan Page.
Moon, J. A. (1999). *Reflection in learning and professional development: Theory and practice*. London: Kogan Page.
Nendaz, M. R., & Tekian, A. (1999). Assessment in problem-based learning medical schools: A literature review. *Teaching and Learning in Medicine, 11*, 232–243.
Nesbit, J. C., & Adesope, O. O. (2006). Learning with concept and knowledge maps: A meta-analysis. *Review of Educational Research, 76*, 413–448.
Novak, J. D., & Musonda, D. (1991). A twelve-year longitudinal study of science concept learning. *American Educational Research Journal, 28*, 117–153.
Patel, V. L., Arocha, J. F., & Kaufman, D. R. (2001). A primer on aspects of cognition

for medical informatics. *Journal of the American Medical Informatics Association, 8*, 324–343.
Patel, V. L., Groen, G. J., & Norman, G. R. (1993). Reasoning and instruction in medical curricula. *Cognition and Instruction, 10*, 335–378.
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.
Pirnay-Dummer, P., Ifenthaler, D., & Spector, J. M. (2010). Highly integrated model assessment technology and tools. *Educational Technology Research & Development, 58*(1), 3–18.
Ryan, R. M., & Deci, E. L. (2000). Self-determination theory and the facilitation of intrinsic motivation, social development, and well being. *American Psychologist, 55*, 68–78.
Scaife, M., & Rogers, Y. (1996). External cognition: How do graphical representations work? *International Journal of Human-computer Studies, 45*, 185–213.
Schön, D. A. (1988). Coaching reflective teaching. In P. P. Grimmett, & G. L. Erickson (Eds.), *Reflection in teacher education* (pp. 19–29). New York, NY: Teachers College Press.
Schutz, P. A., & DeCuir, J. T. (2002). Inquiry on emotions in education. *Educational Psychologist, 37*, 125–134.
Shi, Q., Pavey, E. S., & Carter, R. E. (2012). Bonferroni-based correction factor for multiple, correlated endpoints. *Pharmaceutical Statistics, 11*(4), 300–309.
Shute, V. J., Jeong, A. C., Spector, J. M., Seel, N. M., & Johnson, T. E. (2009). Model-based methods for assessment, learning and instruction: Innovative educational technology at Florida state university. In M. Orey (Ed.), *2009 educational media and technology yearbook* (pp. 60–78). Greenwood Publishing Group.
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*, 623–643.
Spector, J. M. (2008). A review of concept mapping for planning and evaluation. *Evaluation and Program Planning, 31*, 217–221.
Spector, J. M., & Anderson, T. M. (Eds.). (2000). *Integrated and holistic perspectives on learning, instruction and technology: Understanding complexity*. Dordrecht: Kluwer Academic Press.
Spector, J. M., Christensen, D. L., Sioutine, A. V., & McCormakc, D. (2001). Models and simulations for learning in complex domains: Using causal loop diagrams for assessment and evaluation. *Computers in Human Behavior, 17*(5–6), 517–545.
Spector, J. M., & Koszalka, T. A. (2004). *The DEEP methodology for assessing learning in complex domains (final report to the national science foundation evaluative research and evaluation capacity building)*. Syracuse, NY: Syracuse University.
Srinivasan, M., McElvany, M., Shay, J. M., Shavelson, R. J., & West, D. C. (2008). Measuring knowledge structure: Reliability of concept mapping assessment in medical education. *Academic Medicine, 83*, 1196–1203.
Stoyanov, S., & Kommers, P. (2008). Concept mapping instrumental support for problem solving. *International Journal of Continuing Engineering Education and Lifelong Learning, 18*, 40–53.
Sung, H. Y., & Hwang, G. J. (2013). A collaborative game-based learning approach to improving students' learning performance in science courses. *Computers and 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 and Education, 50*, 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*, 264–286.
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., Derry, S., & Ge, X. (2017). Guest Editorial: Fostering deep learning in problem solving contexts with the support of technology. *Educational Technology & Society, 20*(4), 162–165.
Wang, M., Kirschner, P. A., & Bridges, S. M. (2016). Computer-based learning environments for deep learning in inquiry and problem solving contexts. In *Proceedings of the 12th International Conference of the Learning Sciences (ICLS). Singapore*.
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.
West, D. C., Park, J. K., Pomeroy, J. R., & Sandoval, J. (2002). Concept mapping assessment in medical education: A comparison of two scoring systems. *Medical Education, 36*, 820–826.
Wu, B., & Wang, M. (2012). Integrating problem solving and knowledge construction through dual mapping. *Knowledge Management & E-Learning, 4*(3), 248–257.
van de Wiel, M. W. J. (2017). Examining expertise using interviews and verbal protocols. *Frontline Learning Research, 5*, 112–140.
van de Wiel, M. W. J., Boshuizen, H. P. A., & Schmidt, H. G. (2000). Knowledge restructuring in expertise development: Evidence from pathophysiological representations of clinical cases by students and physicians. *European Journal of Cognitive Psychology, 12*, 323–355.
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*, 216.
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*, 1064–1093.