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Connecting problem-solving and knowledge-construction processes in a visualization-based learning environment

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ABSTRACT

Learning through problem solving has been widely adopted as an effective learning paradigm in challenging domains such as medical education. For effective learning through practical experience, problem solving and knowledge construction should be highly integrated and reciprocally reinforcing. However, both knowledge construction and problem solving are complex cognitive processes, which cannot be easily captured and mastered. Temporal problem-solving experience can be forgotten, and knowledge embedded in problem-solving experience may not be transferable to new problems. This study aimed to address the challenge via proposing a computer-based learning environment, where a visualization-based cognitive tool was designed to make thinking and learning in a problem context visible and to connect problem-solving and knowledge-construction activities throughout the learning process. An online learning program using the proposed learning environment was delivered to thirty-five students from two medical schools. The design of the proposed learning environment and its effects on problem-based learning are examined with implications for further studies.

1. Introduction

Learning through problem solving is a pedagogical approach that situates learning in problem-solving contexts (Barrows, 1996). In a problem-based learning model, students engage in complex and challenging problems, work collaboratively to solve problems, and reflect on their experiences, while the teacher facilitates the learning process rather than providing knowledge. As a form of constructivist learning, problem-based learning has received increased attention in complex and ill-structured domains such as medical education, and is increasingly used in a variety of settings from kindergarten and school to professional education (Fessakis, Gouli, & Mavroudi, 2013; Scherer & Tiemann, 2012; Spector, 2006). Through problem solving, learners can consolidate and extend their knowledge based on practical experience. Moreover, problem solving is recognized as an important part of expertise development (Schmidt, Norman, & Boshuizen, 1990). In medical education, problem-based learning has been widely adopted over the last two decades. By engaging learners in active thinking and flexible knowledge construction, problem-based learning has been found to be effective in improving learners' reasoning and communication skills and fostering their abilities to cope with uncertainty, and self-directed learning (Albanese & Mitchell, 1993; Dochy, Segers, Van den Bossche, & Gijbels, 2003; Hartling, Spooner, Tjosvold, & Oswald, 2010; Koh, Khoo, Wong, & Koh, 2008; Neville, 2009; Norman & Schmidt, 2000).

However, the effects of problem-based learning on learners' knowledge structure or systemic understanding of basic science has not been found to be superior to those of traditional methods (Albanese & Mitchell, 1993; Colliver, 2000; Dochy et al., 2003; Hartling et al., 2010;

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Newman, 2004). Learners trained in problem-based learning programs have failed to demonstrate the ability to separate basic knowledge from specific cases associated with that knowledge, which inhibits the likelihood of successful transfer of knowledge gained from specific cases to new cases. There are also concerns about the manpower cost when class sizes increase, and about inadequate learning experience because of time and resource constraints (Berkson, 1993; Colliver, 2000; Koh et al., 2008). Although problem-based learning is becoming increasingly popular, studies on the design and implementation of relevant curricula and learning environments have been limited. The implementation of problem-based learning has been considerably dependent on the personal experience of the instructor and there is little consensus regarding pragmatic instructional strategies (Henry, Tawfik, Jonassen, Winholtz, & Khanna, 2012; Newman, 2004). In this context, careful research is needed to understand whether and how the potentials of problem-based learning might be realized (Hmelo-Silver, 2004; Norman, 2008).

On the other hand, information and communications technologies provide clear advantages for education in terms of flexible access to learning resources, on-demand delivery of learning programs, expanded communication with others, and, more importantly, computer-based learning support. Research on intelligent tutoring systems has explored learning behavior analysis and the provision of personalized feedback (Brusilovsky & Peylo, 2003), but these studies have mainly focused on well-structured problems. Other researchers have proposed the use of online forums or other tools to support learning through complex problem solving (Liu & Tsai, 2008). While these tools have provided flexible access to communication and discussion, human instructors have usually been required to guide the discussion. To save the manpower costs, some studies have proposed the use of prompted questions (for example, What do you see as the primary problem?) posted by the instructor to provide general guidance to the whole class (Ge, Chen, & Davis, 2005). Overall, studies on the design of technology-enhanced learning environments for problem-based learning are limited and lack coherent frameworks to guide implementation. Although there exist some guidelines for problem-based learning (Jonassen, 2011), additional efforts are needed to explore and determine effective instructional methods and technology to achieve the potential of problem-based learning (Pogrows, 1996; Spector, 2012).

This study aims to address the challenge of constructing systemic knowledge structures in problem-based learning by exploring a technology-enhanced learning environment to facilitate and integrate problem-solving and knowledge-construction processes in problem-based learning. The design of the proposed learning environment and its effects on the problem-solving and knowledge-construction processes and the overall learning outcomes are examined.

2. Theoretical background and research hypotheses

2.1. Problem solving versus knowledge construction

As a pedagogical approach that situates learning in problem-solving contexts, problem-based learning has its origin in situated-learning. Situated learning theory claims that learning and cognition are fundamentally situated, and the context in which learning takes place is critical (Lave, 1988). In other words, while theoretical knowledge provides a foundation, the insights and skills developed through authentic practice can lead to more meaningful learning. In line with situated learning theory, problem-based learning positions learners in a simulated real world context, helping them to develop problem-solving skills and consolidate and extend content knowledge, and supporting expertise development.

Research on expertise development has found that learning through problem solving involves complex processes that cannot be accounted for by a mere accumulation of experience and knowledge (Ericsson, 2008). Temporal problem-solving experience can be easily forgotten, and knowledge embedded in problem-solving practice may remain inert and not transferrable to new problems (Wu & Wang, 2012). Previous studies have reported that problem solving requires learners to engage in intensive searches for relevant information to find a solution, which can overburden learners' limited working memory (Kirschner, Sweller, & Clark, 2006). As a result, many learners tend to focus on surface features of problems rather than on the development of an adequate understanding of the problem domain (Gick & Holyoak, 1983). It is crucial to determine what is entailed in problem-based learning and examine how it can be better facilitated. In this regard, Brandsford, Brown, and Cocking (1999) examined the role of conceptual knowledge in problem solving and pointed out that experts' abilities to reason and solve problems depend on well-organized knowledge that reflects a deep understanding of the subject matter and affects how they perceive and represent problems. Similarly, Kirschner et al. (2006) found that knowledge organization and schema acquisition, compared with general problem-solving skills and strategies, are more important in expertise development. Nevertheless, the construction of systemic knowledge structures has been overlooked and remained opaque in problem-based learning curricula, which might explain the unsatisfactory learning outcomes of PBL (Norman, 2004). Many existing studies in the field have tackled problem solving and knowledge construction separately, failing to see them as an integrated two-way process (Wu & Wang, 2012).

2.2. Cognitive processes and technology support in problem-based learning

Both problem solving and knowledge construction are complex cognitive processes that cannot be easily captured and mastered. Ericsson (2008) discussed the importance of determining the mental processes and mechanisms involved in problem-solving activities, and of representing acquired knowledge in a progressively more complex conceptual framework. Similarly, Kinchin, Baysan, and Cabot (2008) claimed that practices do not have the capacity to evolve a knowledge base unless they are articulated and anchored to an underlying network of understanding. These views are in accordance with the cognitive apprenticeship model (Collins, Brown, & Newman, 1990), which was established on the basis of situated learning theory. The cognitive apprenticeship model emphasizes that learning in a specific context requires making implicit thinking and learning processes visible and providing guidance and assistance to learners when necessary. This model also suggests a set of strategies to achieve cognitive apprenticeship, namely exploration, modeling, articulation, reflection, coaching, and scaffolding.

However, making the mental processes involved in problem-based learning accessible is difficult as a result of the contextualization and dynamic aspects of actual problem-solving practice, and cognitive tools are therefore recommended for learning through complex problem solving (Jonassen, 2005; Patel, Yoskowitz, Arocha, & Shortliffe, 2009). Cognitive tools can be referred to as a variety of techniques used to represent cognitive structures and processes to engage and foster high-order thinking and meaningful learning. Such cognitive tools as concept maps, semantic networks, causal maps, argument maps, and system models have increasingly been used to augment cognition and facilitate self-directed learning (Jia et al., 2011; Wang, Peng, Cheng, Zhou, & Liu, 2011). More recently, interactive simulations have been used to improve complex learning, for example in medical education (Holzinger, Kickmeier-Rust, Wassertheurer, & Hessinger, 2009; Holzinger, Wassertheurer, Emberger, & Neal, 2008). Furthermore, cognitive tools have been employed to assess learners' understanding of complex issues, for example by allowing learners to articulate their understanding in concept maps (Spector, 2006; Tsai, Lin, & Yuan, 2001). Cognitive tools are deemed to be effective affordances to reveal mental activities in complex learning. However, most work has been limited to the use of such tools in specific teaching or learning activities with little attention to the design of systemic learning strategies or learning environments. Moreover, there is a lack of studies on the design and utilization of cognitive tools for learning in complex problem domains.

2.3. Assessment of problem-based learning

Appropriate assessment is conducive to deep and reflective learning and long-term knowledge retention. The majority of studies on problem-based learning have examined short-term knowledge acquisition measured by standardized tests such as multiple-choices and essay examinations. However, these summative assessment tools, though psychometrically more sound, lack sensitivity to learning in problem contexts (Nendaz & Tekian, 1999; Norman & Schmidt, 2000; Patel et al., 2009). New assessment techniques such as case-based assessment, performance-based assessment, and portfolio assessment have been developed to assess learners' performance reflected in a progressive learning process through problem solving (Gijbels, Dochy, Van den Bossche, & Segers, 2005). In contrast to traditional examination-based summative assessment, these instruments use formative assessment to test learners' reasoning and problem-solving skills, and are thus more congruent with problem-based learning. A set of dimensions such as pertinent findings, performed test, and generated hypotheses are specified to assess learning performance reflected in the problem-solving process, which, however, lack uniformity and consensus across schools and programs and pay little attention to changes in learners' knowledge base.

Assessment in problem-based learning should take into account both the problem-solving skills and the organization of the knowledge base (Gijbels et al., 2005; Neville, 2009). The latter refers not just to the knowledge of separate concepts, but also to the integration of relevant ideas and concepts in the problem domain, which can be reflected in a knowledge profile involving the understanding of core concepts and their relationships (Gijbels et al., 2005). More recently, representations of mental models and cognitive processes with computer-based tools have been used and found to be effective for formative assessment of learning in complex or ill-structured problem domains (Pirnay-Dummer, Ifenthaler, & Spector, 2010; Spector, 2006). In addition, peer and self-assessments are also used in problem-based learning as an integral part of formative assessment (Koh et al., 2008).

2.4. Research purpose and hypotheses

The current literature on problem-based learning pays insufficient attention to knowledge construction which is critical for effective learning through problems. Also, there is a lack of studies on instructional design and technology to facilitate the complex cognitive processes involved in problem-based learning. To fill the gap, this study proposed a visualization-based environment for problem-based learning (V-PBL). Following the cognitive apprenticeship model with its six strategies, the V-PBL environment was designed in such a way as to make implicit thinking and learning processes in a problem context visible and to connect problem-solving and knowledge-construction activities throughout the learning process. In particular, the study proposed a computer- and visualization-based cognitive tool for learners to articulate and reflect on their problem-solving and knowledge-construction processes, a simulated problem context for learners to explore problems and solutions, and computer-based scaffolding and coaching support to facilitate the learning process. Medical education was selected as the domain for this study, as problem-solving experience is regarded as crucial to learning and expertise development in this field.

It was expected that the proposed V-PBL environment would improve learners' problem-solving and knowledge-construction processes as well as their overall learning outcomes. In addition, in technology-mediated learning environment, learner perceptions are found to have a much larger impact on learning (Sitzmann, Brown, Casper, Ely, & Zimmerman, 2008). In this study, it was expected that learners would find the V-PBL environment acceptable; otherwise further exploration into its effects on problem-based learning might not produce reliable and meaningful results. Accordingly, the hypotheses of the study were as follows.

Hypothesis 1 (H1). *The V-PBL environment will be positively perceived by learners.*

Learners' perceptions of the proposed learning environment including the overall system, its main components, and cognitive strategies supported by the learning environment were examined. The correlations between the learners' perceptions of the overall learning environment and those of its cognitive strategies were also analyzed.

Hypothesis 2 (H2). *The V-PBL environment will improve learners' problem-based learning performance in terms of* 1) *learners' overall learning outcomes*, 2) *learners' self-assessment of learning gains, and* 3) *learners' problem-solving and knowledge-construction processes.*

Both summative and formative assessment methods including self-assessment were used to examine the effects of the V-PBL environment on problem-based learning. Traditional examinations were used to assess the overall learning outcomes. Learning products generated by learners using the cognitive tool in the V-PBL environment for work with problem cases were analyzed to assess their problem-solving and knowledge-construction processes. Learners' self-assessment of their learning gains regarding problem-solving and knowledge-construction abilities was obtained through a survey. The results from these assessment methods as well as their consistency were examined.

3. Research design

3.1. Proposed learning environment

The V-PBL environment consisted of three main components: a) an exploratory problem context for students to work on problems, b) a dual-mapping cognitive tool to visualize and integrate problem-solving and knowledge-construction processes, and c) scaffolding and coaching support to facilitate learning through problem solving. As shown in Fig. 1, the simulated exploratory problem context was provided for learners to interact with a problem so as to explore the problem and its solution. The information concerning the problem case was represented in texts, charts, and images.

The dual-mapping cognitive tool helped learners to articulate their cognitive processes in problem solving and knowledge construction in the form of visual maps for further reflection. The tool integrated the argument mapping and concept mapping techniques, as outlined in Fig. 2. Argument mapping, a visual representation of an argument using informal logic (including fact, claims, explanations, evidence, and rebuttals), was intended to support critical thinking and reflection in solving a problem. Concept mapping, a visual representation of key concepts and their relationships, was to support the construction of knowledge underlying the problem-solving experience.

In order to integrate the problem-solving and knowledge-construction processes, learners were encouraged to connect the nodes in the concept map with relevant nodes in the argument map to indicate the knowledge that supported the problem-solving process, as well as connect the nodes in the argument map with relevant nodes in the concept map to explicate the knowledge generated from the problem-solving process.

To facilitate the complex learning process, computer-based scaffolding and coaching support was provided. As shown in Fig. 3, the scaffolding support (the left part) was mainly a recommended flowchart of steps to go through in the learning process, while the coaching support (the right part) involved computer-generated learning guidance for individuals based on their learning progress and the expert knowledge.

The recommended learning flowchart included seven steps with a loop. Learners could click each step to view the detailed guidelines for performing the learning task, as summarized in Table 1.

Coaching support was provided in the form of process- and problem-related advice adapted to the needs of individuals. The process-related advice involved suggestions on what to do next according to the learner's current progress. The problem-related advice was relevant to the resolution of the case and was categorized into clinical actions, critical information, relevant knowledge, problem hypotheses, and reasoning and justifications. Moreover, a summative report on the analysis and resolution of each case prepared by the domain experts could be accessed by the learner after he/she had completed that case.

3.2. Participants

Invitations to participate in this study were sent to a number of medical schools in China, and the medical schools of Tongji University (in Shanghai) and the Southeast University (in Nanjing) eventually agreed to join the project. In both medical schools, problem-based learning had been implemented in a number of courses. Nephrology was selected as the learning domain of this study because of its complexity. Two domain experts and one instructor from the schools participated in the study. All were nephrologists from teaching hospitals associated with the medical schools. They had more than five years' clinical experience as physicians, and had been involved in clinical onsite training for medical students. In this study, they provided support in selecting the clinical cases and in assessing students' learning performance.

A pilot study was first conducted with a small number of students of the two medical schools to collect their initial feedback on the V-PBL environment, based on which the learning system was refined, mainly its interfaces. The main study was then conducted with thirty-five other students in the schools. Students' participation in this program was fully voluntary. The participants were in the third year or higher of their seven-year medical school curriculum. In China, a seven-year curriculum is widely adopted in medical schools and includes five years of undergraduate study for a Bachelor's degree and two years of postgraduate study for a Master's degree. In the fourth year, students start their clinical studies before entering teaching hospitals for a clerkship in the fifth year.

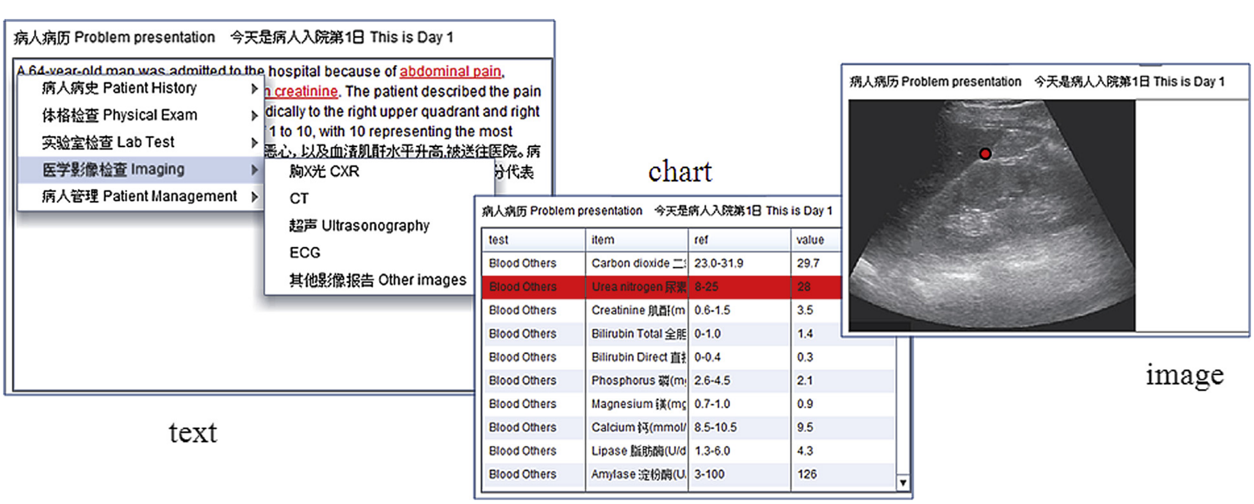

Fig. 1. Screenshots of the exploratory problem context.

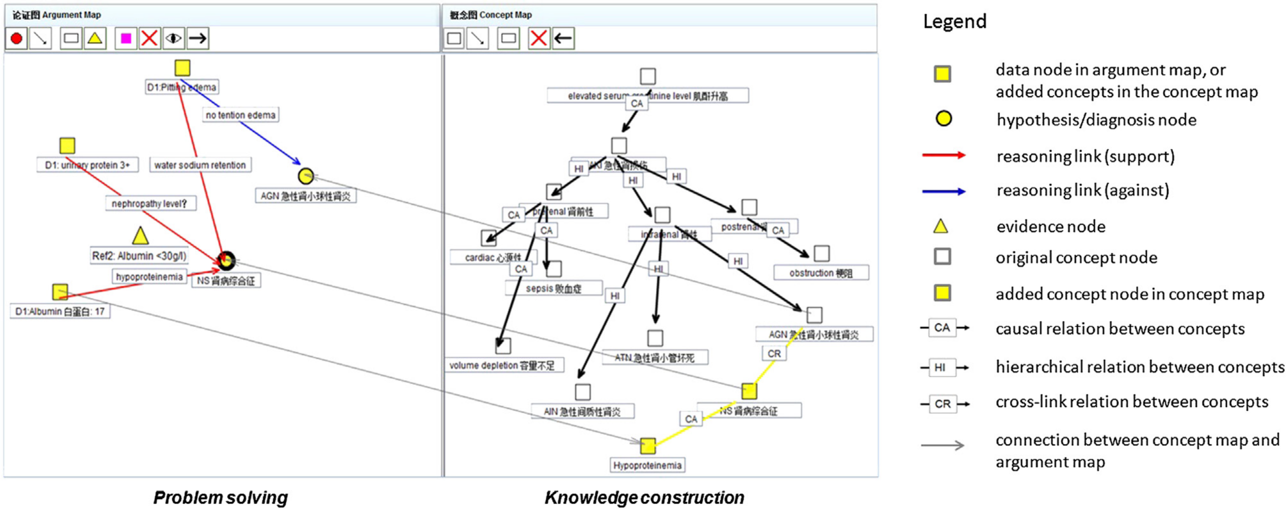

Fig. 2. Screenshots of the dual-mapping cognitive tool.

3.3. Procedure

An online learning program involving five clinical cases was delivered in the V-PBL system. The five cases included a sample case for demonstration and four for self-study by the learners. These cases were collected and adapted from clinical practice and academic references recommended by the domain experts.

A face-to-face demonstration of how to use the V-PBL environment for problem-based learning was provided to fifty students at the beginning of the learning program. Thirty-five of them agreed to participate in this study. A questionnaire survey was then administered to collect demographic information about the participants including gender, grade level, computer skill level, and intention to use technology for learning. The participants continued their learning with the other four cases in the system. For each case, students interacted with the problem to capture critical information, performed clinical actions to obtain further information, and performed problem-solving and knowledge-construction activities with the argument map and the concept map. During the learning program, learners could access expert guidance and help information provided by the system for each case. The instructor was available to provide limited support when needed. Students were also free to utilize other learning materials or resources external to the system.

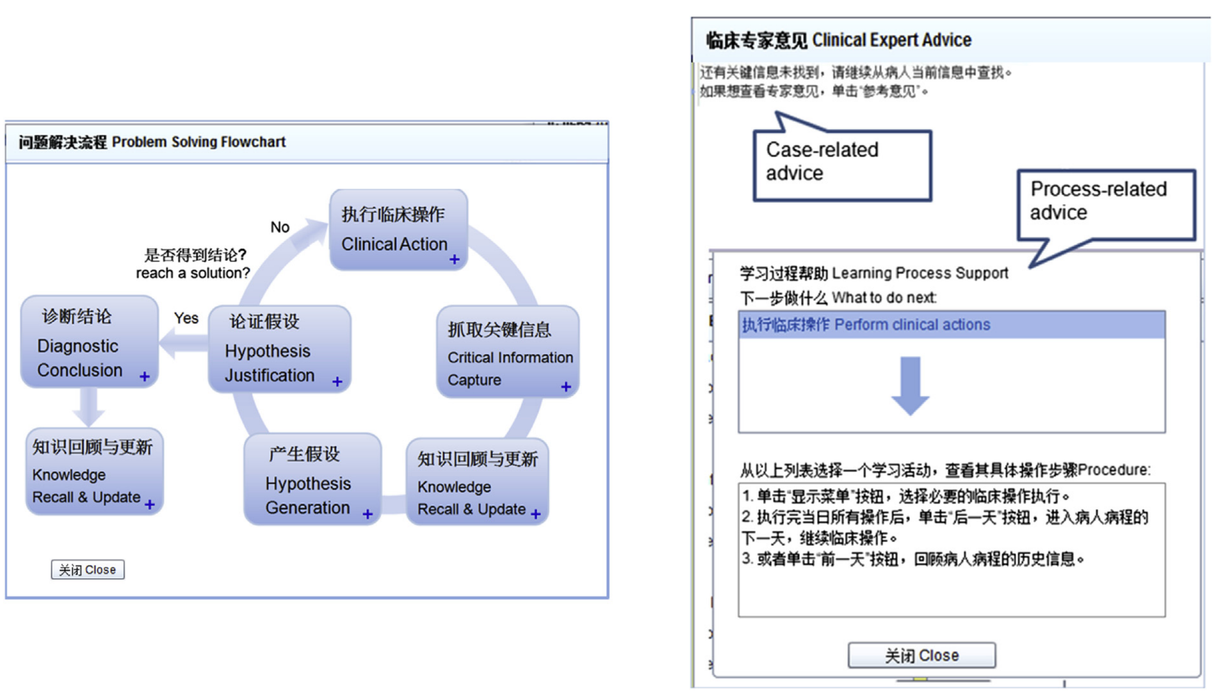

Fig. 3. Screenshots of computer-based scaffolding and coaching support.

Table 1
Problem-based learning flowchart.

Clinical action	The learner selects and interacts with a clinical case to find initial information (for example, chief complaint of the patient) as well as performing clinical actions to explore the case further.
Critical information capture	Once the critical information of the case is identified, the learner may generate relevant data nodes in the argument map.
Knowledge recall and update	The information captured from the problem may trigger the recall of prior knowledge to analyze the problem, which can be externalized into a set of linked concepts in the concept map and can be further updated throughout the learning process.
Hypotheses generation	Based on the problem information and relevant knowledge, the learner may propose one or more hypotheses, and add them as hypothesis nodes in the argument map.
Hypotheses justification	To reach a solution, the learner needs to justify the hypotheses by creating reasoning links between the hypothesis nodes and the data nodes and adding brief text or evidence nodes to explain or support the reasoning links.
Diagnostic conclusion	After justifying the hypotheses, the learner can make a diagnostic conclusion, represented as a diagnostic node in the argument map. Otherwise, additional clinical actions are needed to explore additional information for further analysis.

Learners were required to complete the learning program in their free time within four weeks. They were asked to pace themselves, but were advised to spend 5 h per week with the V-PBL system. Their access to the system was recorded in the log file. Learners were also required to complete two tests (pretest and posttest) to assess their overall learning outcomes, and submit their learning products (i.e., the dual maps) of the first and last cases for formative assessment of their learning performance reflected in their learning process. Moreover, at the end of the program, the participants were asked to complete a survey at the end of the program, which collected their perceptions of the V-PBL environment including the overall system, its main components, and cognitive strategies supported by the V-PBL system, as well as their perceived learning gains regarding their problem-solving and knowledge-construction abilities. Finally, interviews were arranged to obtain the students' open comments on the learning environment and their learning experience. Codes, not names or other personal identifiers, were used on all instruments to protect confidentiality.

3.4. Instrumentation

3.4.1. Survey for perceptions of the learning environment and its cognitive strategies

A survey questionnaire was used to collect learners' perceptions of the learning environment and its cognitive strategies. Responses to all the items were ranked on a 5-point Likert scale. The items measuring learners' *perceptions of the learning environment* (usefulness, ease of use, and intention to use) were adopted from the information technology acceptance literature (Arbaugh, 2000; Davis, 1989; Holzinger, Searle, & Wernbacher, 2011), and have been internationally validated and widely adopted. Examples of items include "The system is useful for my learning", "The system is easy for me to use", and "I have intention to use the system."

The items measuring learners' *perception of the cognitive strategies* supported by the learning environment were adopted and adapted from the instrument evaluating clinical instruction and learning environment in the clinical practice setting (Stalmeijer, Dolmans, Wolfhagen, Muijtjens, & Scherpbier, 2010). The instrument consisted of 19 questions for 6 subscales: modeling, coaching, scaffolding, articulation, reflection, and exploration. The validity and reliability of the instrument have been well established (Stalmeijer, Dolmans, Wolfhagen, Muijtjens, & Scherpbier, 2008; Stalmeijer et al., 2010). Examples of items include "The system facilitates my reflection of the problem-solving process", "The system provides me the opportunity to exhibit my understanding of domain knowledge", and "The expert advice provided by the system is helpful for my study."

3.4.2. Survey for self-assessment of the learning gains

The survey also included students' self-assessment of their learning gains regarding problem-solving and knowledge-construction abilities. The measuring items were adopted from the well-established Student Assessment of their Learning Gains (SALG) instrument (WCER, 2001). Examples of items include "I have made progress in identifying critical information of problems as a result of the learning program", "I have made progress in proposing diagnostic hypotheses as a result of the learning program", and "I have made progress in evaluating and justifying hypotheses as a result of the learning program."

3.4.3. Tests for assessing the overall learning outcomes

Pretest and posttest were used to assess the overall learning outcomes of diagnostic problem solving in nephrology. The questions in both pretest and posttest were adapted from relevant textbooks (Clatworthy, 2010). Each test included three multiple choice questions, ten extended matching questions, and four essay questions for solving a kidney case. The validity of the tests was established by comparing the tests with the sample tests used by the teaching hospital of Tongji University, with further confirmation by the domain experts. The scores of the tests were normalized to a scale between 0 and 1.

3.4.4. Learning products for assessing problem-solving and knowledge-construction processes

According to the literature, learners' performance reflected in the problem-solving process involves capture of critical information, formulation of plausible hypotheses, and justification of hypotheses through appropriate reasoning; while learners' performance reflected in the knowledge-construction process concerns identification of key concepts and generation of relations between the concepts in the problem domain (Gijbels et al., 2005; Nendaz & Tekian, 1999).

In this study, the learning products (i.e., the dual maps generated by learners using the dual-mapping cognitive tool) were analyzed to assess learners' performance reflected in their problem-solving and knowledge-construction processes. The assessment was based on a set of predefined rubrics adapted from prior studies (Facione & Facione, 2008; Srinivasan, McElvany, Shay, Shavelson, & West, 2008) and focused on five dimensions: captured critical information, formulated hypotheses, performed reasoning, identified concepts, and generated concept relations. Accordingly, the rubrics involved the quantity and quality of the five elements in the dual map, that is, data nodes, hypothesis nodes, and reasoning links in the argument map, and concept nodes and concept relations in the concept map, as shown in Table 2. Each of

Table 2
Rubrics for assessment of problem-solving and knowledge-construction processes.

Dimensions	Elements	Descriptions
Problem-solving process (argument map)		
Captured critical information	Data nodes in the argument map	Identify critical data from the patient information 0: No critical, well described data nodes 4: Mostly critical, well described data nodes
Formulated hypotheses	Hypothesis nodes in the argument map	Formulate hypotheses 0: No plausible hypotheses 4: Plenty of plausible, differential diagnostic hypotheses in a strategic sequence of from general to more specific
Performed reasoning	Reasoning links in the argument map	Perform reasoning links to support/refute hypotheses 0: No justified, incorrect reasoning links 4: Sufficient well-justified reasoning links
Knowledge-construction process (concept map)		
Identified concepts	Concept nodes in the concept map	Trigger concept nodes from identified critical information 0: None or irrelevant concept nodes 4: Plenty of closely-related, problem solving-oriented concept nodes
Built relations between concepts	Concept relations in the concept map	Construct concept relations among concept nodes in the concept map 0: None or incorrect concept relations 4: Plenty of well-organized, thought-provoking, and cross-linked concept relations

the five elements was scored on a 5-point Likert scale from 0 to 4, and the overall dual-mapping score was the average of the scores for the five elements. The dual map presented in Fig. 2 is used as an example to illustrate the assessment and scoring methods, as described in the Appendix.

3.4.5. Interviews

For qualitative and interpretive analysis of the V-PBL environment, interviews were arranged with learners to collect their responses to open questions regarding the advantages and disadvantages of the learning environment and their reflections on their learning experience. The instructor and domain experts were also interviewed for their comments on the V-PBL environment. Responses from all the interviews were transcribed and coded by two research assistants separately, with constant discussion to resolve discrepancies and unclear parts. Cohen's Kappa was used to measure the agreement between the raters on the themes identified from the interview data, and the result .78 indicated a high degree of consensus between the two raters (De Wever, Schellens , Valcke, & Van Keer, 2006).

4. Data analysis and results

All thirty-five students completed the online learning program in the V-PBL system. The demographic information of the subjects is outlined in Table 3. The participants were in the third year or higher of their five-year undergraduate curriculum with fundamental medical knowledge but little clinical experience. Most of them reported having intermediate or good computer skills, and holding a neutral or positive intention to use technology for learning.

Table 3
Demographic information of the subjects.

	Frequency	Percentage (%)
Gender		
Female	26	74.3
Male	9	25.7
Grade level		
Undergraduate year 3	8	22.9
Undergraduate year 4	18	51.4
Undergraduate year 5	9	25.7
Computer skill level		
Very good	3	8.6
Good	10	28.6
Intermediate	22	62.9
Poor	0	0
Intention to use technology for learning		
Strongly disagree	0	0
Disagree	1	2.9
Neutral	15	42.9
Agree	17	48.6
Strongly agree	2	5.7

Table 4
Perceptions of the overall system and its main components (5-point Likert scale: 0 represented “strongly disagree” and 4 represented “strongly agree”) ($n = 35$).

	OVER_USE	EPC_USE	DMT_USE	SCS_USE	OVER_SAT
M	2.68	2.68	2.67	2.55	2.50
SD	.66	.55	.76	.64	.62
	OVER_EOU	EPC_EOU	DMT_EOU	SCS_EOU	OVER_ITU
M	2.19	2.42	2.15	2.65	2.38
SD	.84	.69	.78	.72	.70

OVER: overall system; EPC: exploratory problem context; DMT: dual-mapping tool; SCS: scaffolding and coaching support.
USE: usefulness; EOU: ease of use; ITU: intention to use; SAT: satisfaction.

Table 5
Perceptions of the cognitive strategies supported by the V-PBL environment (5-point Likert scale: 0 represented “strongly disagree” and 4 represented “strongly agree”) ($n = 35$).

	MOD	COA	SCA	ART	REF	EXP
M	2.75	2.72	2.71	2.75	2.86	2.77
SD	.64	.72	.68	.76	.66	.70

MOD: modeling; COA: coaching; SCA: scaffolding; ART: articulation; REF: reflection; EXP: exploration.

4.1. *Perceptions of the learning environment and its cognitive strategies (H1)*

Learners' perceptions of the V-PBL environment including the overall system and its main components were presented in Table 4. Internal consistency of the instruments was estimated using Cronbach's α (Cronbach, 1951). The learners' perceptions of the overall system and its main components, including the exploratory problem context, the dual-mapping cognitive tool, and the scaffolding and coaching support, were rated. The reliability coefficients for the subscales were .93 for usefulness of the overall system, .75 for ease of use of the overall system, .87 for usefulness of the exploratory problem context, .71 for ease of use of the exploratory problem context, .96 for usefulness of the dual-mapping tool, .85 for ease of use of the dual-mapping tool, .98 for usefulness of the scaffolding and coaching support, .93 for ease of use of the scaffolding and coaching support, .86 for satisfaction with the system, and .85 for intention to use the system. All had acceptable reliability, i.e., $\alpha > .70$.

As outlined in Table 4, the overall system and its main components were perceived to be useful. As for ease of use, learners' perceptions of the problem context and learning support were found to be positive, and those of the overall system and the dual-mapping tool weakly positive. Accordingly, learners' satisfaction with the overall system and their intention to use it were positive but not strong.

Learners' perceptions of the cognitive strategies supported by the V-PBL environment are summarized in Table 5. The perceptions of the six strategies were rated, and the reliability coefficients were .91 for modeling, .95 for coaching, .77 for scaffolding, .97 for articulation, .96 for reflection, and .95 for exploration. Positive feedback was received on all the strategies, of which *reflection* received the highest score, followed by *exploration*, *modeling* and *articulation*, while *coaching* and *scaffolding* received slightly lower scores.

Table 6 shows that learners' perceptions of the usefulness of the V-PBL environment and their satisfaction with the V-PBL environment were significantly correlated with their perceptions of the cognitive strategies supported by the V-PBL environment. In particular, their perceptions of the overall usefulness of the V-PBL environment were most highly-correlated with their perceptions of the articulation strategy, while their overall satisfaction was highly related to their perceptions of the scaffolding, articulation, and modeling strategies supported by the V-PBL environment.

4.2. *Overall learning outcomes reflected in tests (H2.1)*

Results of the traditional tests for assessing the overall learning outcomes are summarized in Table 7. The paired-sample *t* test indicated that there was a significant increase in the mean score of the posttest (Pretest $M = .32$, SD = .17; Posttest $M = .44$, SD = .16; Pretest–Posttest: $t = 3.21[35]$, $p < .01$). The effect size[1] (Cohen, 1988) indicated moderate progress in test performance (Cohen's $d = .75$).

4.3. *Self-assessment of learning gains (H2.2)*

Learners' self-assessment of the learning gains in terms of problem-solving and knowledge-construction abilities were summarized in Table 8. The reliability coefficients were .79 for knowledge-construction ability and .85 for problem-solving ability. All had acceptable reliability, i.e., $\alpha > .70$. The results show that the participants reported making a nearly moderate level of progress in both problem-solving and knowledge-construction abilities, consistent with their test performance.

4.4. *Performance of problem-solving and knowledge-construction processes (H2.3)*

The dual maps (i.e., the learning products generated by learners in the V-PBL environment) were analyzed to assess learners' problem-solving and knowledge-construction processes. Learners' dual-mapping scores for the first and last cases are presented in Table 9. The scores in the 5-point Likert scale between 0 and 4 were normalized to a scale between 0 and 1. The maps were scored by the two domain experts

[1] $d = \bar{x}_1 - \bar{x}_2/s$, where $s = \sqrt{(n_1-1)s_1^2 + (n_2-1)s_2^2/n_1+n_2}$.

Table 6
Correlations between perceptions of the overall system and perceptions of the cognitive strategies ($n = 35$).

	MOD	COA	SCA	ART	REF	EXP
OVER_USE	.62**	.53**	.62**	.68**	.57**	.66**
OVER_SAT	.68**	.55**	.69**	.68**	.59**	.55**

**$p < .01$.
OVER_USE: usefulness of the overall system; OVER_SAT: satisfaction with the overall system.

using blind assessment, and the inter-rater reliability was .91, significant at the .01 level. The average scores based on the two raters' ratings were used for analysis. The overall dual-mapping scores for the last case were found to be significantly correlated with the posttest scores ($r = .52$, $p < .05$). A significant improvement in the overall score was found from the first case to the last case ($t[35] = 5.00$, $p < .01$). The effect size indicated a moderate level of progress in dual-mapping performance (Cohen's $d = .63$), consistent with the test results and learners' self-assessment of the learning gains.

With respect to the scores of the five elements in the dual map, there was a significant increase from the first case to the last in all elements. When the scores of the five elements were linked to the learners' problem-solving and knowledge-construction performance, it was found that the learners' problem-solving performance (reflected in data nodes, hypothesis nodes, and reasoning links in the argument map) was much better than their knowledge-construction performance (reflected in concept nodes and concept relations in the concept map) in both the first and the last cases. However, learners made bigger improvement in their knowledge-construction performance than in their problem-solving performance.

Connections between problem-solving and knowledge-construction activities reflected in the dual maps were also analyzed. As shown in Table 10, there was a significant improvement from the first case to the last case ($t[35] = 3.36$, $p = .004$) in the number of connections from problem solving to knowledge construction (represented by links from the argument map to the concept map). However, there was no significant difference between the first and last cases in the number of connections from knowledge construction to problem solving (represented by links from the concept map to the argument map).

4.5. Additional analysis of individual factors (H2.3)

In view of the impact of individual factors on learning performance, correlations between the dual-mapping score and individual factors (gender, grades, computer skills, and intention to use technology for learning) were analyzed. Results of a repeated measure ANOVA revealed that the dual-map scores differed significantly between different grades/years of study and different levels of intention to use technology for learning (Grade: $F[2, 32] = 6.53$, $p < .01$; Intention: $F[3, 32] = 4.09$, $p < .05$). There was no evidence concerning the impact of learners' gender and computer skills on their dual-mapping performance.

As shown in Fig. 4, learners' dual-mapping scores was found to be negatively correlated with their grades, but positively correlated with their intention to use technology for learning. The findings are in line with previous findings on intention to use technology as a factor affecting learning performance (Coffin & MacIntyre, 1999; Rodgers, 2008; Rozell & Gardner, 2000), and support the findings that using cognitive tools for knowledge representation might have more of an impact on the learning of less experienced learners (Kanselaar et al., 2003).

4.6. Findings from interviews with learners (H1)

Thirty-five students participated in the interviews. Most of them reflected that the V-PBL environment was useful and innovative, able to attract their attention and engage them in open-ended and self-directed learning. Some of the participants mentioned that the V-PBL environment provided a clear and systemic picture of the main tasks and the knowledge involved in complex problem solving, which was very helpful for developing logic thinking and reasoning skills. One participant commented, "It is usually difficult to manage complex and separate pieces of knowledge for clinical problem solving, but this system provides a useful approach to making knowledge well-organized and connected." In particular, many learners felt very interested in the visual representations employed in this study, and would like to use such representations for their thinking and learning in future studies. Learners also felt that the personalized learning guidance and expert feedback provided by the system was helpful for checking the missing points in their thinking and learning.

On the other hand, learners commented on the limitations of the VPSL system. Some of them felt that the dual-mapping tool was not very user-friendly, and suggested that more descriptions and demonstrations should be provided on how to use the system. Some learners also said that nephrology was a complex field, and the clinical cases provided in the system were difficult, especially in the situations with less immediate face-to-face instructions. Others reported that learning through problem solving was challenging, and they needed more time and training to get used to it. In particular, they mentioned that they usually relied on complete information provided by the teacher in diagnosing a clinical case, rather than using a hypothesis-led search to explore the problem in a progressive way.

In addition, many participants expressed their intention to pay more attention to integrating clinical experience with systemic knowledge construction for effective problem-based learning in their future studies. To achieve the change, they highlighted the need to include more practical learning experiences and relevant facilities such as the V-PBL environment into their current programs. Moreover,

Table 7
Test performance (scores range from 0 to 1) ($n = 35$).

Pretest		Posttest		Paired-sample *t* tests		
M	SD	*M*	SD	*t*	df	*p*
.32	.17	.44	.16	3.21	34	.004**

**$p < .01$.

Table 8
Self-perceived learning gains (5-point Likert scale: 0 represented "no progress" and 4 represented "large progress") ($n = 35$).

	PSA	KCA
M	2.33	2.15
SD	1.05	1.10

PSA: problem-solving ability; KCA: knowledge-construction ability.

Table 9
Dual-mapping performance (scores range from 0 to 1) ($n = 35$).

	First case		Last case		Paired-sample *t* tests		
	M	SD	*M*	SD	*t*	df	*p*
Data nodes	.52	.17	.62	.18	3.43	34	.002**
Hypothesis nodes	.39	.21	.46	.15	2.27	34	.032*
Reasoning links	.34	.25	.46	.29	2.96	34	.007**
Concept nodes	.19	.20	.39	.29	5.14	34	.000**
Concept relations	.10	.16	.21	.23	4.05	34	.000**
Overall score	.29	.15	.39	.17	5.00	34	.000**

*$p < .05$.
**$p < .01$.

they stated that they had developed a new understanding of learning from this experience; that is, integrating theoretical understanding and clinical experience for a systemic knowledge structure.

4.7. Findings from interviews with domain experts and instructor (H1)

Interviews with the instructor and two domain experts were arranged to solicit their comments on the V-PBL environment. The instructor and domain experts mentioned that the VPSL system was innovative and unique in helping learners to develop problem-solving skills and consolidate and extend their domain knowledge. One expert said, "Most students in China are grade-driven and not good at active thinking and in-depth learning. Also, most medical schools do not allocate sufficient time and resources for teaching the sophisticated skills of problem solving. In this situation, there is a high demand for incorporating such a flexible and self-directed learning environment into traditional programs." The instructor was impressed by the effectiveness of the V-PBL environment in stimulating learners' motivation and sense of autonomy for learning. He expressed his clear interest in further participation in this project and in using the V-PBL system in his teaching programs. The instructor also commented that the VPSL environment and the traditional classroom could well be integrated and complement each other to benefit more learners.

5. Summary of findings and discussions

5.1. Design of the V-PBL environment

The V-PBL environment proposed in this study aimed to address the challenge of facilitating and integrating complex problem-solving and knowledge-construction processes in problem-based learning. The design of the V-PBL environment was based on the cognitive apprenticeship model and its cognitive strategies along with situated learning theory, which highlight the importance of situating learning in real world contexts, externalizing tacit knowledge, and offering expert support to novices. Accordingly, the V-PBL environment included a simulated exploratory problem context, a dual-mapping cognitive tool to visualize and integrate the problem-solving and knowledge-construction processes, and scaffolding and coaching support to facilitate the self-directed learning process.

5.2. Perceptions of the V-PBL environment and its cognitive strategies

The V-PBL environment and its main components were perceived by learners to be useful and acceptable, while the ease of use of the system was perceived to be weakly positive. Among all the evaluation aspects, the exploratory problem context was the most positively perceived by learners, reflecting a strong feature of the V-PBL environment in situating learning in problem contexts. Further interviews

Table 10
Number of connections between problem solving and knowledge construction in the dual maps ($n = 35$).

	First case		Last case		Paired-sample *t* tests		
	M	SD	*M*	SD	*t*	df	*p*
PS2KC	2.47	1.59	4.00	2.06	3.36	34	.004**
KC2PS	4.12	1.87	3.82	1.78	.79	34	.611

**$p < .01$.
PS2KC: from problem solving to knowledge construction.
KC2PS: from knowledge construction to problem solving.

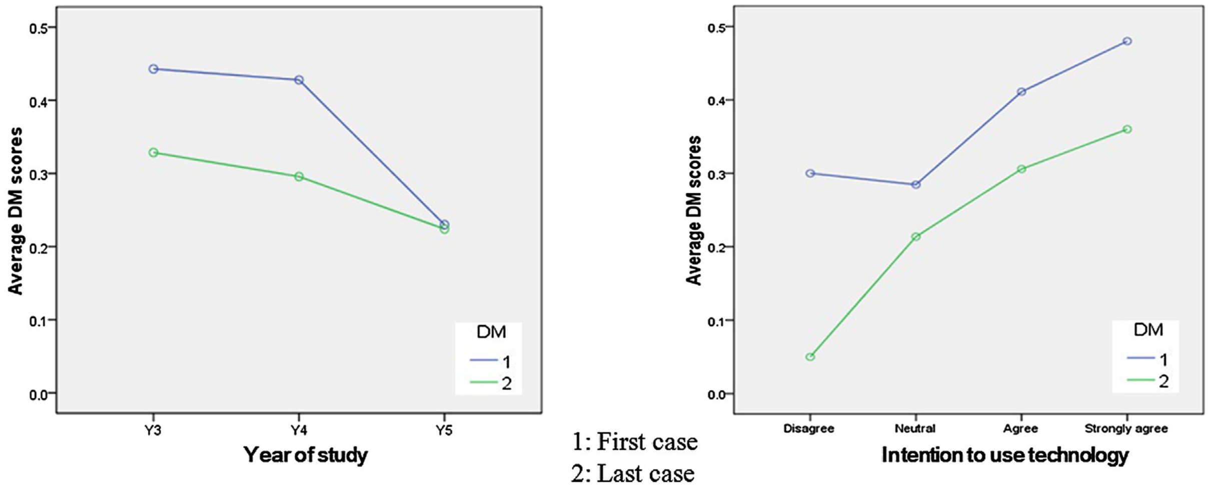

Fig. 4. Impact of individual factors on the dual-mapping score.

revealed that the participants found the V-PBL environment innovative and attractive, while they felt that improvement was needed to make it more user-friendly. Moreover, both the instructor and the students thought that the V-PBL could foster students' autonomous or self-directed learning with complex problems. Accordingly, the instructor and students expressed their intention to incorporate the V-PBL system into their learning programs.

Positive perceptions were also reported regarding the cognitive strategies supported by the V-PBL environment, which were consistent with learners' perceptions of the overall V-PBL system. Similar findings have been indicating that instructional design is an essential factor that may influence perceived usefulness and satisfaction toward the e-learning environment (Jiang & Ting, 2000; Swan, 2001). In this study, the overall usefulness of the V-PBL system was found to be more correlated with the articulation strategy, and learner satisfaction more related to the scaffolding, articulation and modeling strategies. Interview results supported this finding in that learners felt that the V-PBL system was particularly useful in externalizing complex processes in problem solving and knowledge organization, and that learners enjoyed the visual facilities for thinking and learning as well as the personalized expert support offered by the system.

5.3. *Effects the V-PBL environment on problem-based learning*

The effectiveness of the V-PBL environment in improving problem-based learning was found in learners' overall learning outcomes reflected in the tests, learners' problem-solving and knowledge-construction performance reflected in their dual-mapping learning products, and learners' self-assessment of their learning gains in problem-solving and knowledge-construction abilities. A moderate improvement was evidenced in all these assessments. The assessment results also suggested that the dual-mapping cognitive tool was consistent with the traditional paper-and-pencil-based test in assessing learners' performance in problem-based learning. This is in line with the current trend of using cognitive tools to assess knowledge and skill development in complex learning situations (Pirnay-Dummer et al., 2010).

Furthermore, the dual-mapping learning records provided a richer assessment of the learning process in the following aspects: 1) learners made a significant improvement in both problem solving and knowledge construction through the learning program; 2) learners made more progress in knowledge construction than in problem solving in the learning program; 2) learners performed better in problem solving than in knowledge construction at beginning and end of the learning program; and 4) learners made a significant improvement in making connections from problem solving to knowledge construction, but not from knowledge construction to problem solving. It was noted that learners made more improvement in knowledge construction, although their knowledge-construction performance was still weaker compared with their performance in problem solving. This finding was consistent with the feedback received from the interviews indicating that many students in China tend to be grade-driven and lack active thinking and in-depth learning abilities, and that the proposed V-PBL system could be a promising approach to improving problem-based learning.

6. Conclusions and implications

Learning through problem solving has been recognized as an important approach to constructivist learning. While it has been found that learning can be better acquired through problem-solving experience, knowledge learnt from the experience is difficult to retain and reuse. Moreover, the contextualization and dynamic aspects of actual problem-solving practice make it difficult to elicit the mental processes and mechanisms involved in problem-based learning. This study has proposed a visualization-based learning environment that helped learners to articulate and connect complex problem-solving and knowledge-construction processes in problem-based learning. In addition to the dual-mapping cognitive tool, the simulated exploratory problem context and computer-based scaffolding and coaching support were incorporated into the learning environment, to facilitate self-directed learning through problem solving.

The principles underlying the design of a problem-based learning environment can be summarized as follows: situating learning in an exploratory problem context, making problem-solving and knowledge construction visible and integrated in the learning process, and making learning support and expert knowledge accessible to novices. Based on such a design, problem-based learning can be supported by engaging learners into a mode of exploring problems on their own, helping learners to articulate and integrate problem-solving and knowledge-construction processes, scaffolding learners by decomposing the complex problem-based learning process into a flowchart of steps, and providing personalized coaching support based on expert knowledge.

With respect to the key element of the proposed approach – the dual-mapping cognitive tool, argument mapping and concept mapping play different roles in the learning process. Argument mapping helps to sharpen learners' problem-solving skills through building a coherent and well-grounded argumentation structure. Concept mapping elicits domain knowledge and helps to conceptualize contextual knowledge. More importantly, the two types of mapping processes are integrated in such a way that the argument map explicates problem-solving experience for generating new understanding for reuse, while the concept map provides anchored points for solving problems based on relevant knowledge and for integrating new understanding with prior knowledge. In short, the dual-mapping learning approach helps learners to uncover complex processes involved in problem solving and construct knowledge into a progressively more complex and systemic structure.

The proposed V-PBL environment was found to be useful and innovative, and to engage learners in in-depth thinking and active learning through complex problem solving. The positive perceptions were found highly related to the articulation strategy supported by the learning environment, which provided learners with a clear and systemic picture of the main tasks and the knowledge involved in learning through complex problem solving. The effectiveness of the V-PBL environment was consistently evidenced by multiple assessments including tests for summative assessment, dual-mapping learning products for formative assessment, and perceived learning gains for self-assessment.

Implications of the study are discussed from the viewpoints of theory and practice. *In terms of theory*, this study identified and addressed the challenge of integrating problem-solving and knowledge-construction processes in problem-based learning. The findings contribute to the field of instructional design and technology for problem-based learning in complex domains. Considering that the implementation of problem-based learning curricula has relied considerably on instructors' personal experiences, and that technology-enhanced learning environments have often been developed with incompatible foundations (Wang, Vogel, & Ran, 2011), this kind of design-based study becomes more critical to examine pragmatic strategies and technology for problem-based learning. Moreover, the developed V-PBL environment provides a platform for further studies on how problem solving and knowledge construction interact and reinforce each other.

On the other hand, the findings of this study contribute to the field of formative assessment of problem-based learning. The dual-mapping learning records produced from the V-PBL environment were found to be consistent with traditional tests in assessing problem-based learning and provide richer assessment of problem-solving and knowledge-construction performance. The findings indicate the potential of the dual-mapping cognitive tool in assessing problem-based learning. While problem-based learning is increasingly being used in medical education and other domains, there is a concern about its weakness in general study design and assessment criteria (Gijbels et al., 2005; Hartling et al., 2010). In addition to traditional tests, new assessment techniques such as case-based and performance-based assessment have been proposed, among which representation of mental models and cognitive processes with tools was found to be effective for learning complex problem domains (Pirnay-Dummer et al., 2010; Spector, 2006).

In terms of practice, the proposed V-PBL environment can be used in problem-based learning and assessment practice, particularly in improving learners' performance in knowledge construction through problem-solving experience. While problem-based learning is increasingly being used in educational practice, there is concern about its weakness in terms of general study design and assessment criteria. The findings of the study provide insights into pragmatic strategies for learning and assessment. Moreover, given the challenge of cost and resource constraints faced by problem-based learning curricula, the proposed V-PBL environment provides clear advantages for problem-based learning in terms of flexible access to learning resources, on-demand delivery of learning programs, and, more importantly, computer-based learning support for self-directed learning.

In addition, it should be noted that the V-PBL environment serves not only as a learning platform, but also as a knowledge base, for the retention and sharing of valuable teaching and learning resources and expert knowledge for problem-based learning. The knowledge base in the V-PBL environment goes beyond traditional learning resources by including expert knowledge for problem solving, which plays an important role in expertise development. This issue can be referred to as knowledge management, which is becoming increasingly important for education and professional development especially in the medical and health sector (Abbott, 2010). The knowledge management issue also indicates another challenge of problem-based learning, that is, that problem-based learning curricula require much more focused time commitment and professional effort of the part of instructors than conventional curricula (Albanese & Mitchell, 1993; Berkson, 1993). In this regard, knowledge-based learning systems such as the V-PBL environment have the potential to benefit learners and instructors beyond one class or one school by retaining and sharing expert knowledge with learning resources to facilitate problem-based learning.

The study has some obvious limitations. *First*, the design without a control group may mean that the findings do not fully reflect the effectiveness of the V-PBL environment. Considering the complexity involved in real educational settings and the nature of learning, it is not easy to determine whether any learning outcome is affected by a single medium. The present study therefore did not use a control group design to compare the learning outcomes achieved from the proposed environment with that achieved from another environment. The control group design will be carefully implemented in future studies. *Second*, findings from a small number of participants may not be sufficient to generalize the effectiveness of the V-PBL environment to a broader population, and volunteer participants may not be representative of the target population. In addition, there may have been cultural influences affecting the findings as the participants were from one country. These limitations will be addressed in further studies.

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Appendix. Dual-mapping assessment of the example presented in Fig. 2

Items	Grade	Notes
Data nodes in the argument map	3 (More critical, properly described data nodes)	- Two critical data nodes (pitting edema & urinary protein) generated from chief complain - Further data (low-level albumin/hypoproteinemia) obtained from the test
Hypothesis nodes in the argument map	3 (More plausible, differential diagnostic hypotheses)	- Two hypotheses formulated: acute glomerulonephritis (AGN) and nephrotic syndrome (NS) - Both hypotheses make sense
Reasoning links in the argument map	4 (Sufficient well-justified reasoning links)	- NS well justified via reasoning based on three data nodes (pitting edema, urinary protein sign, low-level albumin/hypoproteinemia) - AGN not supported by the pitting edema symptom
Concept nodes in the concept map	3 (More closely-related, problem-solving-oriented concepts nodes)	- Two key concepts related to the problem added: acute glomerulonephritis (AGN) and nephrotic syndrome (NS)
Concept relations in the concept map	3 (Most properly-organized concept relations)	- Two added concepts linked to other concepts - Proper use of causal relation and cross-link
Overall	3.2	

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