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Design of a Dual-Mapping Learning Approach for Problem Solving and Knowledge Construction in Ill-Structured Domains

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ABSTRACT

Problem solving has been increasingly used as an important approach to learning especially in ill-structured domains. It is assumed that knowledge can be better consolidated and extended through problem-solving experience. However, many learners do not have the ability to separate general knowledge from specific cases, which inhibits successful transfer of knowledge to new situations. This study addressed the challenge by proposing a dual-mapping learning approach that involves argument mapping and concept mapping to externalize and integrate problem-solving and knowledge-construction processes in problem-based learning. A preliminary study of the design and effects of the approach is reported. Findings show its effectiveness in improving both problem-solving and knowledge-construction performance.

Keywords

Problem-based learning, Problem solving, knowledge construction, Educational technology

Introduction

A critical element of fostering learning is to have learners to carry out tasks or solve problems in an environment that reflects the use of knowledge into practice (Brown, Collins & Duguid, 1989). It is assumed that learning can be better acquired through problem-solving experience. However, many learners do not have the ability to separate general knowledge from specific cases as they focus on surface features of problems rather than on the development of an understanding of the problem domain (Kirschner et al., 2006). This problem inhibits the likelihood of successful transfer of knowledge to new situations. While problem-based learning (PBL) is increasingly used in medical education and other ill-structured domains, there is a concern about its impact on learners' knowledge base (Albanese & Mitchell, 1993; Gijbels et al., 2005; Hartling et al., 2010).

It is crucial to reveal what is entailed in PBL experience and examine how knowledge construction can be better supported in PBL. However, both problem solving and knowledge construction are complex cognitive processes that cannot be easily captured and mastered. Knowledge gained from practice is found difficult to retain and reuse as a result of contextualization and dynamic aspects of actual problem-solving practice (Patel et al., 2009a). Although situated learning and cognitive apprenticeship (Collins, Brown & Holum, 1991) theories offered guidelines and strategies to facilitate learning in problem contexts, how practice and knowledge reciprocate each other has been overlooked in existing studies.

This study aims to address the challenge by proposing a dual-mapping learning (DML) approach for externalizing and integrating complex problem-solving and knowledge-construction processes. 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. Moreover, computer-based technology is increasingly used in various aspects of medical education (Kushiniruk, 2011). The DML approach focused on a computer-based dual-mapping cognitive tool and implementation of the tool into an online environment for PBL.

The objective of the study was to design, implement, and evaluate the DML approach. A design-based research paradigm was therefore adopted for the study. Design-based research is a systematic methodology that creates, builds, and evaluates innovative artifacts or interventions to deal with identified problems in educational practices (Reeves, 2006). Although PBL has advantages of promoting active and reflective learning, there are concerns about its weakness in general study design, and careful research is needed to understand whether and how potentials of PBL might be realized (Hmelo-Silver, 2004). Design-based research is particularly important in such kind of situations that complex and ambitious educational reforms are ill-specified and the implementation process is uncertain (Wang, Vogel & Ran, 2011). Design-based research contains two key components: design and evaluation of the proposed artifact or intervention. Accordingly, the research questions of the study include: (1) how can the DML approach be designed to externalize and integrate problem-solving and knowledge-construction processes? and (2) how effectiveness is the DML approach in PBL?

Design-based research usually involves four steps: problem analysis, solution development, solution testing and refinement, and reflection on design principles (Reeves, 2006). In this study, the requirement of constructing systemic knowledge in PBL is analyzed in the introduction and related work sections; a theory-driven design of the DML approach is discussed in the theoretical framework, conceptual design, and implementation sections; testing of the DML approach is reported in the evaluation section; and findings of the study in terms of answers to the two research questions are summarized in the discussion section, followed by conclusions at the end.

Related work

Problem-based learning (PBL)

PBL is a pedagogical approach that situates learning in complex problem-solving contexts. In view of its emphasis on active, transferable learning and its potential for motivating students, PBL has been increasingly adopted in ill-structured domains such as medicine education, and widely used in a variety of settings from school to professional education. For effective learning through practical experience, problem solving and knowledge construction should reciprocally reinforce (DeGrave, Boshuizen & Schmidt 1996). However, many studies have tackled problem solving and knowledge construction separately, failing to see them as an integrated two-way process. In the medical domain, many studies examined the novice-expert difference in problem-solving behaviors including data identification, hypothesis generation, and reasoning and justification, while other studies investigated structures or models used by experts to organize their knowledge (Patel et al., 2009b), with little connections between the two themes.

Interactions between problem solving and knowledge construction

While there is no doubt that problem solving requires well-organized knowledge in addition to general problem-solving skills and strategies, it remains somewhat opaque how an expert’s knowledge base is successfully constructed (Wu & Wang, 2012). Practical experience is found to train more routine experts than adaptive experts who continually learn and update their knowledge based on experiences with novel problems and situations (Mylopoulos & Regehr, 2007). Similar views can be found from the study on mind-practice dualism in professional skills development (Dall’Alba & Sandberg, 2006). In response to the challenge, there are a few studies to investigate the transformation from practice to knowledge. Studies on cognitive apprenticeship claimed that masters often have difficulties instructing novices by failing to take into account the implicit processes involved in carrying out complex skills, and teachers are therefore encouraged to identify the processes of abstract tasks and make thinking involved in these tasks visible to learners (Collins et al., 1991). Jonassen (2011) emphasized the problem representation as a key to problem-centered learning. Ericsson (2009) and Dall’Alba and Sandberg (2006) highlighted the importance of revealing mental processes and mechanisms involved in problem-solving activities to understand learning from practical experience. Kinchin, Cabot and Hay (2008) suggested to routinize the interactions between practice and underlying understanding to improve expertise development in higher education. However, these views and suggestions are limited to initial conceptions, lacking investigations on viable methods to realize the ideas and their effects on PBL practice.

Computer-based cognitive tools

Computer-based cognitive tools are recommended to facilitate learning in problem contexts (Jonassen, 2005). By reflecting human cognition through visual representations on the screen, computer-based cognitive tools have been increasingly used to augment cognition, foster thinking, and facilitate inquiry and self-directed learning (Wang et al., 2011). Two types of cognitive tools are directly relevant to this study. *First*, argument mapping can be used to represent reasoning and decision making processes in problem solving (Fox et al., 2007). It is a visual representation of an argument's structure in informal logic involving fact, claims, explanations, evidence, and rebuttals (Kirschner et al., 2003). *Second*, concept mapping can be used to represent conceptual understanding underlying problems. It is a visual representation of concepts and their relationships, mainly for representing and organizing domain knowledge (Novak & Canas, 2008) and is increasingly used to facilitate and assess in-depth understanding and critical thinking in complex situations (Spector, 2006). However, most studies on cognitive tools have been limited to the use of the tools in specific teaching or learning activities, rather than the design of systemic teaching or learning strategies or environment.

Theoretical framework

The proposed DML approach was underpinned by the cognitive apprenticeship model (Collins et al., 1991), an instructional paradigm based on situated cognition and directly aligned with PBL. Based on the cognitive apprenticeship model, learning in problem contexts should consider: (a) situating abstract tasks in authentic contexts, (b) making complex tasks and thinking processes visible, and (c) providing necessary help to learners. Different from traditional schooling methods, the cognitive apprenticeship model emphasizes that abstract tasks and thinking processes must be made visible, i.e., making expert knowledge and practice explicit for learners to observe, enact, and finally practice. Further, six cognitive strategies including articulation, reflection, exploration, modeling, coaching, and scaffolding are proposed in the cognitive apprenticeship model.

In addition to the cognitive apprenticeship model, the DML approach was proposed based on the need for integrating problem-solving and knowledge-construction processes and the potential of computer-based cognitive tools in facilitating cognitive processes. Accordingly, the DML approach was featured by a dual-mapping cognitive tool designed based on two models for problem solving and knowledge construction, respectively. *First*, the SOI (selecting, organizing, and integrating) model proposed by Mayer (1996) describes the *knowledge-construction* process and mechanism. The model involves three sequential cognitive steps: (a) selecting relevant information for further processing in working memory (WM), (b) organizing incoming information into a coherent representation in WM, and (c) integrating incoming information with prior knowledge in long-term memory (LTM). To externalize these mental activities in knowledge construction, *concept mapping* can be directly applied to conceptualize knowledge and extend it into a progressively more complex network of understanding.

Second, a computational model proposed by Dougherty, Thomas and Lange (2010) outlines the hypothesis-led *problem-solving* process and mechanism. The model focuses on the relationships among the environment (e.g., perceptual information), memory system (including exemplar/episodic memory and semantic memory), and problem-solving behaviors (including hypothesis generation, probability judgment, and hypothesis testing). While solving a problem, the observed data trigger traces from the exemplar memory, which, in turn, matches the known hypotheses from the semantic memory. During the matching process, possible hypotheses are generated and tested before making a judgment. The process is iterative and dynamic, where hypotheses can be updated when new data are encountered. To make such complex, dynamic processes visible to learners, argument mapping can be directly applied to represent and justify problem-solving activities.

Conceptual design

The DML environment was design to consist of (a) an exploratory problem context for interaction with problems, (b) a dual-mapping cognitive tool for articulation and integration of problem-solving and knowledge-construction processes, and (c) expert support to facilitate the learning process. The dual-mapping tool is the core of the DML environment. It involves concept mapping and argument mapping for externalizing and integrating problem-solving and knowledge-construction processes. The learner starts the learning process by selecting and exploring a problem case and representing problem-solving actions into hypothesis generation, hypothesis justification, and diagnostic conclusion in an argument map. While solving the problem, the learner needs to recall prior knowledge or derive new understanding, which can be represented in a concept map for easy reference and update throughout the learning process.

Argument mapping and concept mapping play different roles in the DML approach (see Figure 1). Argument mapping helps to sharpen problem-solving skills through building coherent and well-grounded argumentation structure (Fox et al., 2007). Concept mapping helps to pull out domain knowledge and conceptualize contextual knowledge (Spector, 2006). More importantly, the two types of mapping processes are integrated so that (1) the argument map explicates problem-solving experience for generating new understanding for reuse; and (2) the concept map provides anchored points for solving problems based on relevant knowledge and for integrating new understanding with prior knowledge.

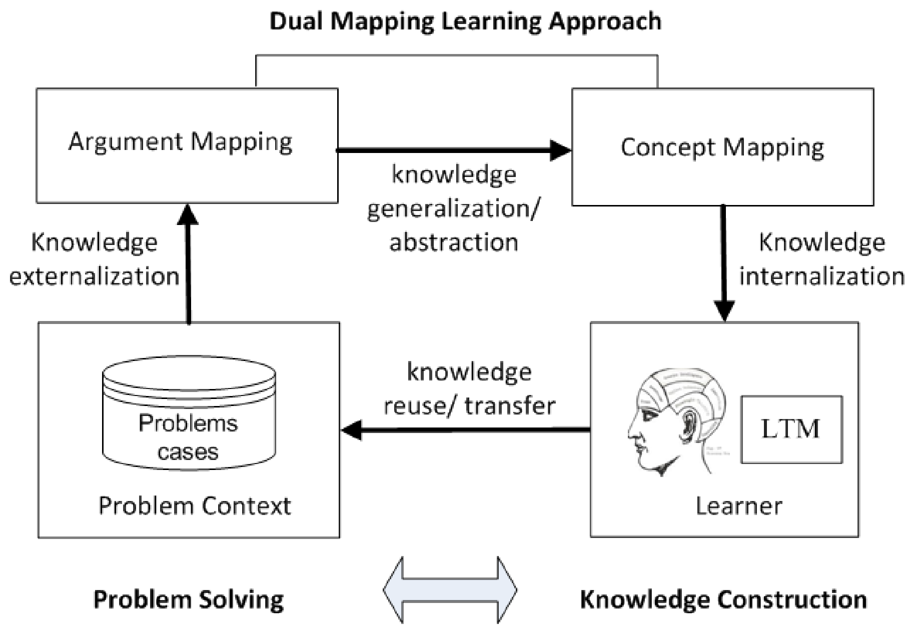

Figure 1. Conceptual framework of the DML approach

The six cognitive strategies rooted in the cognitive apprenticeship model are incorporated into the DML approach.

- *Exploration* refers to pushing learners into a mode of problem solving on their own. In this study, a problem context was set up to help learners to explore problems and solutions autonomously.
- *Articulation* refers to getting learners to articulate their knowledge, reasoning, or problem-solving processes. In this study, the dual-mapping cognitive tool was proposed to help learners to articulate their problem-solving and knowledge-construction processes.
- *Reflection* refers to enabling learners to compare their own problem-solving processes with those of others. In this study, learners could review their PBL processes presented in dual maps and compare them with feedback or advice from the expert.
- *Modeling* refers to providing learners with examples of desired performance usually from teachers or experts. In this study, the PBL process with a sample case using the DML environment was demonstrated to learners.
- *Coaching* refers to observing a learner’s performance and providing feedback and advice on the performance. In this study, computer-generated adaptive feedback and hints were provided for individual learners throughout the learning process.
- *Scaffolding* refers to providing help to learners for tasks that learners are unable to complete autonomously. In PBL, learners may suffer from high cognitive load, and easily get lost and feel frustrated by a number of complex, dynamic tasks. In this study, the PBL process was decomposed into a set of tasks, the flowchart of which was provided to scaffold the complex learning process.

Implementation

Based on the conceptual framework, a web-based DML system for learning with clinical diagnostic problems was implemented. It consisted of the following key components.

Exploratory problem context

The learner could start the learning process by accessing a clinical case in the "exploratory problem context" window. The case information was represented in texts, charts, and images, as shown in Figure 2. The information was organized first by clinical date and then by content, categorized into patient history, physical examinations, lab tests, imaging records, patient state, and prescription history. The learner could check the initial information of the case and perform clinical actions to achieve additional information.

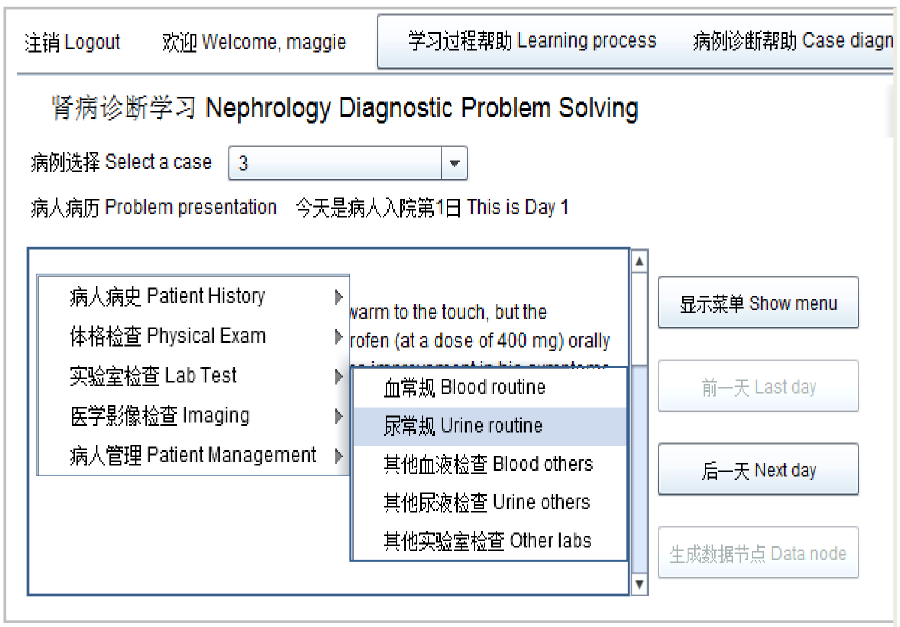

Figure 2. Exploratory problem context

Most clinical cases are progressive, in other words, a patient's information is not received in one snapshot. In the DML system, each piece of patient information was given a label starting with "Dx" to indicate the patient data for the x-th day. To obtain sufficient information of a case, the learner had to make hypothesis-led information search in a progressive way.

Dual-mapping cognitive tool

The dual-mapping cognitive tool was designed to visualize and integrate the problem-solving and knowledge-construction processes in PBL. As shown in Figure 3, the tool consisted of an argument mapping panel and a concept mapping panel. The learner could use the argument mapping panel to represent the diagnostic and reasoning processes in the argument map. In addition to data nodes, the learner could generate one or more hypothesis nodes in the argument map. The strength of a hypothesis was reflected by the border of the hypothesis node - the heavier the border the stronger the hypothesis, while the strongest one was the diagnosis node. Each hypothesis node could be linked with relevant data nodes based on two types of reasoning links, namely support and against. The strength of a reasoning link was reflected by the width of the arrow-line that linked the nodes, the wider the arrow-line the stronger the link. The learner could justify their reasoning actions by adding brief text to the reasoning links. Further, the learner could generate one or more evidence nodes to support the justification, and each evidence node could be linked to external references such as journal articles and books.

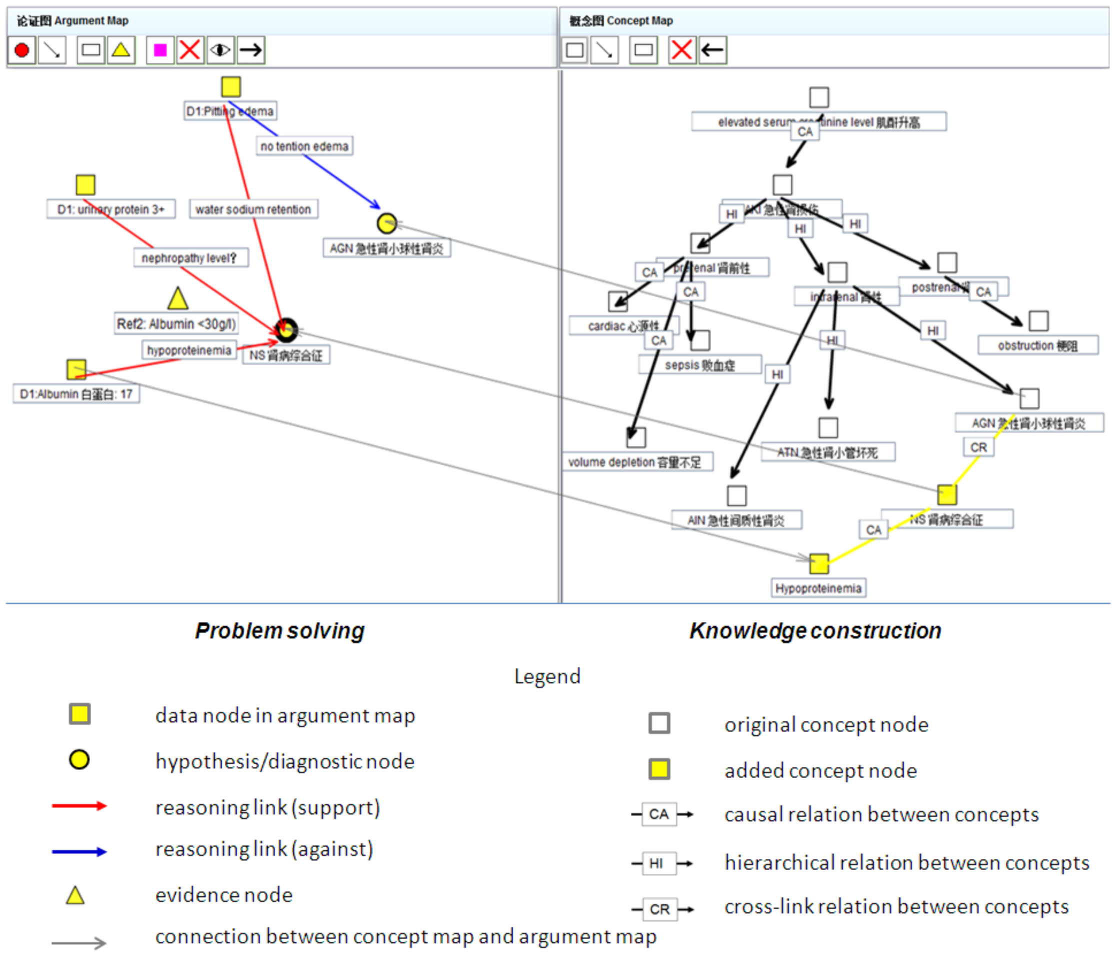

Figure 3. Dual-mapping cognitive tool

On the other hand, the learner could use the concept mapping panel to represent his/her understanding of the domain knowledge into concept nodes and their relations (including hierarchical, causal, and cross-link). An initial version of the concept map covering a few basic concepts with their relations was provided in the system. The learner was required to update the concept map by adding missing concepts and relations. New concept nodes could be generated by retrieving relevant terms or adding new terms from the system.

To capture interactions between problem solving and knowledge construction, the learner could connect nodes in the concept map with relevant nodes in the argument map to indicate the knowledge that supports the problem-solving process, or connect nodes in the argument map with relevant nodes in the concept map to explicate the knowledge generated from the problem-solving process. Moreover, the learner could use other features of the tool to zoom in/out the maps, show/hide explanations or evidence nodes, and adjust the display of hypothesis nodes according to its strength.

Figure 3 represents a part of the DML process for diagnosing a nephrotic syndrome case. First, pitting edema and urinary protein are generated as two data nodes in the argument map according to the patient’s chief complaint. The captured data trigger the recall of knowledge about acute glomerulonephritis (AGN) and nephrotic syndrome (NS). The former is already represented in the concept map while the latter is not. Therefore, NS is added to the concept map and linked with AGN. Further, the two concepts are applied to generate two hypotheses in the argument map. The pitting edema symptom supports the NS hypothesis since renal retention of sodium and water may cause edema. However, this symptom does not support the AGN hypothesis as AGN is more likely to cause tension edema rather than pitting edema. Moreover, the urinary protein sign corroborates the possibility of NS and raises the doubt of nephropathy-level protein in urine. A 24-hour urine protein test is then requested, and the low-level albumin (also called hypoproteinemia) confirms the NS hypothesis by the evidence of albumin less than 30g/L. Accordingly, hypoproteinemia is added to the concept map with a causal link to NS.

Scaffolding and coaching support

Problem solving usually contains a number of complex, dynamic, and interactive tasks, making learners easily get lost and feel frustrated. In this study, the PBL process is decomposed into a set of tasks to scaffold the complex learning with problems.

- *Perform clinical actions*. The learner accesses the initial information (e.g., chief complaint) of the case and performs clinical actions for further information.
- *Identify critical information*. After identifying the critical information of the case, the learner generates relevant data nodes in the argument map.
- *Recall and update knowledge*. While solving the problem, the learner recalls relevant knowledge, which can be represented in the concept map, and updates the concept map throughout the learning process.
- *Generate hypotheses*. Based on the case information and relevant knowledge, the learner generates one or more hypotheses in the argument map.
- *Justify hypotheses*. To reach a conclusion, the learner justifies the hypotheses by adding reasoning links and supporting evidence to the argument map.
- *Make a diagnostic conclusion*. After some iterative explorations and analyses, the learner makes a diagnostic conclusion in the argument map.

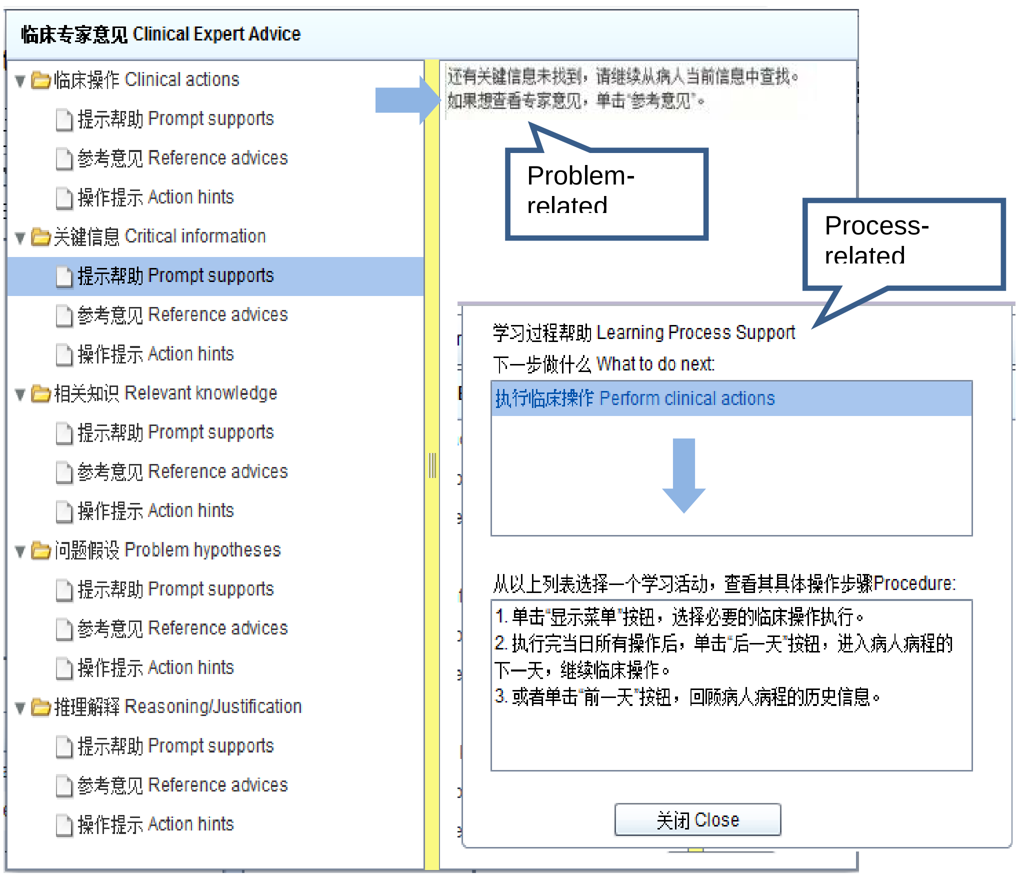

Figure 4. Coaching support

In addition to the scaffolding of the general learning process, individual coaching was provided to learners. The coaching support involved process- and problem-related guidance as shown in Figure 4. Both were generated by the system and adaptive to individuals. The process-related guidance involved suggestions on what to do next according to the learner's progress. The problem-related guidance was relevant to the solution of the case, categorized into clinical actions, critical information, relevant knowledge, problem hypotheses, and reasoning and justifications. In addition, a summative report of the solution to the case made by the expert could be accessed by the learner after he/she completed the learning with that case.

Evaluation

To examine the effectiveness of the proposed approach, the DML environment was used and evaluated by medical students. A preliminary evaluation was carried out with two first class medical schools in China, one at Tongji University and another at Southeast University. PBL had been adopted by both schools, but limited in scope. Two domain experts and one instructor from the two schools were invited to participate in the study. They provided support in selection of the clinical cases and assessment of students' learning outcomes. An online PBL program involving five clinical cases about the kidney disease was provided in the system. The cases were collected and adapted from clinical practice and academic references.

A combination of quantitative and qualitative methods including surveys, interviews, tests, and DML products were used for evaluation. Data triangulation was employed by using both survey and interviews to examine participants' perceptions of the DML system, and by using traditional tests, self-perceived learning gains, and DML products to assess the learning outcomes.

Participants

Twenty-nine students from the two schools participated in the preliminary use and evaluation of the DML environment. They had fundamental medical knowledge but little clinical experience. Their participation in this study was fully voluntary. 65.5% of the participants were females and 34.5% males. Most of them (65.5%) were in the fourth year of their seven-year medical curriculum (including five years of undergraduate study and two years of graduate study). Most of them reported to have intermediate (41.4%) and good (41.4%) computer skills. Their intention to use technology for learning was between neutral (41.4%) and positive (41.4%).

Procedure and instruments

Before using the DML system, participants were administered a survey to collect their demographic information. A face-to-face demonstration of how to use the system to perform PBL with a sample case was then provided to the participants. After some exercise with the sample case, the participants started to learn with other four cases in the system. They were required to complete the learning program in their free time within four weeks. During the learning period, the instructor helped to facilitate the learning process when needed.

A *pre-test* and *post-test* were used to assess the learning outcome. The questions of the tests were adapted from relevant text books (Clatworthy, 2010) for assessing problem-solving knowledge and skills in diagnosing the kidney disease. At the end of the learning program, learners' evaluations of the DML environment and their perceived learning gains were collected in a *survey*. The items measuring learners' perceptions (usefulness, ease of use, and intention to use) of the learning system were adopted from the information technology acceptance literature (Davis, 1989). The items measuring learners' perceived learning gains with regard to problem-solving and knowledge-construction abilities were adopted from the well established Student Assessment of their Learning Gains (SALG) instrument (WCER, 2011). These measures have been internationally validated and widely used. Internal consistency of these instruments was assessed in this study using Cronbach's α, and the reliability coefficients for all the subscales were higher than .70.

Semi-structured interviews were arranged with all the participants at the end of the program to collect their comments on the advantages and disadvantages of the DML system. The interview data were coded and analyzed by two raters, and Cohen's Kappa was used to measure the agreement between the raters on the themes identified from raw interview responses. The result (Cohen's Kappa = .87) showed a high degree of consensus between the raters. Moreover, students' *DML products* generated in the learning system were assessed based on the criteria adapted from prior studies (Srinivasan et al., 2008; Facione & Facione, 2008; Jonassen, 2011). The rubrics involve quantity and quality of five items including data nodes, hypothesis nodes, and reasoning links in the argument map, and concept nodes and relations in the concept map. Each item was scored on a 5-point Likert scale and normalized to a scale between 0 and 1. The overall dual-mapping score of a case was the average of the scores of the five items. Moreover, the connections between the argument map and the concept map built by learners were analyzed to examine the interactions between the problem-solving and knowledge-construction processes.

Findings

Findings from evaluation survey

Learners' evaluations of the DML environment and its main functions collected from the survey questionnaire are summarized in Table 1. The overall system and its main functions were perceived to be useful. Regarding ease of use, learners' evaluations of the problem context and scaffolding and coaching support were found positive, while their evaluations of the overall system and the dual-mapping tool were weakly positive. Accordingly, learners' intention to use the system was weakly positive.

Table 1. Learners' evaluation

	OVER_USE	EPC_USE	DMT_USE	SCS_USE	OVER_ITU
M	2.62	2.68	2.57	2.55	2.47
SD	.81	.72	.84	.64	1.04
	OVER_EOU	EPC_EOU	DMT_EOU	SCS_EOU	
M	2.05	2.40	2.07	2.21	
SD	.99	.67	.92	.83	

Note. USE: usefulness; EOU: ease of use; ITU: intention to use; OVER: overall system; EPC: exploratory problem context; DMT: dual-mapping tool; SCS: scaffolding and coaching support (5-point Likert scale: 0 represented "strongly disagree" and 4 represented "strongly agree")

Learning outcomes

The learning outcomes were assessed based on the tests, self-perceived learning gains, and DML products. The test papers were graded by the instructor, and the scores were normalized to a scale between 0 and 1. The paired-sample *t* test indicated that there was no significant difference between the pre-test and post-test scores, albeit a slight increase in the mean score (pre-test $M = .24$; post-test $M = .29$, $p > .05$).

With regard to the self-perceived learning gains, participants reported nearly moderate level of progress in both problem-solving and knowledge-construction abilities (see Table 2).

Table 2. Self-perceived learning gains

	PSA	KCA
M	1.87	1.97
SD	.88	.98

Note. PSA: problem-solving abilities; KCA: knowledge-construction abilities (5-point Likert scale: 0 represented "no progress" and 4 represented "large progress")

On the other hand, the dual maps generated by learners from the first and last case were blindly assessed by the two domain experts based on the predefined rubrics. The inter-rater reliability of assessment by the two raters was .91, significant at the .01 level. The average of the two raters' ratings was used for further analysis. In addition, Pearson's correlation coefficient was calculated to test the consistency between the dual-mapping score and test result. The dual-mapping scores of the last case were found to be significantly correlated with the post-test scores ($r = .73$, $p < .01$).

Details of the descriptive statistics and paired-sample *t* tests to compare the dual-mapping performance between the first and last case were presented in Table 3. A significant improvement in overall performance was found from the first to the last case ($t(28) = 5.72$, $p = .000$). The effect size (Cohen, 1988) was 1.17, indicating large progress in dual-mapping performance from the first to last case. As the dual-mapping performance in the five items were concerned, there was a significant improvement from the first to the last case in all items except the "reasoning links." When associating the five items with learners' problem-solving and knowledge-construction performance, it was found that participants' problem-solving performance (reflected in data nodes, hypothesis nodes, and reasoning links) was better than their knowledge-construction performance (reflected in concept nodes and concept relations) for both the first and last case. Furthermore, the knowledge-construction performance presented larger variations among the participants in the last case than in the first case.

Table 3. Dual-mapping scores for the first and last case (scores range from 0 to 1)

	First case		Last case		Paired-sample *t* tests		
	M	*SD*	*M*	*SD*	*t*	*df*	*p*
DaN	.44	.16	.58	.12	3.92	28	.002**
HyN	.25	.15	.35	.13	2.80	28	.017*
ReL	.23	.17	.35	.20	1.73	28	.111
CoN	.17	.16	.35	.31	3.45	28	.005**
CoR	.13	.17	.23	.25	2.80	28	.017*
Overall	.24	.11	.38	.14	5.72	28	.000**

DaN: data nodes; HyN: hypothesis nodes; ReL: reasoning links; CoN: concept nodes; CoR: concept relations
* $p < .05$;
** $p < .01$

To further analyze the change of dual-mapping performance from the first to the last case, Table 4 presents the descriptive statistics and the paired-sample *t* test results regarding the numbers of connections between problem solving and knowledge construction. There was a significant improvement from the first to the last case ($t(28) = 2.67$, $p = .045$) in the number of connections from problem solving to knowledge construction (represented by the links from the argument map to the concept map), but no significant difference in the number of connections from knowledge construction to problem solving (represented by the links from the concept map to the argument map).

Table 4. Numbers of connections

	First case		Last case		Paired-sample *t* tests		
	M	*SD*	*M*	*SD*	*t*	*df*	*p*
PS2KC	2.33	1.50	3.83	1.79	2.67	28	.045*
KC2PS	2.17	1.17	2.50	1.39	0.79	28	.465

Note. PS2KC: from problem solving to knowledge construction; KC2PS: from knowledge construction to problem solving.
* $p < .05$

Findings from interviews

All the participants were interviewed regarding their comments on the advantages and disadvantages of the DML system. Table 5 outlines the interview result.

Table 5. Summary of interview responses from learners (n = 29)

Positive comments	No. of hits
The DML environment is useful for knowledge construction.	20
The DML environment is useful for problem solving.	19
The expert support is helpful for learning.	10
The DML environment is innovative.	5
The problem cases are well-prepared.	5
The DML environment supports self-directed learning	3
Negative comments	No. of hits

The dual-mapping tool is somewhat complicated.	15
Some interfaces of the system are not very user-friendly.	7
More guidance on dual-mapping learning is needed.	6
Problems cases should cover different levels of difficulty	3

Most learners found the DML environment useful for both problem solving and knowledge construction. As one mentioned, “The system gives us a clear and systemic picture of main tasks involved in clinical problem solving. It is very helpful for developing logic thinking and reasoning skills.” Another participant commented, “It is usually difficult to manage complex and separate pieces of knowledge for clinical problems, but this system provides a useful approach to making knowledge well organized and connected.” Learners also felt the expert support provided by the system helpful for their self-directed learning, especially for checking missing points in their understanding and thinking. Some of them mentioned that the DML was innovative and the clinical cases were well-prepared, and they felt such kind of learning system could benefit a large number of learners for clinical professional development. On the other hand, many learners reported that the dual-mapping cognitive tool was somewhat complicated, and some interfaces that were perceived not very user-friendly. Some participants also felt DML challenging especially under the situation without immediate face-to-face instructions. They suggested more learning guidance provided for DML.

The instructor and domain experts were also interviewed for their comments on the DML system and its impact on teaching. They expressed their clear interest in the DML approach and positive comments on DML system with its ability to stimulate learners’ motivation and sense of autonomy for learning. As the instructor said, “Different from traditional spoon-fed learning, the proposed system is unique in activating learners’ curiosity for learning with real problems. It provides learners with valuable experience of learning with a high degree of autonomy.” Further, they commented that most medical schools in China did not allocate sufficient time and resources for teaching sophisticated skills of problem solving, and that there was a high demand to incorporate such kind of problem-centered learning system into the traditional classroom to benefit more learners from blended learning experiences.

Discussions

The findings of the study are discussed as the answers to the two research questions. With regard to the *first question*, a DML environment was designed and implemented for externalizing and integrating problem-solving and knowledge-construction processes. Based on the cognitive apprenticeship model and its cognitive strategies, the DML environment was designed to incorporate an exploratory problem context for *exploration* with problems and solutions, a dual-mapping cognitive tool for *articulation* and *reflection* of cognitive processes in problem solving and knowledge construction, and *scaffolding* and *coaching* support to facilitate the complex learning process. In particular, the computer-based dual-mapping cognitive tool, a core element of the DML environment, was designed by taking into account the hypothesis-led mechanism for problem solving and the SOI (selecting, organization, and integrating) model for knowledge construction. It involved argument mapping and concept mapping techniques to articulate and integrate key cognitive elements involved in problem-solving and knowledge-construction processes. In brief, the DML environment was designed to facilitate PBL by enabling learners to explore with problems in authentic situations, externalize and reflect on their problem-solving and knowledge-construction processes, and improve their knowledge by aligning new understanding from problems into existing knowledge structure; and, on the other hand, by providing learners with sufficient guidance to ensure effective learning experiences.

With respect to the *second question*, the DML system was evaluated based on learner perceptions and learning outcome. *In terms of learner perceptions*, the survey results show that the DML system was perceived to be useful, but not very easy to use. Interview results confirmed that many learners regarded the DML environment useful and innovative, but they suggested some interfaces of the dual-mapping cognitive tool to be improved and more guidance to be provided for DML. Moreover, the instructor and domain experts commented that the DML environment offered valuable learning experiences and stimulated students’ sense of autonomy in learning. They also indicated the need for incorporating such learning environment into regular teaching programs.

In terms of learning outcomes, learners reported to make moderate progress in problem-solving and knowledge-construction abilities, consistent with a significant improvement found in their DML products, although no significant difference was found between the pre-test and post-test scores with the four-week period. The result is consistent with previous studies in that what students learn from PBL is mixed especially based on traditional examination scores (Gijbels et al., 2005; Hartling et al., 2010). Researchers have argued for more rigorous and authentic measures of knowledge and skills that are more sensitive to the effects of PBL (Patel et al., 2009a). In this study, learners' dual-mapping scores for the last case were found to be significantly correlated with their post-test scores, indicating that the proposed dual-mapping cognitive tool was consistent with the traditional paper-and-pencil-based test in assessing PBL outcome. This finding is in line with the current trend of using cognitive tools to assess knowledge and skill development especially in complex learning (Pirnay-Dummer, Ifenthaler & Spector, 2010).

More importantly, the dual-mapping scores were found to provide more formative assessment of PBL performance than traditional tests in the following aspects: learners made a significant improvement from the first to the last case in both problem solving and knowledge construction; learners performed better in problem solving than in knowledge construction for the first and last case; learners improved in directing problem solving to knowledge construction from the first to the last case; and the knowledge-construction performance varied more than the problem-solving performance among learners in the last case. These results further demonstrated the effectiveness of the DML approach in improving problem solving and knowledge construction as well as in building connections between the two. Moreover, by comparison with problem solving, knowledge construction was found to be more challenging to most learners and more difficult to be improved in a short period of time.

Conclusions

Learning through problem solving has been increasingly adopted as an important approach to education and expertise development especially in complex domains. However, the effect of PBL on construction of systemic knowledge is not found satisfactory. Many learners do not have the ability to separate general knowledge from specific cases and apply it to new situations. There is a clear need to reveal how practice and knowledge reciprocate each other. This study addressed the challenge by proposing a dual-mapping learning approach for externalizing and integrating complex cognitive processes in problem solving and knowledge construction.

The findings of the study have implications for research and practice in PBL. While PBL has become a critical strategy of curriculum reforms and pedagogical innovations in many disciplines, more studies are needed to enrich design principles and assessment methods of PBL, especially with technology support. This study contributes to the instructional design, technology, and assessment for learning in complex problem contexts. In the meantime, the proposed DML environment provides a platform for further studies on how problem solving and knowledge construction interact and reinforce each other in PBL.

The limitations of the study should be noted that the design in a local context may not easily generate valid design principles and preliminary findings from a small number of participants may not be sufficient enough to claim the effectiveness of the approach for a broader population. Future work will address these limitations. Meanwhile, by its nature of design-based research, this study needs iterative analysis, design, and implementation to test and refine the proposed approach as well as to develop relevant design principles and theories for a better understand of and better approaches to support learning in problem contexts.

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