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Deep Learning towards Expertise Development in a Visualization-based Learning Environment

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ABSTRACT

With limited problem-solving capability and practical experience, novices have difficulties developing expert-like performance. It is important to make the complex problem-solving process visible to learners and provide them with necessary help throughout the process. This study explores the design and effects of a model-based learning approach implemented in a web-based learning environment that not only allows learners to capture and reflect on their problem-solving process in visual formats but also helps them to identify the gap between their performance and that of the expert for effective reflection and improvement. The proposed approach attempts to utilize expert knowledge to transform open-ended problem-solving experience into a systematic and deliberate effort towards expertise development. Twenty-five medical students participated in the study by using the proposed learning environment to complete a number of diagnostic problem-solving tasks. The results show that the approach positively affects students' achievements in subject knowledge, problem-solving performance, and perceptions and motivation for learning in the proposed learning environment.

Keywords

Problem solving, Expertise development, Professional development, Visualization, Computer-based learning environment, Model-based learning and instruction

Introduction

As a form of constructivist learning, problem solving has received wide attention in educational practice, especially in complex and ill-structured domains such as scientific inquiry and medical education (Jonassen, 1997). Problem-solving experience can help learners to develop critical thinking, communication, and problem-solving skills as well as improve the construction of knowledge (Hmelo-Silver, 2004). Given that learning with real-world problems is constrained in classroom settings, computer-based environments have been increasingly explored as a way to support learning through problem solving in virtual environments. Computer-based learning environments have clear advantages in affording flexible access to learning resources, on-demand delivery of learning programs, flexible communication with others, and more importantly computer-based learning support.

However, effective learning through problem solving is difficult to realize in both classroom and computer-based settings. Solving a real-world problem often involves a sophisticated process of understanding the problem, linking abstract knowledge to problem information, and applying relevant methods and strategies to solve the problem. Learning in such contexts can generate a heavy cognitive load for learners (Kirschner, Sweller, & Clark, 2006) that instructors or experts often underestimate, as for them many of the requisite processes have become largely automatic or subconscious with experience. With limited abilities to capture the complex problem-solving process, many learners fail to adequately engage in authentic task experience and achieve desired learning outcomes.

Learning through problem-solving experience has been widely adopted in medical education by way of problem-based learning curricula, case-based sessions, and internship programs. Several reviews of the literature have shown that problem-based learning improves students' reasoning and communication skills, fosters their abilities to cope with uncertainty, and empowering 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). At the same time, researchers have reported inconclusive and inconsistent findings on the superiority of problem-based learning over conventional instructions, mainly in systematic construction of subject knowledge and the development of efficient reasoning process (Coderre, Mandin, Harasym, & Fick, 2003; Patel, Yoskowitz, Arocha, & Shortliffe, 2009). A major concern is that completing a problem-solving task such as clinical diagnosis involves complex cognitive processes in the search for problem information about multiple aspects, integrating the problem information with subject-matter knowledge, and reasoning with interactive components to analyze the problem (Delany & Golding, 2014; Wang, Wu, Kinshuk, Chen, & Spector, 2013).

Previous studies report that scaffolding supports learning in complex task situations mainly by using prompts or tips to bring learners' attention to important issues or by decomposing a complex task into a set of main actions or key questions (Ge, Chen, & Davis, 2005; Hmelo-Silver, Duncan, & Chinn, 2007). Recent research has highlighted that when working with complex problems, making thinking visible with the support of visualization-based learning technology is important (Wang & Jacobson, 2011). Externalization of complex cognitive processes or mental models promotes deep learning and improves learning outcomes in inquiry learning and problem-solving contexts (Gijlers & de Jong, 2013; Linn, 2000; Suthers, Vatrapu, Medina, Joseph, & Dwyer, 2008; Van Bruggen, Kirschner, & Jochems, 2002; Wu, Wang, Grotzer, Liu, & Johnson, 2016). In doing so, visual representations and graphic forms play an important role in representing complex thinking and cognition in flexible ways.

In addition to enabling learners to capture their cognitive process or mental model for deep thinking and self-reflection, there is a need to explore how learners' performance can be further improved by allowing them to reflect on the gap between their process and that of the expert so as to promote expertise development. Research on expertise development has revealed that desired learning outcomes in problem-solving contexts cannot be achieved through a mere accumulation of experience, but require systematic and deliberate effort with expert support (Ericsson, 2008; Jarodzka, Scheiter, Gerjets, & van Gog, 2010). Further to our prior studies on scaffolding thinking and reflection by externalizing and visualizing a set of cognitive elements in problem-solving contexts (Wang et al., 2013; Wu & Wang, 2012; Wu et al., 2016), the present study aims to explore how novice performance can be further improved through the utilization of expert knowledge and visualization-based learning facilities.

This study uses a visualization-based learning environment design that helps medical students to capture the complex process of diagnostic problem solving with the support of expert feedback. The design features model-based learning, which attempts to enable students to capture and reflect on their problem-solving process and improve their performance by identifying the gap between their process and that of the expert. The research questions (RQs) of the study are specified as follows:
RQ1: How can a computer-based learning environment be designed to help medical students capture the complex process of solving a diagnostic problem with expert support?

RQ2: What are the effects of the proposed approach on student learning in a diagnostic problem-solving context?

Theoretical framework

Learning through problem solving positions learners in real-world problem contexts, helping them to develop critical thinking and problem-solving skills as well as consolidate and extend content knowledge. Learning in problem-solving contexts is supported by situated cognition theory (Brown, Collins, & Duguid, 1989) and situated learning theory (Lave & Wenger, 1991). The two theories share a common view that situation and cognition are interdependent. Cognition is a process that occurs in physical and social contexts where knowledge is created and applied. Problem-solving experience is also recognized as an integral part of expertise development (Ericsson, 2008; Schmidt, Norman, & Boshuizen, 1990).

Given that open-ended exploration with complex problem-solving tasks can overburden learners, the provision of scaffolding or support to learners has been widely recognized as an important part of learning in such situations (Hmelo-Silver et al., 2007). The use of scaffolding to support student learning with complex problems is aligned with the cognitive apprenticeship model (Collins, Brown, & Holum, 1991), which claims that carrying out a complex task usually involves implicit processes. It is critical to make such processes visible for novices to observe and practice, and to provide them with expert help. At the same time, when scaffolding learning in complex situations, it is important that the scaffolding or support does not undermine the open-endedness of the task and individual endeavor.

Making complex tasks and thinking processes visible can be linked with model-based learning and instruction, i.e., the use of mental models to uncover the cognitive processes and architectures to gain insight into the nature of complex problem solving (Greca & Moreira, 2000; Seel, 2003). A mental model is "what people really have in their heads and what guides their use of things" (Norman, 1983). Effective learning in problem-solving contexts requires the externalization of the implicit mental models that are associated with sequences of actions and the underlying knowledge in complex problem-solving processes (Bradley, Paul, & Seeman, 2006). Model-based learning and instruction has two different modes: self-guided and expert (Seel, 2003). In the self-guided mode, students are expected to develop their own mental models with little support or guidance, which is more suitable for well-structured problem solving, or when students have profound knowledge and experience in a given domain. In the expert mode, experts' mental models are externalized as support and a guide to help students solve complex problems or accomplish learning tasks. It is more suitable for ill-structured problem solving, or when students have limited prior knowledge and experience.

Methods

This study uses the design-based method because it aims to develop a computer-based learning environment for diagnostic problem solving and examine its effects on student learning. As a systematic and scientific methodology, design-based research involves iterative analysis, design, development, and implementation to create and evaluate innovative interventions to solve discovered problems (The Design-Based Research Collective, 2003; Reeves, Herrington, & Oliver, 2004; Wang & Hannafin, 2005). It has been employed to the design of educational interventions to promote sustained and practical development in technology-enhanced learning environments (Dede, 2004). It is particularly suitable when complex and ambitious educational reform policies are ill specified and the implementation process is uncertain (Wang, Vogel, & Ran, 2011).

Informed by relevant learning theories and instructional models, a computer-based, expert-supported learning environment has been designed to help medical students to capture the complex process of diagnostic problem solving to improve their problem-solving expertise (Yuan, Wang, Kushniruk, & Peng, 2016). An empirical study has been conducted with medical students to determine the effects of the proposed approach by examining students' learning outcomes using the proposed approach.

Glaucoma diagnosis was chosen as the learning subject because it is a part of the learning content of general courses in medical schools and is considered to involve ill-structured problem solving. Two domain experts with over ten years of clinical and academic experience in glaucoma diagnosis and treatment participated in this study. They supported the preparation of clinical cases and the assessment of learning outcomes. A medical teacher with years of teaching experience in a public medical school participated in the study to support the arrangement of learning activities with students.

Seven clinical cases were used for the study. Five of these were used for learning tasks, and the other two for assessing student performance before and after the study. All of the cases were selected and adapted from authentic clinical cases by the experts. The selection criteria were that the cases should be representative and clearly presented and have referenced solutions validated by the experts. The reference solutions were used to assess student performance and provide feedback to students during the task process.

Proposed learning environment

Glaucoma Diagnosis & e-Learning System (GDeL), a computer-based learning environment used to support students' learning and expertise in glaucoma diagnosis, has been developed and includes the following main functions.

Exploratory problem-solving context

The exploratory problem-solving context allows learners to work with a number of simulated diagnostic problems. After selecting a case in the system, the learner can view a primary description of the patient's background information (e.g., age, gender, and medical history) and chief complaint. Based on the initial information, the student forms an initial assessment of the case. Moreover, the learner can conduct clinical examinations of the patient to obtain further information, as shown in Figure 1. For each selected clinical examination, the learner can view the examination results (in the form of laboratory data, images, and brief inspection reports) and make intermediate judgments based on the results. After obtaining adequate information via several rounds of examination and judgment, the student makes a diagnostic conclusion for the case.

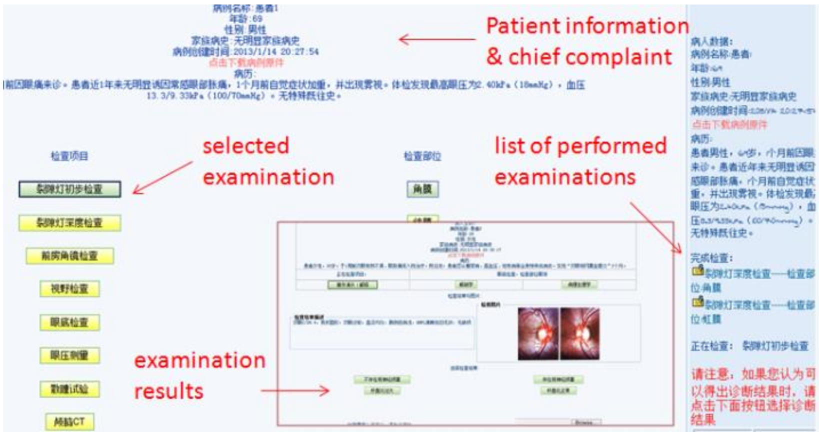

Figure 1. Simulated problem-solving context

Visualization of the problem-solving process

For each case, the diagnostic problem-solving process performed by the learner can be captured by the system and shown in a flowchart (see Figure 2). A diagnostic flowchart covers the initial information about the patient, clinical examinations selected for the patient, intermediate judgments made upon receiving the examination results, and a diagnostic conclusion. By externalizing the diagnostic process in a visual format, the system allows the learner to review and reflect on his/her task process and performance.

Figure 2. Visualization of the problem-solving process

Expert support

The learner can practice with the same case repeatedly. After each diagnosis, the learner can view the feedback about his/her performance that the system generates by comparing his/her performance with that of the expert, e.g., “Your process missed some examinations.” The feedback focuses on three key aspects of the performance, i.e., selection of clinical examinations, intermediate judgment based on the examinations, and diagnostic conclusion. The feedback allows the learner to recognize whether he/she has missed necessary examinations or judgments or included unnecessary or inappropriate examinations, judgments, or conclusions. The feedback is not concerned with the sequence of actions (e.g., the order of the clinical examinations), which involves certain flexibility. The performance in collecting initial information about the case was not taken into account, as all of the learners were provided with the same original information for each case, which was very limited and useful for diagnostic analysis.

Once the overall similarity in task performance between the student and expert reaches 60% or more, or the learner has tried to solve the case 10 times, the learner can view the expert’s diagnostic process, together with the expert’s summary of the key points and common errors in case diagnosis (see Figure 3).

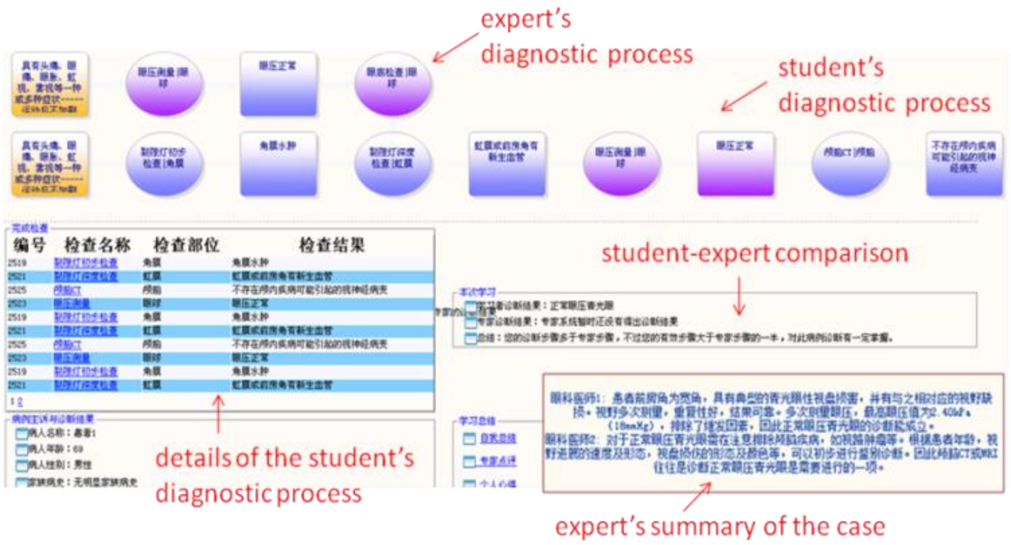

Figure 3. Expert support

Construction of knowledge in mental map

The system also includes a diagram tool, which allows students to build a mental map to externalize the subject-matter knowledge underlying the diagnostic processes. Students are encouraged to reflect on the knowledge underlying all cases at the end of the study and represent it in a mental map in a flexible way (see Figure 4).

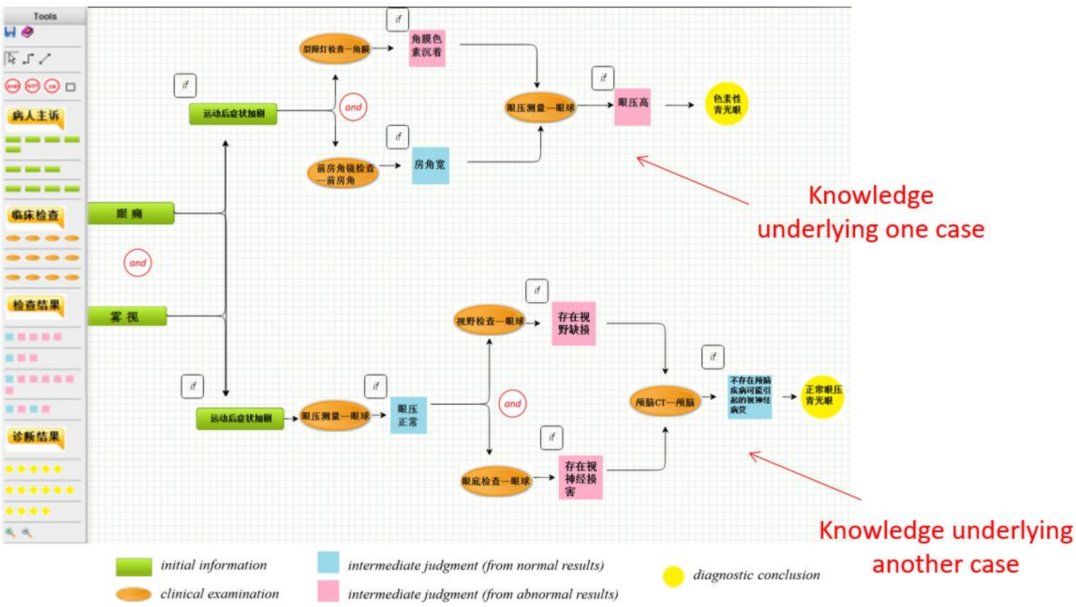

Figure 4. Knowledge construction in a mental map

The overall design of the GDeL system is aligned with the six strategies proposed in the cognitive apprenticeship model: modeling, coaching, scaffolding, articulation, reflection, and exploration. The learning environment features an exploratory problem context for exploration with authentic problems. The complex process of a diagnostic task is scaffolded by highlighting key actions in clinical examination, intermediate judgment, and diagnostic conclusion. Learners are able to capture and reflect on their problem-solving process. Learners receive coaching via feedback on their performance, which is associated with the expert model that helps learners to determine the gap between their performance and the expert performance. Based on experience over multiple cases, learners are encouraged to articulate the knowledge underlying the problem-solving process.

Participants

Twenty-five Year 4 students from a public medical college participated in the study. The participants had basic knowledge and skills needed for clinical reasoning and diagnosis.

Learning task

The participants used the proposed learning environment to complete five simulated glaucoma cases. The task process was designed to mirror clinical encounters in that learners were given incomplete information about a problem and had to collect further information by selecting clinical examinations and making intermediate judgments based on the examination results in several rounds before reaching a diagnostic conclusion.

Students could diagnose a case more than once. After each diagnosis, they could review their diagnostic process in a visual format, and receive feedback about the degree of similarity between their performance and that of the expert. Moreover, as noted earlier, in due course the learner was able to view the expert's diagnostic process and summary of the key points and common errors in case diagnosis. After accomplishing all of the cases, the learner was encouraged to externalize the subject-matter knowledge underlying the diagnostic processes of all of the cases in a mental map using a diagram tool provided by the system.

Procedure

The learning program lasted for six weeks. In the first week, students signed the consent forms for their participation in the study. A questionnaire survey was then administered to the participants to collect their demographic data. A pre-test was also administered to assess their subject knowledge, and they were provided with a clinical case to assess their diagnostic problem-solving performance. Students were then given a face-to-face, one-hour introduction on how to use the system to perform diagnostic problem solving and reflective learning with clinical cases. A sample case was used to demonstrate the learning process, and to enable students to practice and become familiar with the learning environment.

Students started their self-directed learning in the second week. They were asked to complete five simulated cases within four weeks. They were advised to pace themselves, and spend three to four hours per case. During the task period, there was no teacher involvement except for assistance with technical problems. Students could use online forums for flexible discussion and communication with other participants.

In the sixth week, a post-test was arranged with students to assess their knowledge achievement, and a clinical case was administered to assess their diagnostic problem-solving performance. A questionnaire survey was administered to collect students' perceptions of the learning environment and the cognitive strategies supported by the learning environment, in addition to students' motivation for learning. A semi-structured written interview was used to collect students' comments and feedback about the learning program by requiring students to write the responses on the paper.

Measures

The learning outcomes were assessed using subject knowledge tests and diagnostic problem-solving tasks before and after the learning program, and a questionnaire survey and semi-structured written interview at the end of the study.

Pre-test questionnaire

The pre-test questionnaire was used to collect students' gender and self-assessment of their computer skills (very poor, poor, intermediate, good, very good) and intention to use computer-assisted learning applications (from strongly disagree to strongly agree).

Post-test questionnaire

The post-test questionnaire was used to collect students' perceptions of the learning system and the cognitive strategies supported by the learning system, and students' motivation for learning using the proposed approach. The survey used a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). The items measuring learner perceptions of the learning environment were adapted from widely used information technology acceptance instruments (Arbaugh, 2000; Davis, 1989). These items measure students' perceptions of the learning system in terms of usefulness, ease of use, and intention to use. Examples of the items include "The system is useful for my learning," "The system is easy for me to use," and "I have an intention to use the system."

The items measuring learners' perception of the cognitive strategies supported by the learning environment were 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 six subscales: modeling, coaching, scaffolding, articulation, reflection, and exploration. The validity and reliability of the instrument has been well established (Stalmeijer, Dolmans, Wolfhagen, Muijtjens, & Scherpbier, 2008; 2010). Examples of the 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."

The instrument for evaluating motivation developed by Keller (2010) was adapted to measure student motivation for learning using the proposed approach. The instrument involves four scales including attention, relevance, confidence, and satisfaction. Examples of the items include "The learning program inspires my curiosity," "The learning program is related to my expectations and goals," "I feel confident that I will do well in this learning program," and "I feel satisfied with what I learnt from this program."

Knowledge tests

The knowledge achievement made by students was assessed before and after the study using two traditional knowledge tests (pre- and post-test). Different questions of similar difficulty were used for the two tests. Each test comprised 10 single-choice, 10 multiple-choice, and 10 true-or-false questions. The scores ranged from 0 (incorrect) to 1 (full credit) for each question, with a test range of 0 to 30 rescaled to the range between 0 and 1. All of the questions were selected from the question bank of a medical school. The validity and appropriateness of the test questions and reference answer were endorsed by the two experts. Each test was completed within 45 minutes.

Problem-solving tasks

The problem-solving performance of the participants was assessed before and after the study using two cases at the same level of difficulty. The assessment was based on the degree of similarity between the student's and expert's performance as reflected in their diagnostic records. The assessment focused on three aspects: (1) selection of clinical examinations to collect further information, (2) intermediate judgments based on examination results, and (3) diagnostic conclusion. The performance in collecting the initial information about the case was not taken into account, as all of the learners were given the same original information for each case, which was very limited and useful for diagnostic analysis.

The performance in each of the three aspects was assessed based on the number of valid items, unnecessary items, and missing items in the diagnostic record, defined and specified as follows.

- Valid items are the elements present in the expert's diagnostic record as well as in the learner's diagnostic record.
- Unnecessary items are the elements present in the learner's diagnostic record, but not in the expert's diagnostic record.
- Missing items are the elements present in the expert's diagnostic record, but missing in the learner's diagnostic record.

Tversky's (1977) contrast formula was used to measure the degree of similarity between the student's performance and the expert's performance in each of the three aspects, such that performance in each aspect is determined by the following formula.

$$\frac{\text{Number of valid elements}}{\text{Number of valid items} + 0.5 * \text{Number of unnecessary items} + 0.5 * \text{Number of missing items}}$$

The average score of the three scales represents the overall problem-solving performance. Therefore, the similarity scores ranged from 0 (indicating the diagnostic records are totally different) to 1 (indicating the diagnostic records are identical).

Two assessors who were blind to student identification and test information (i.e., pre- or post-test) appraised the diagnostic records independently. One rater graded the test papers and diagnostic records with reference to expert solutions, while the other checked and confirmed the grades. Any disagreements arising during the process were resolved through discussion.

Semi-structured written interview

The interview was used to collect students' comments and feedback on the learning program by requiring students to write the responses on the paper. The interview included two open-ended questions: (1) the strengths and weaknesses of the learning program and (2) suggestions for improving the learning program.

Results

All 25 students (12 males, 13 females) completed the study. Most had between intermediate (48%) and good (40%) computer skills, and none self-reported as poor computer users. Consistent with this, most of the participants showed a positive intention (agree 56%, strongly agree 32%) to use computer-assisted learning applications.

Questionnaire survey

Perceptions of the learning environment

The participants reported positive perceptions of the learning system in terms of its usefulness (Mean = 4.08, *SD* = 1.11), the ease of use of the system (Mean = 4.14, *SD* = .92), and their intentions to use it (Mean = 4.06, *SD* = 1.01). An internal consistency analysis using Cronbach's alpha confirmed that all of the subscales were reliable (.93 for usefulness, .91 for ease of use, and .94 for intention to use).

Perceived cognitive strategies

The participants had positive perceptions about the cognitive strategies supported by the learning environment in terms of modeling (Mean = 4.21, *SD* = .94), coaching (Mean = 4.21, *SD* = .93), scaffolding (Mean = 4.16, *SD* = .99), articulation (Mean = 4.13, *SD* = .94), reflection (Mean = 4.09, *SD* = .90), and exploration (Mean = 4.08, *SD* = .90). An internal consistency analysis using Cronbach's alpha confirmed that all of the subscales were reliable (.97 for modeling, .97 for coaching, .97 for scaffolding, .96 for articulation, .95 for reflection, and .96 for exploration).

Table 1. Correlations between perceptions of the learning system and perceptions of cognitive strategies (n = 25)

	Modeling	Coaching	Scaffolding	Articulation	Reflection	Exploration
Usefulness	0.812^{**}	0.895^{**}	0.903^{**}	0.853^{**}	0.784^{**}	0.855^{**}
Ease of use	0.921^{**}	0.951^{**}	0.916^{**}	0.861^{**}	0.862^{**}	0.889^{**}
Intention to use	0.880^{**}	0.932^{**}	0.907^{**}	0.854^{**}	0.897^{**}	0.882^{**}

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

The correlations between the learners' perceptions of the overall learning environment and their cognitive strategies were analyzed using Spearman correlation coefficients. As shown in Table 1, learners' perceptions of the GDeL environment were significantly correlated with their perceptions of the cognitive strategies supported by the GDeL environment. In particular, the scaffolding strategy supported by the system was most highly correlated with the perceived usefulness of the GDeL system, while the coaching strategy supported by the system was most highly correlated with the perceived ease of use of the system and intention to use it for learning.

Motivation to learn

The participants had a clear motivation to learn using the proposed learning environment, as shown by the scales of attention (Mean = 4.11, *SD* = .98), relevance (Mean = 4.12, *SD* = .96), confidence (Mean = 4.13, *SD* = .96), and satisfaction (Mean = 4.08, *SD* = .99). As shown by the data, students had a strong interest in learning using the proposed approach, and felt that the learning program was highly relevant to their expectation. Moreover, they felt confident during the learning program, and were satisfied with the learning experience. An internal consistency analysis using Cronbach's alpha confirmed that all of the subscales were reliable (.96 for attention, .96 for relevance, .97 for confidence, and .97 for satisfaction).

Knowledge tests

The students had significantly improved subject knowledge after completing the learning program (Pre-test: Mean = .48, *SD* = .08; Post-test: Mean = .60, *SD* = .09; $p < .001$).

Problem-solving tasks

As shown in Table 2, students made significant progress in all subscales of problem-solving performance after the learning program. From pre- to post-test, the mean value increased from .38 to .67 on selection of clinical examination to collect further information, from .18 to .54 on intermediate judgment based on examination results, and from .08 to .40 on diagnostic conclusion. Consequently, the mean value of overall problem-solving performance increased from .21 to .54. Their performance on intermediate judgment based on examination results improved the most, as depicted in Figure 5.

Table 2. Descriptive statistics and the paired-sample t-test for problem-solving tasks (n = 25)

Scales		Descriptive statistics				Paired sample *t*-test		
		Pre-test		Post-test		*t*	*df*	*p*
		Mean	*SD*	Mean	*SD*			
Clinical examination	Number of valid items	1.76	.72	3.36	.86	-7.16	24	$.000^{***}$
	Number of unnecessary items	4.32	1.35	2.80	1.66	3.48	24	$.002^{**}$
	Number of missing items	1.24	.72	.64	.86	2.68	24	$.013^{*}$
	Similarity to expert	.38	.15	.67	.19	-5.41	24	$.000^{***}$
Intermediate judgment	Number of valid items	.80	.76	2.60	1.00	-8.05	24	$.000^{***}$
	Number of unnecessary items	5.28	1.54	3.72	1.82	3.21	24	$.004^{**}$
	Number of missing items	1.24	.72	.64	.86	2.68	24	$.013^{*}$
	Similarity to expert	.18	.17	.54	.20	-7.32	24	$.000^{***}$
Diagnostic conclusion	Number of valid items	.08	.28	.40	.50	-2.87	24	$.008^{**}$
	Number of unnecessary items	.92	.28	.60	.50	2.87	24	$.008^{**}$
	Number of missing items	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Similarity to expert	.08	.28	.40	.50	-2.87	24	$.008^{**}$
Overall		.21	.14	.54	.18	-6.46	24	$.000^{***}$

Note. $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$.

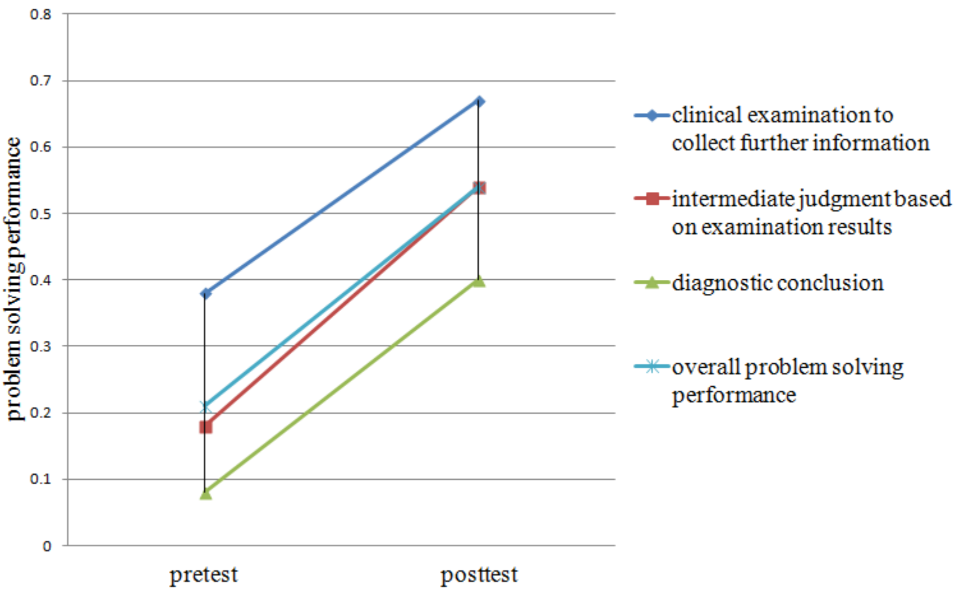

Figure 5. Differences in problem-solving performance between pre- and post-test

Semi-structured interview

The comments shared by students in their responses are presented in Table 3. In terms of strengths of the proposed learning program, almost all of the participants reported that the online learning program provided them with plenty of flexibility and convenience in learning. Most found the learning system easy to use and supportive for self-directed learning and practice with the support of expert feedback. Many students enjoyed building a mental map to represent their knowledge underlying the diagnostic tasks, which made their knowledge more solid and systematic. Accordingly, students commented that the learning program was helpful for improving their subject knowledge and diagnostic problem-solving capability. The participants also mentioned weaknesses of the learning program and provided relevant suggestions for improvement. First, they mentioned that more learning materials, particularly multimedia learning content (e.g., videos for clinical examinations) and diversified exercises (e.g., short questions) for self-practice could be added to the system. Second, students suggested including more learning cases into the online learning system for self-directed learning and practice. Third, they reported that some operations of the system (e.g., the diagram tool building mental maps) were complicated and could be simplified.

Table 3. Students' responses to semi-structured interview questions

Students' comments	Count
Strengths of the learning program	
Plenty of flexibility in learning, without time and space constraints.	24
The learning system is easy to use.	16
Expert support is helpful for self-directed learning and practice.	13
Constructing the knowledge in a mental map is helpful for thinking and learning.	12
Improving my subject knowledge, making my understanding more solid and systematic.	11
Enhancing my diagnostic problem-solving capability.	10
Weaknesses of the learning program	
Some functions of the system are complicated, e.g., the diagram tool for building mental maps.	7
Inadequate learning cases.	4
Inadequate learning materials.	3
Suggestion for improving the learning program	
Inclusion of more diversified learning materials (e.g., videos for clinical examinations, short questions for self-practice).	7
Inclusion of more learning cases.	4

Discussion

Design of the model-based learning environment

The proposed GDeL environment is characterized by: (1) an authentic problem-solving experience in a simulated environment, (2) a complex process made accessible to students, and (3) the provision of expert support. The design is supported by the model-based learning approach: students are free to capture and reflect on their own models or task processes; meanwhile, the expert model is externalized to support and guide students to develop expert performance. The proposed design is aligned with the cognitive apprenticeship model. The learning environment involves an exploratory problem context for exploration with authentic problems. The complex process of diagnostic problem solving is scaffolded by highlighting its key actions involving clinical examination, intermediate judgment, and diagnostic conclusion. Learners are encouraged to capture and reflect on their problem-solving process during the task. Coaching is provided to individuals via feedback on their performance, which is associated with the expert model that helps learners to determine the difference between their performance and expert performance. Finally, based on the experience with multiple cases, learners are encouraged to articulate the knowledge underlying the problem-solving process.

Effects on learner perceptions and motivation for learning

Learners felt that the proposed GDeL environment was useful and easy to use. As a result, they reported a clear intention and motivation to use this approach. The participants also had positive perceptions of the cognitive strategies supported by the learning environment. Moreover, learners' perceptions of the learning environment were significantly correlated with their perceptions of the cognitive strategies supported by the learning environment. Similar findings have indicated that instructional design is an essential factor that can influence learner satisfaction and acceptance of e-learning environments (Swan, 2001; Wang et al., 2013).

Interview results supported the above findings. Learners found the GDeL system helpful in improving their subject knowledge and diagnostic problem-solving capability, and enjoyed the self-directed learning afforded by the expert support from the system and the online learning mode. In addition, students enjoyed using the diagram tool to build a mental map to represent their knowledge underlying their diagnostic processes. They found the mental mapping activity helpful for improving their thinking and systematic understanding. Similar findings have demonstrated that student learning outcomes in problem-solving contexts can be significantly improved when learners are able to externalize the complex problem-solving process and the knowledge underlying the task process with the support of computer-based cognitive tools (Wang et al., 2013; Wu et al., 2016).

Effects on knowledge achievement and problem-solving performance

After completing the learning program, the students had significantly improved subject knowledge and problem-solving performance in selecting clinical examinations to collect further information, making intermediate judgments based on examination results, and drawing diagnostic conclusions. The results are consistent with the perceived learning gains in subject knowledge and diagnostic problem-solving capability the students reported in interviews. Students' achievements also echoed their comments on the benefits of expert support for the learning system and the advantage of constructing the mental map to articulate their underlying knowledge on the diagnostic tasks. The findings demonstrate the effects of model-based learning, which can be attributed to the representation of mental models and cognitive processes as well as the use of expert models to improve student performance. The findings align with the results of related studies (e.g., Ifenthaler, 2009; Schwarz, 2009).

Conclusion

Effective learning through problem solving is difficult to realize because learning in such contexts involves complex processes. Many learners tend to engage in surface rather than deep learning towards an in-depth understanding of the problem. Deep learning is characterized by a high level of engagement in learning driven by intrinsic motivation and more importantly supported by effective learning approaches or strategies that allow learners to manage complexity and key challenges (most on cognitive aspects) to sustain engagement and achieve a high level of understanding and performance (Wang, Kirschner, & Bridges, 2016). Owing to a lack of studies on how deep learning can be adequately empowered in complex problem contexts, the design and implementation of problem-oriented learning has been considerably dependent on the instructor's personal experience (Henry, Tawfik, Jonassen, Winholtz, & Khanna, 2012). Recent research has highlighted and demonstrated the importance of making thinking visible in complex situations, with a focus on self-constructed mental models or processes for deep learning and self-reflection by learners. With limited problem-solving capability and practical experience, it is still difficult for novices to develop expert-like performance without necessary support.

This study explores the design and effects of a model-based learning approach implemented in a web-based learning environment that allows learners to capture and reflect on their problem-solving process in visual formats as well as identify the gap between their performance and that of the expert when working with a number of clinical cases. The proposed approach attempts to utilize expert knowledge to transform open-ended problem-solving experience into a systematic and deliberate effort towards expertise development. The results show that the approach has promising positive effects on students' achievements in subject knowledge and problem-solving performance and their perceptions and motivation for learning using the proposed learning environment. The effects of the proposed will be further examined by a control group design in a future study.

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