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Research on Cognitive Load Theory and Its Design Implications for Problem Solving Instruction*

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The purpose of this study was to develop the problem solving instruction facilitating novice learner to represent the problem. For the purpose, we mainly focused on three aspects of problem solving. First, learner should represent the targeted problem and its solutions for problem solving. Second, from crucial notions of cognitive load theory, learner's mental load should be optimized for problem representation. Third, for optimizing students' mental load, experts may support making their thinking more visible and mapping from their intuition to expert practice. We drew the design principles as follows. First, since providing worked examples for the targeted problem has been considered to minimize analogical errors as well as reduce cognitive load in problem representation at line of problem solving and instructional research, it is needed to elaborate the way of designing. The worked example alternatively corresponds to expert schema that consists of domain knowledge as well as strategies for expert-like problem representation and solution. Thus, it may help learner to represent what the problem is and how to solve it in problem space. Second, principle can be that expert should scaffold learner's self-explanations. Because the students are unable to elicit the rationale from worked example, the expert's triggering scaffold may be critical in that process. The unexplained and incomplete parts of the example should be completed not by expert's scaffold but by themselves. Critical portion of the expert's scaffold is to explain about how to apply and represent the given problem, since students' initial representations may be reached at superficial or passive pattern of example elaboration. Finally, learner's mental model on the designated problem domain should be externalized or visualized for one's reflection as well as expert's scaffolding activities. The visualization helps learner to identify one's partial or incorrect model. The correct model of learner could be constructed by expert's help.

Keywords : problem representation, cognitive load, worked example, self-explanation, scaffolding, externalization

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Introduction

For both school education and industrial training, problem solving skills have been considered as one of the most critical capabilities for their processes. The first and important step of problem solving processes is the problem representation, that learner must accurately represent the given problem, solution steps, and the solutions in problem space(Bruer, 1993; Chi, Glaser, & Rees, 1982; Feltovich, Spiro, Coulson, & Feltovich, 1996, Kim, 1992).

In this paper, we reviewed related researches on supporting strategies of problem representation. Secondly, from lines of self-explanation research(Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Stark, Mandl, Gruber, & Renkl, 2002) and externalization principles perspectives(Bell, 2002; Suthers & Hundhausen, 2002), we draw design principles for supporting learner to represent a problem in computer based instruction.

Review on the Studies of Self-Explanation and Externalization

Problem solving and example-based learning

Problem solving researchers have been noted that there are qualitatively enormous differences between expert and novice problem solving performances from their expert-novice comparison studies. Those differences correspond to amount of time to search solutions, the number of errors, inappropriate problem representation in terms of the given states, goal states and inefficient uses of cognitive or metacognitive strategies. The most noticeable difference between the expert and the novice is the initial representation in problem space, which can be a significant breakthrough for generating solutions as well as monitoring problem solving process.

Learner might acquire problem solving skills in various domains by the analogy process(Chi & Bassok, 1989; Renkl, Stark, Gruber, & Mandl, 1998). Experts could precisely represent the targeted problem and its solutions by analogizing the correct mental model in the well- or ill-defined problems. But novice often makes the analogical errors due to connecting given problem state and one's intuitive thinking or preconception(Anderson, 1989; VanLehn & Jones, 1993). In these processes, because (s)he doesn't know how to manage self-repair errors, expert's helps regarding how to do them are seriously demanded.

One of the expert's helps may be accomplished by providing the worked-out example(WOE). To minimize analogical errors, it has been researched about the example-based learning in various domains. The worked example comprises a given problem, solving procedures, and the final solution as the specification for solving the problem. Novices try to relate the problem to be solved with the worked example. The use of expert schema reduces analogical errors and increases the success possibility of problem representation(Anderson, Fincham, & Douglass, 1997; Anderson, Greeno, Kline, & Neves, 1981; Atkinson, Derry, Renkl, & Wortham, 2000). According to the empirical evidences on worked example, the experimental group focused on the deep structure of the problems, used effective problem solving strategies, and successfully solved the problem. The control group focused on the surface structure of the problems depending on mainly a weak problem solving strategy such as means-ends analysis(Cooper & Sweller, 1987; Ward & Sweller, 1990; Zhu & Simon, 1987).

Despite the fact that the worked example has been shown to be useful strategy, it does not always guarantee successful problem representation. The learner characteristics have an effect on the example processing patterns(Chi & Bassok, 1989; Chi et al., 1989; Chi & VanLehn, 1991; Renkl, 1997). The example elaboration has the self-generated, active, reactive and shallow features(Renkl, 1997; Stark et al., 2002). Although learner should actively engage in making the mental effort to represent a problem, most of them passively or superficially elaborate example, and accordingly result in poor performance(Atkinson et al., 2000; Renkl et al., 1998).

The relations of problem representation and self-explanation: from cognitive load theory perspectives

The mental effort is the aspect of cognitive load that is actually allocated to the task that determines the success of an instruction intervention. The amount of mental effort dedicated to a particular task may affect cognitive processing patterns, which is measured by cognitive load. According to cognitive load theory(CLT), mental effort reflects example processing behavior. That is, the learner's active elaboration activities need mentally demanding. After all, learner should put more efforts into the example elaboration for problem representation.

CLT discerns among three types of cognitive load. Germane cognitive load(GCL) refers to demands placed on working memory capacity that is imposed by mental activities. This load contributes directly to problem solving skills acquisition(Kim, Kim, Rho, & Kim, 2005; Sweller, van Merrienboer, & Paas, 1998). Intrinsic cognitive load(ICL) is the portion of load that is imposed by inherent nature of the task. And extraneous cognitive load(ECL) is the burden resulting from poorly designed instruction. Both ICL and ECL is ineffective load.

The studies of strategies to decrease ECL or ICL for increasing GCL were largely investigated. Recently, some related studies(Paas, Renkl, & Sweller, 2004), where GCL was increased when it was considered directly relevant to schema construction, was reported. The reduction of ICL or ECL results in unused working memory capacity. Although ICL or ECL decrease presumably encourages conscious cognitive processing, the unused working memory space guarantees GCL increasing and is not directly relevant to build on mental model(Kirschner, 2002; Paas, Renkl, & Sweller, 2004). Therefore, we focuse on cognitive load directly relevant to example elaboration(Kalyuga, Ayres, Chandler, & Sweller, 2003).

The relationship between example elaboration behaviors and cognitive load in cognitive skills acquisition step is shown in figure 1(Gerjets & Scheiter, 2003). In initial phase, learner has more or less mental load due to ICL or ECL imposed by expertise level, task complexity, and instructional design. During intermediate stage, learner attempts to understand the given problem task with worked example. The worked example consists of a problem formulation, solution steps, and final solution. The learner has to actively self-explain the rationale of solutions from example, and it results in reducing ECL and increasing GCL. After problem representation using specific pattern of example elaboration, the learner's GCL or ECL goes up or down. Finally, the learner comes into the last stage in which the problem solving skill is acquired.

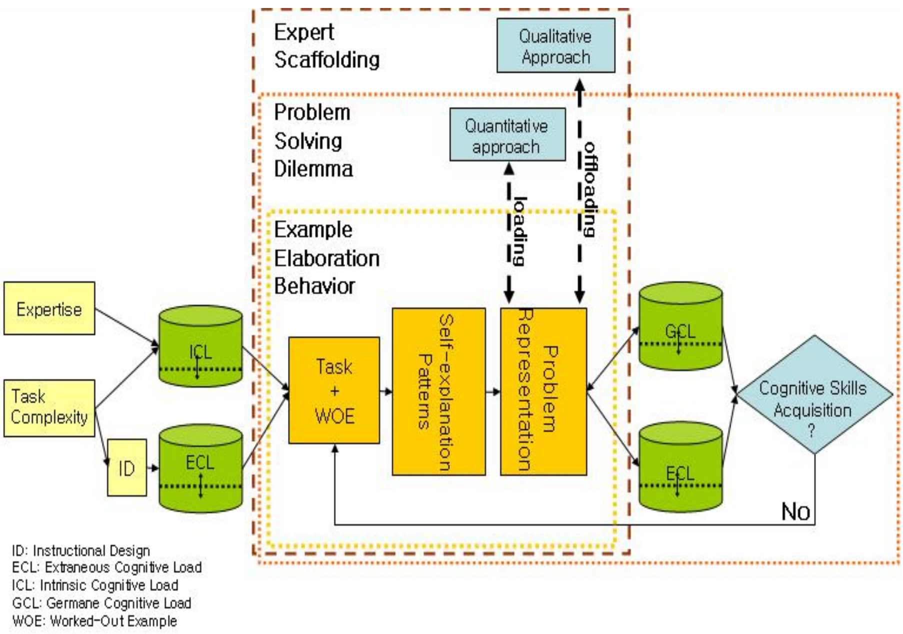

Figure 1. Example elaboration behaviors(self-explanation) and cognitive load
(Revised model based on Gerjets and Scheiter(2003)'s model)

There are various types in example elaboration activity(Renkl, 1997). For example, the type of principle-based explanation is the understanding of an example including expert's systematic approach to problem solving and results in cognitive skills acquisition(Renkl & Atkinson, 2003). But most learners' cognitive processing is very passive and results in the low GCL and failure of problem representation.

A number of approaches have been proposed for promoting learners to self-explain while processing examples(Bielaczyc, Pirolli, & Brown, 1995; Catrambone, 1998; Chi, de Leeuw, Chiu, & LaVancher, 1994; Lin, 1994; Renkl, 1997). These include fostering self-explanations by structural handling, directly training, and reciprocal teaching(Brown & Palinscar, 1989). The purpose of these quantitative approaches is to make learner's self-explaining as many as possible. It is possible imposing additive cognitive load rather than removing ineffective cognitive load under name of helping problem representation. This is called 'problem solving dilemma'.

We focus on the quality of example processing behaviors in order to optimize learner's cognitive load(Renkl & Atkinson, 2003) rather than to increase the number of learner's the behaviors(Chi et al., 1989). To optimize cognitive load, GCL is properly high and the others are set at a minimum level within a limited working memory capacity (Stark et al., 2002). GCL is necessarily required problem representation, but the excessively high GCL as a kind of cognitive load is not helpful for that purpose.

This qualitative approach stands for the mental efficiency which combines the amount of mental effort being exhausted by learners with the level of performance achieved(Sweller et al., 1998). The scaffolded explanation is a kind of qualitative approach(Hausmann, Chi, & Roy, 2004; Ploetzner, Dillenbourg, Praier, & Traum, 1999; Suthers, 1998; van Bruggen, Kirschner, & Jochems, 2002). Learner could explain the worked example with help of expert within ZPD(Zone of Proximal Development)(Vygotsky, 1978), so his(her) cognitive demands for mental integration is offloaded(Zhang, 1997). This might permit the learner to attend to higher-level representation.

Implications from problem solving research

We draw four implications for facilitation of problem representation according to above described discussions. First, we focus on GCL-increasing. Recently, the underpinning of CLT research lies on ECL- or ICL-reduction for generating unused working memory capacity for increasing germane load(Paas, 1992; Sweller, 2003; van Merrienboer, 1997). These approaches are significant efforts, but could not assure the unused working memory capacity for learner in elaborating the material more deeply. In the GCL-increasing approach, the unused working memory capacity will be used for cognitive skills acquisition. Because GCL-increasing directs learner's attention to cognitive processes that are relevant for learning. This approach could be realized by stimulating the learner to self-explain the worked example more actively.

Second, we concentrate on expert's long-term working memory as external memory aid. Novices have little domain-specific principles and robust strategies. If novices are provided the worked example, most of them could hardly self-explain the rationale of solutions due to high cognitive load demands such as means-ends analysis. We could assume that expert may play external memory function for offloading novice's cognitive burden. Student is able to process the worked example effectively explaining the rationale of elaborated solution steps with expert supports(Ericsson & Kintsch, 1995). We review on utilizing the expert's long-term working memory.

Third, learner's internal cognitive activities should be envisioned by some sorts of external representation. For example, the typical types of external representation are diagrams, graphs, and pictures, etc. External pictures could give people accessibility to knowledge and skills that are unavailable from internal representations(Linn & Hsi, 2000). The visualization of mental model could show

how expert thinks about the problem and bridge between novice intuitions and expert disciplinary thinking. Also, the graphical representation could make use of a visuospatial scratchpad component in working memory, which might reduce the working memory load(van Bruggen et al., 2002).

Fourth, we consider mental efficiency. In general, the worked example doesn't give details about how it works and why it works like that. Student should create conjecture rules that are instantiations of principles established in the example(Chi et al., 1989). But, (s)he superficially processes the worked example with high cognitive load resulting from using weak strategy. To optimize the cognitive load, the GCL must be maximized and the others are maintained at a minimum level within a limited capacity of working memory.

In the following section, we examine how to self-explain, scaffold learners, and externalize mental model from a mental efficiency aspect in turn.

Design Principles for Supporting Problem Representation

Design principles of self-explanation

When learner solves a specific problem, self-explanation activity might facilitate him(her) to grasp deep structure related to the problem(Neuman & Schwarz, 1998). In problem solving learning, learner tries to reason the common features of examples through understanding examples. (S)He learns problem solving ability from self-explaining the principles and solutions of the worked example(Renkl & Atkinson, 2003).

Although self-explanation is an essential part in problem solving learning, most of the learners could not do this activity effectively. Learner superficially and passively understands the example owing to cognitive load of working memory. The self-explanation might be considered as a way of reducing learner's ineffective cognitive load. However, self-explanation activity for novice might lead to a cognitive load because novice has little domain knowledge. Therefore, there are a variety of efforts to devise training techniques for the self-explanation.

Considering extraneous burden in working memory, supports have to be offered when learner explains the solution to oneself in self-explanation training. If helps are provided to novice, (s)he could represent a problem in minimum cognitive load. It is important to scrutinize learner's mutual action to do a self-explanation with learning partners. We are drawing design principles which enable novice to do a scaffolded explanation with learning partners.

The cognitive and metacognitive dimensions of self-explanation

As seen in table 1, the design principles of explanation are divided into the cognitive and metacognitive dimension(Chi et al., 1989; Stark et al., 2002). The cognitive dimension of example elaboration activity consists of the principle-centered consideration, goal-operator combination, pattern recognition, and situation elaboration. The metacognitive dimension of explanation is the self-monitoring.

First, in the domain specific principle, self-explanation is designed to help student explicating main principles and concepts from example. The principle-based consideration is beneficial for novice's focal point to transform from surface to deep features of example. Second, in goal-oriented principle, it is designed to help student explaining either goal or goal-operator combination from example. Learner should find out proper solutions using strong strategies. Third, in pattern recognition, it is designed to help student noticing coherence between the examples studied. Learner should represent goal state in problem space applying similar principle and procedure elicited from examples. Fourth, in elaboration of example, it is designed to help student constructing problem situation from example. Learner should generate conjecture and try to associate it with expert practices. Finally, regarding metacognitive control, it is designed to help student working on example information more deeply and intensively. Learner should monitor, reflect, and correct one's example elaboration activity.

Learner's explanations about mapping between intuitive thinking and worked example might be understood as interactivity continuum. Because giving explanations to oneself or to others have different levels of interactivity.

Table 1. Cognitive and metacognitive dimension of self-explanation

dimension	principle	how to use
cognitive	principle-based consideration	the explanation of domain-specific principle by identifying underlying concepts
	goal-operator combination	the explanation either (sub)goal or goal-operator combination by identifying goal achieved by solution steps
	pattern recognition	the explanation of similarities between the present example and a prior example
	situation elaboration	the construction of situation model of the problem
metacognitive	monitoring	the reflection on principles or concepts from example

Interactive dimensions of self-explanation

As noted previously, self-explanation is an individual cognitive processing to elaborate how expert strategically solves a problem and why (s)he makes the decisions from worked example. In that case, learner lacks the background knowledge, (s)he could not learn by the example.

Considered the explanations with learning partners as interactivity continuum, the one extreme is that individual explains to oneself. This interactivity level happens to interact with nobody except example as learning partner(instructional material as expert model)(Dillenbourg, Baker, Blaye, & O'Malley, 1996). The other is that learner co-constructs explanations with peers by negotiating meaning and sharing understanding. This interactivity level happens that people collectively develop the goup expertise. Here, knowledgeable peer is the learning partner.

The some point of interactivity continuum is that the novice explains to oneself or other by expert's scaffolds. That is, self-explanation is largely categorized self-directed explanation, other-directed explanation, and co-construction(Hausmann et al., 2004; Ploetzner et al., 1999). We review the design principles of scaffolded explanation as a kind of other-directed explanation.

Scaffolded Explanation

In general, learner has short-term working memory due to the limited duration and capacity of cognitive processing. Ericsson & Kintsch(1995) recognized that the capacity limitations of short-term working memory might disappear in case of expert. The novice-expert differences result from the capacity limitations of working memory. When dealing with unfamilar information, novice has to remember each element separately which is beyond working memory capability(cognitive overload). When the working memory limitations are irrelevant, it could be described as long-term working memory. Expert's long-term working memory could be used for scaffolded explanation. That is, the unused space of expert working memory is used for instructional guidance of problem representation and facilitation of mental model change.

Table 2 depicts the design principles of scaffolding for guidance and facilitation. First, it is designed (for conceptual change) to promote knowledge integration. To encourage student to coordinate problem related intuitive thinking with worked example, generate working hypotheses, and explain evidences about claims, it is needed supporting tools. The concept map, visual organizer, expert prompts, or rich cases might serve as the mediational means that student could use to construct explicit problem representation. On condition providing tool to student, it should be considered to minimizing the extraneous cognitive load(van Merrienboer, Kirschner, & Kester, 2003)

Second, it is designed to justify evidence-based explanations. To further student to apply one's experiences to practices, it is needed externalization of thought experiment and simulation of externalized process(Linn & Hsi, 2000). Also, student should be given feedback concerning one's explanations.

Table 2. The design principles of scaffolding

principle	how to use
promote knowledge integration	providing tools, cases, prompts to minimize extraneous cognitive load
facilitate applying integrated knowledge to practices	structuring cognitive processing based on underlying concept providing feedback

The design principles of externalization

To scaffold novice's problem representation, expert should evaluate and advise one's externalized explanations. And novice should externalize one's thinking in problem space, compare one's model with expert model(worked example), and modify one's model. They share and refer to each other's mental models by externalization in shared problem space(Bell, 2002).

The externalization design principles(see table 3) illustrate cognitive, social, and evaluative dimension for shared representation(Suthers, 1998; Suthers & Hundhausen, 2002). First, in cognitive dimension, it is designed to record individual conceptual change. Learner's explanations should be externalized by keeping track of what (s)he has done and what (s)he has to do. The conceptual progress including history and future agenda provides scaffolds information to expert and state of knowing to novice. Second, in social dimension, it is designed to assist collaboration. Sharing tasks and referring to each other's ideas during interaction should be visualized by artifacts(symbol or diagram)(Hewitt, 2002). Third, in evaluative dimension, it is designed to provide advices or assessment to learner. Learner could self-correct one's own model comparing with expert model. Also expert could estimate and correct novice's externalized mental model.

Table 3. Design principles of externalization

dimension	principle
cognitive	tracking conceptual progress including history and future agenda
social	sharing tasks and ideas by artifacts
evaluative	assessing cognitive process and understanding level, self-refining and evaluation

The Development of Problem Solving Instruction

We have drawn several design principles based on self-explanation, scaffolding and externalization in order to support novice who could not explain from the worked example in problem solving. We examined how these principles could be represented in the learning program, '‡ Interbreeding Pea Plants with Mendel(IPPM)'.

IPPM was developed for the third grade of middle school students to learn the Mendel's Law. This program starts with a scene that Dukong(novice) wonders why he doesn't take after parents during looking at a family picture. This experience could help him(her) to connect his(her) intuitive thinking with expert model(Mendel). Dukong could conduct an experiment with simulated expert's help. (S)He guesses the types of seeds, flowers, and trunks of pea plants that are cross-fertilized. To prove working hypothesis, (s)he tries to make an experiment on Mendel's Law and learns the heredity.

The self-explanation principle is applied to following the figure 2 and 3. Figure 2 illustrates the screens for developing his(her) principle-based consideration and

‡ This program was developed by Hanyang University undergraduate students using Macromedia Director, Adobe Photoshop and etc.

pattern recognition in cognitive dimension. In the upside of figure 2, (s)he considers the heredity principles in setting up a hypothesis and explaining the reasons. (S)He is required to explain the heredity patterns in choosing two of pea plants having allelomorph in the downside of figure 2.

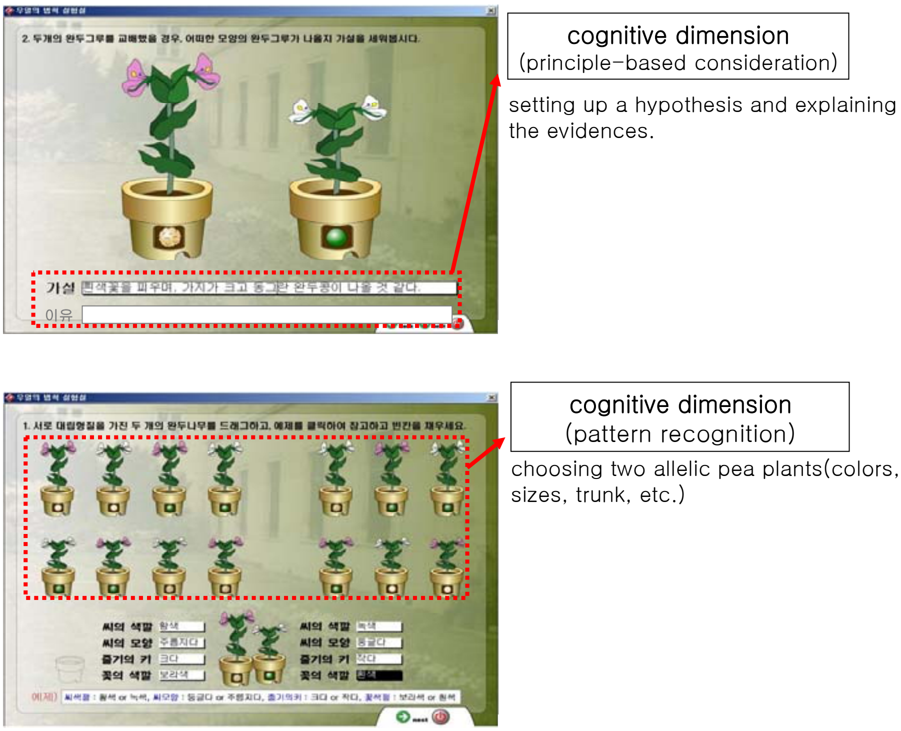

Figure 2. Screens applied to self-explanation principle

Figure 3 shows the screen for goal-operator combination and situation elaboration in cognitive dimension, and monitoring in metacognitive dimension. It provides the hypothesis including a goal-operator combination and the allelomorph of the chosen pea plants to him. He could reflect the differences between his hypothesis and the results of experimental process.

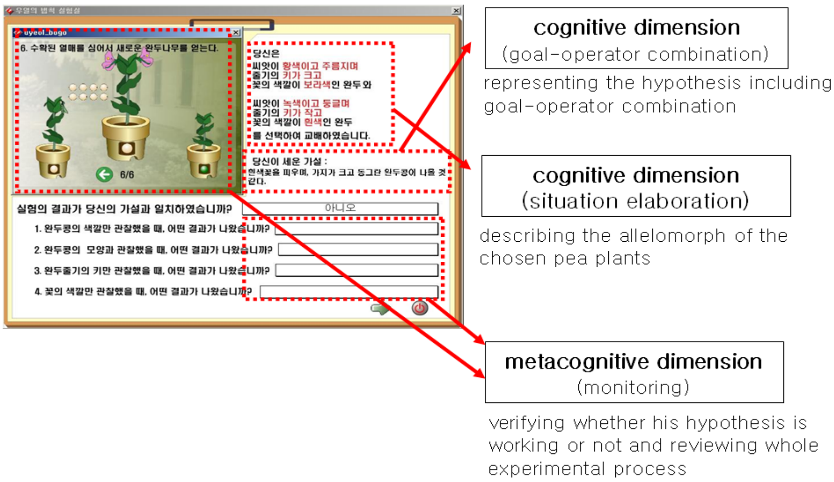

Figure 3. Screen applied to self-explanation principle

Screens shown from figure 4 to figure 7 are to embody scaffolding principles. Figure 4 is to refine intuitive thinking through experiment with tools and offer the expert's mental model.

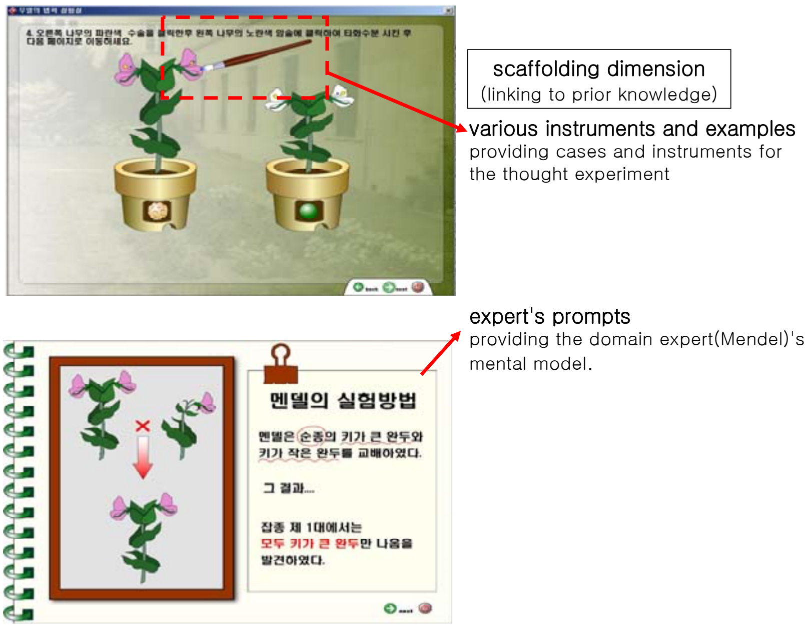

Figure 4. Screens applied to scaffolding principle

In figure 5, extraneous cognitive load is minimized by physically integrating the space for experiment and setting up a hypothesis. Based on the hypothesis, the expert diagnoses his(her) state of knowing and cognitive load, and then help him(her) during the experiment.

scaffolding dimension
(linking to prior knowledge)

providing scaffolds according to the state of knowing and cognitive load based on his(her) hypothesis.
integrating the physical space for an experiment and a hypothesis to reduce the cognitive load .

Figure 5. Screen applied to scaffolding principle

Figure 6 illustrates the screens for verifying whether the hypothesis is working or not. (S)He could observe what kinds of pea plants appear by raising the peas derived from cross-fertilization.

scaffolding dimension
(applying to a real case)

externalization of mental model
externalizing Dukong's mental model through the experiment.

simulation
choosing two pea plants, cross-fertilizing the selected ones, and then observing the result in the simulation.

Figure 6. Screens applied to scaffolding principle

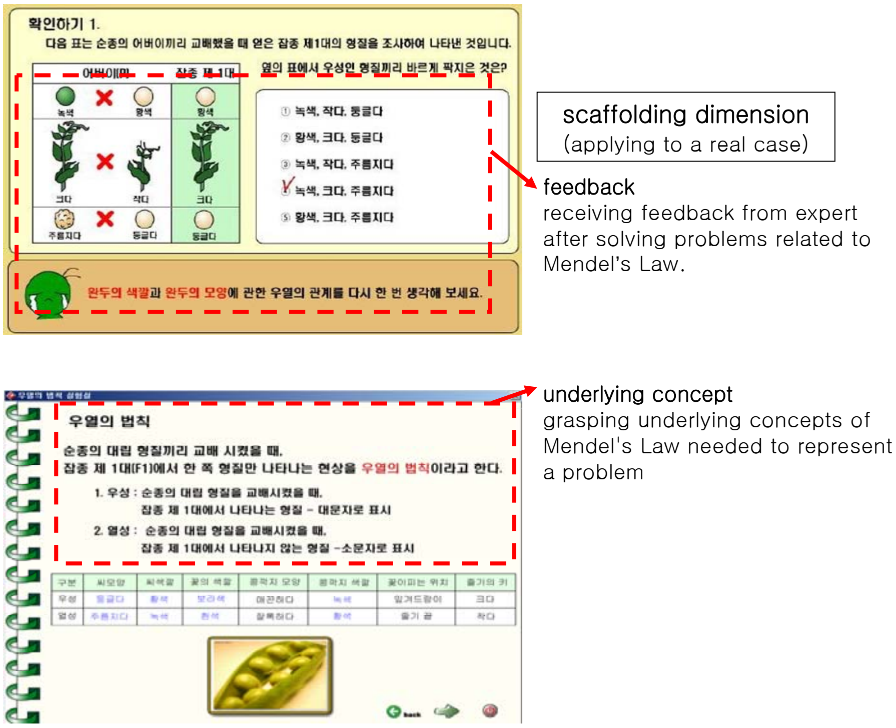

Figure 7. Screens applied to scaffolding principle

Screens shown in from figure 8 to figure 10 are for the externalization principles to visualize Dukong's mental model. Figure 8 shows the screens for externalization principles in the cognitive dimension. It allows him to review the whole experimental process and provides explicitly the problems to be solved.

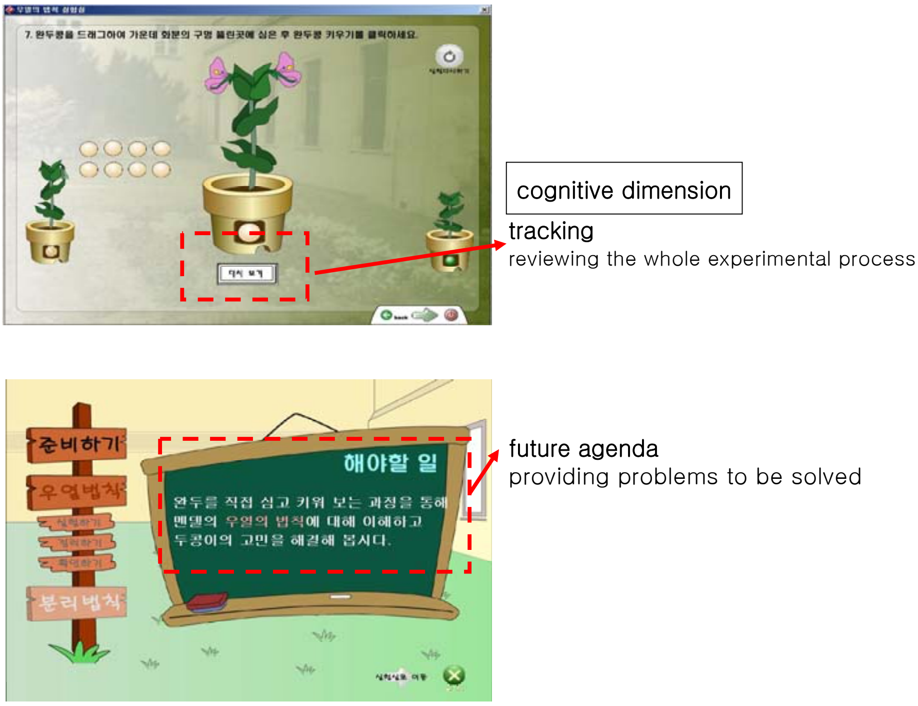

Figure 8. Screens applied to externalization principle

Figure 9 shows the screens for externalization principles in the social dimension. We provide problems and the expert's mental model to Dukong. (S)He shares with a computer-generated expert, Mendel.

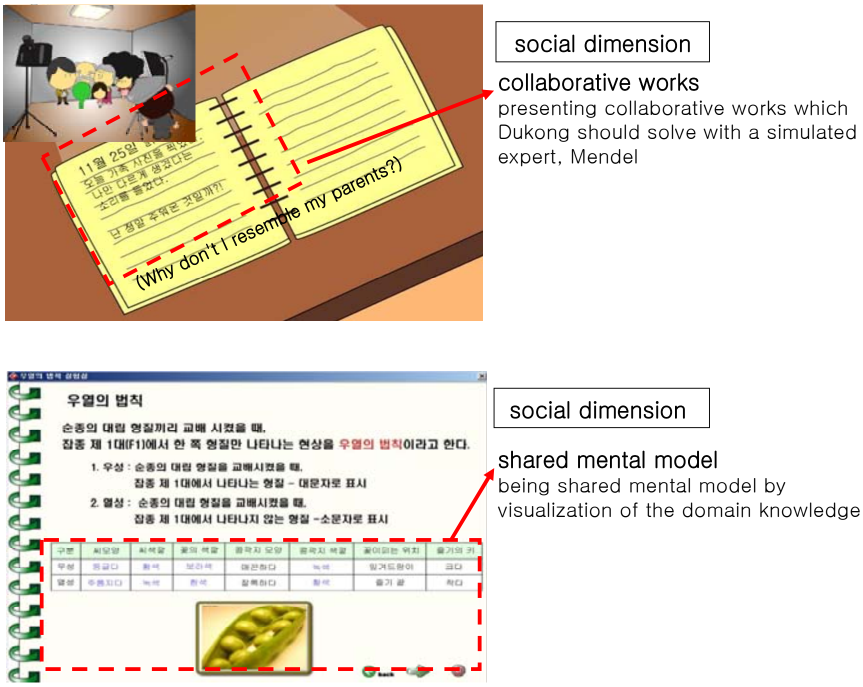

Figure 9. Screens applied to externalization principle

Figure 10 shows the screen in the evaluative dimension. After solving problems, Dukong writes down reflective thinking on a note and receives the feedbacks from expert.

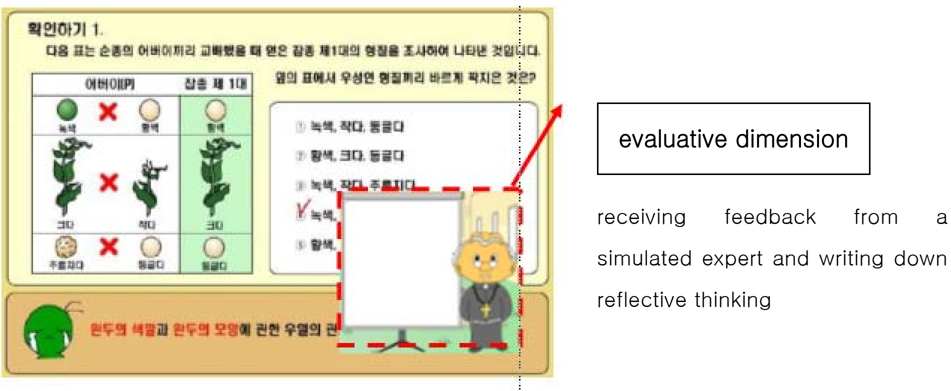

Figure 10. Screen applied to externalization principle

Conclusions

To support the problem representation, the followings should be considered.

First, self-explanation is needed for the learner to reason about the rationale from the worked example. When (s)he tries to connect one's own intuitive thinking to the problem, the analogical errors occur. To reduce the errors, the worked examples which include the expert's solution have to be provided. By providing the worked examples which contain enough domain knowledge and strategies, it could be helpful for novice to represent a problem and reduce cognitive load.

Second, expert's scaffolding is needed for the learner to elaborate the unexplained parts of the example. Although the learner has to make a mental effort to represent a problem, (s)he is unable to elicit the rationale from the worked example. Expert should scaffold learner's self-explanations. Critical portion of the expert's scaffolding is to explain about how and why information.

Third, when learner represents a problem, one's mental model is to be externalized. If novice expresses an intuitive thinking related to the problem using graphic or text, an expert could diagnose the current level of the novice and offer scaffolding to him(her). Learner has a chance to refine mental model and transforms one's intuitive thinking into expert-like mental model.

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