What Do You Mean by to Help Learning of Metacognition?

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Abstract. Several computer-based learning support systems and methods help learners to master metacognitive activity. Which systems and methods are designed to eliminate which difficulties associated with the learning of metacognitive activity through its clear specification? We adopt a method in our research that supports learning by eliminating salient difficulties. We believe that it is possible to eliminate or decrease them through appropriate design only after specifying those difficulties associated with learning. In this study, we analyze difficulties in performing cognitive activity, distinguish factors of difficulty from other factors, and construct our framework, which represents difficulties in performing metacognitive activity. Finally, we organize existing support systems and methods based on that framework.

1. Introduction

Several kinds of methods support learning. One kind divides a learning process whose grain size is large into two or more sequential steps, such as getting learner motivated, providing necessary knowledge about it, showing how to use it, and asking the learner to follow these steps in order. Such a method helps learners learn by reducing their cognitive load because it distributes that load among two or more steps. Another kind of method supports learning by eliminating an essential difficulty associated with the learning of interests. We adopt this latter method in our research. First, we specify difficulties associated with learning because we believe that it becomes possible to design how to eliminate or decrease them only after specifying such difficulties.

Recently, several computer-based learning support systems and support methods have been proposed. They help learners master metacognitive activity. It is worth investigating whether or not these systems and methods are designed to eliminate difficulties associated with the learning of metacognitive activity through its clear specification. The concept of metacognitive activity is vague [3, 23]. Several terms are currently used to describe the same basic phenomena (e.g., self-regulation, executive control), or aspects of those phenomena (e.g. meta-memory)[19]. Moreover, these terms are often used interchangeably in the literature [3, 5, 7, 8, 9, 11, 21, 22, 23, 26, 32, 35]. To further complicate matters, two approaches to metacognition exist. On one hand, some researchers consider metacognitive activity as something different from the cognitive activity and attempt to clarify its mechanism [26, 29, 21, 26]. On the other hand, some researchers suppose that metacognitive activity is a similar process to cognitive activity [23, 24]. Such confusion shows that many interpretations of metacognitive activity exist, thereby creating a situation in which difficulties in mastering metacognitive activity are not specified well. Let us take two examples. One example is that the target of a support system changes from the first version and the second version, whereas the authors claim each of them supports mastering metacognitive activity without making the change explicit[11]. The second example is that in spite of the fact that the targets of support are different from one another, the support methods share the same objective. Reciprocal Teaching [4, 27] and ASK to THINK – TEL WHY [21] have the same method and objective: reciprocal tutoring and help of mastering metacognitive activity. By analyzing the learner's cognitive activities when the learner plays a tutor role in both methods, we can see that Reciprocal Teaching causes the learner to observe "the learner's own problem solving process" and ASK THINK to THINK – TEL WHY causes a learner to observe "other learners' problem solving processes." Thus the learner's cognitive activities when playing a tutor role in Reciprocal Teaching and ASK to THINK – TEL WHY vastly differ from each other, even though they both claim to support learning of "metacognition".

Under this situation in which researchers share little common conception of "metacognition", it is difficult to recognize common properties among existing systems to support learning metacognitive activity and their differences. It is almost impossible to reuse one method across systems. Our objective is to support learners in their mastery of metacognitive activity. First, we investigate metacognitive activity itself, which we should support. It fosters our correct understanding of metacognitive activity. Secondly, we specify the factors of difficulties found in mastering it, then discuss functionality for support in eliminating them. We require a framework that represents metacognitive activity from the viewpoint of its difficulty in mastering it. Thereby, we can specify the factors of such difficulties. Using the framework, we can organize existing computer-based support systems and support methods and can understand common and reusable features across systems. However, we do not intend to claim that our framework is valid in terms of cognitive psychology. We provide a common framework for discussing the particularity of each computer-based support system from a technological point of view. Supporting a learner in an attempt to master metacognitive activity would be meaningful if we could gain useful information, based on our framework, for building a computer-based learning support system.

This paper is organized as follows. After analyzing difficulties in performing cognitive activity and distinguishing the factors of that difficulty from others, we construct our framework, which represents metacognitive activity from the viewpoint of the difficulty in mastering it. Finally, we organize existing systems and methods based on that framework.

2. Analyzing Factors of Difficulty in Performing Cognitive Activities

What causes difficulty in performing metacognitive activity? To answer this question, we assume the consideration of metacognitive activity by Lories et al. [24]: 'metacognitive activity processes the contents of (working) memory by standard cognitive process.' In other words, the same architecture can be applicable to both cognitive and metacognitive activities – only their targets are different. The assumption allows us to enumerate factors of difficulties in performing metacognitive activity by analyzing difficulties in performing cognitive activity. In this section, we investigate kinds of cognitive activity, its time-related attributes and its targets, based on Baddeley's Working Memory Model [2]. The term working memory (WM) refers to a system that has evolved for short-term memory and manipulation of information necessary for the performance of such complex tasks as learning, comprehension, and reasoning.

2.1 Kinds of Cognitive Activity and Its Time

Humans have knowledge in the form of so-called operators to achieve goals. Operators are procedures for changing the current state into another that brings us closer to the goal. In general, multiple operators can be applicable to a state, and a critical task is selecting the one to apply. There are some other cognitive activities such as evaluation of the current state which accompany the selection of operators. We divide cognitive activities into five kinds: *rehearsal,* *observation, evaluation, virtual application,* and *selection*. *Observation* is watching something carefully and creating products in WM. It has *focusing* as its subtask. As WM is very rapidly forgotten [2], *Rehearsal* is a critical task for maintaining contents in WM. *Evaluation* is assessing the state of WM and its subtask is *comparison*. By *virtual application,* we mean to apply retrieved operators virtually. *Selection* is choosing appropriate operators among them based on the virtual application results and generating an action-list in WM.

Time attribute is categorized into two measurements of interest to us: one is the time necessary for execution of a cognitive activity; the other is the elapsed time after the execution. Simultaneity of multiple actions and length of an execution time belong to the former; the latter is used to talk about WM and LTM, that is, the memory of action taken is heavily dependent on the elapse time after its execution.

2.2 Targets of Cognitive Activity

Among several cognitive activities, we pay special attention to cognitive operation. By cognitive operation, we mean an operation to generate a new (cognitive) product by applying operators to the contents of WM. For instance, as Fig. 1 shows, the transformation of products-A(t) to products-A(t+1) is a cognitive operation; observation is a cognitive activity. Because a cognitive operation can become the target of (meta)cognitive activity, it is meaningful to distinguish cognitive operations from other cognitive activities. Note here that we do not claim that cognitive operation is not a cognitive activity.

The outside world and a representation stored in WM can be the target of cognitive activity. A representation is encoded information such as a symbolic abstraction of a thing. For instance, observing a car, a person creates a representation of it in WM. A representation is categorized into three according to its target: *outside world*, *cognitive operation,* and *LTM*. By *outside world,* we mean a representation which is created by observing the outside world. A person creates a representation whose target is *cognitive operation* if one observes how another person solves a problem. Concerning *cognitive operation*, it is also important to distinguish one that is created by observing one's own cognitive operation from one that is created by observing others' cognitive operation.

There are two kinds of targets of cognitive activity: an object and a process. An object includes an abstract one. Both objects and processes have two subcategories respectively: outside-world objects and inner-world (mental) objects; outside-world processes and inner-world (mental) processes.

As the number of factors associated with an activity increases, a learner performs the activity with increasing difficulty.

3. Constructing a Framework of Difficulty in Performing Metacognitive Activity

We construct our framework representing the difficulty in performing metacognitive activity by combining all kinds of cognitive activities with their targets, though it is not perfect. First, we will describe our two-layer model of cognitive activity (Fig. 1).

3.1 A Two-Layer Model of Cognitive Activity

This subsection presents a model of problem solving based on Baddeley's Working Memory Model [2]. An individual initially observes a task condition and creates elements in WM (products-A(t)) as its model when a learner solves a problem. That learner evaluates the problem and investigates if he has some domain knowledge useful to accomplish the task, and if the result is positive, then he retrieves applicable operators from his knowledge base and

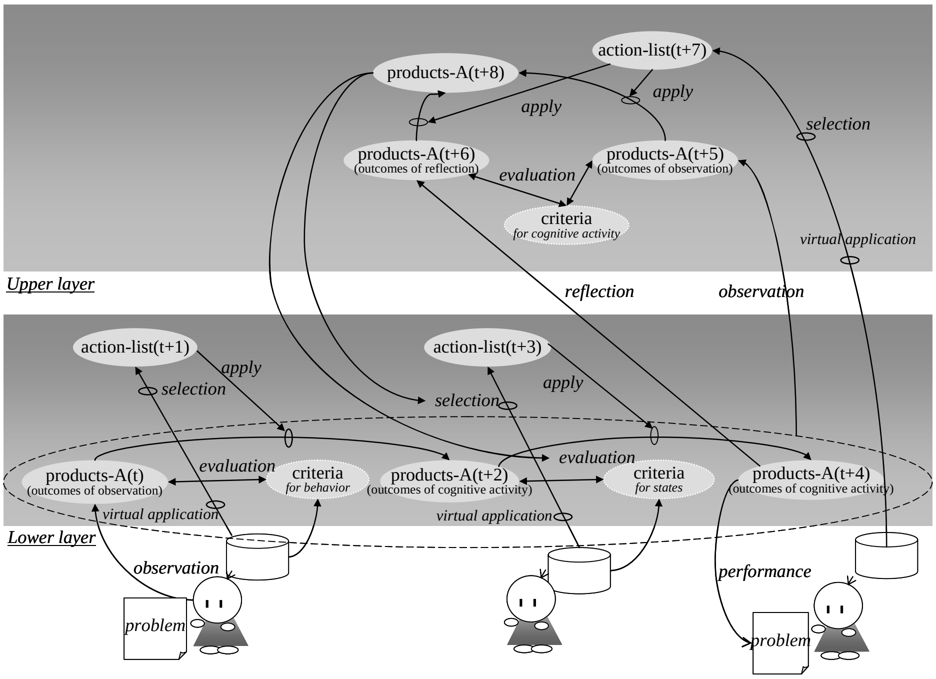

Figure 1. A Computational Model of Problem Solving

applies them to the WM elements (products-A(t)) virtually. Next, evaluating the application results, the learner selects appropriate operators and makes an action-list (action-list(t+1)). Then, the learner applies operators in the action-list to the elements, and creates new elements in his own WM (products-A(t+2)). The process is repeated until achieving the goal, and finally he engages in an observable behaviour (concrete actions to the real world) based on the final elements (products-A(t+4)). Thus, normal problem solving performs cognitive activities that update the state in the lower layer of WM.

Concerning the lower layer of Fig. 1, elements in WM are usually not the target of “observation” but the target of other cognitive activities. However, we occasionally need to observe elements in WM consciously. In this case, where do we create the results of observation? Generally, observation means to observe something in an outside world and to create corresponding elements in WM. As described in the above, the target of observation and its products belong to different worlds from each other. Accordingly, observation of elements in WM creates elements in another world. For that reason, it would be valid to suppose a two-layer model of WM [18]. Supposing a two-layer model, when one observes elements at the lower layer, he can create new elements at the upper layer in WM (products-A(t+5)). Such observation is sometimes called reflection. Many definitions in the literature of reflection exist. Most concur that it is an active, conscious process. Schon divides reflection into two kinds: reflection-in-action (thinking on your feet) and reflection-on-action (retrospective thinking) [29]. We also divide observation of elements in WM into activities of observation and reflection. The former is called conscious observation, to observe a body of existing elements in WM and their operation process and create elements at the upper layer (Products-A(t+5)). We call the latter reflection. By reflection, we mean retrospective creation of elements at the upper layer. One observes some existing elements at the lower layer. Based on them, one infers a past cognitive operation process and creates elements at the upper layer (Products-A(t+6)). For instance, if we are shown some mistakes, we occasionally call and review retrospectively problem-solving processes to identify the reason for the failure.

3.2 Our Framework for Metacognitive Activity

Table 1 shows factors of difficulty in performing a cognitive activity based on our framework that comprises two dimensions such as cognitive activities and their targets. Whatever the

Table 1. Difficulty in Performing a Cognitive Activity

Target		Rehearsal	Observation	Evaluation	Virtual Application	Selection
Out side World	Ordinary Object					
	Resulting object of others' cognitive operations		(d2)			
	Ordinary process		(d1)			
	Others' cognitive operation processes		(d1) (d2)			
Repre sen tation	LTM object (a representation of the retrieved thing)		(d4)			
	Representation of ordinary object at an outside world	(d3)		(d4)	(d4)	(d4)
	Representation of ordinary process at an outside world	(d3)		(d4)	(d4)	(d4)
	Representation of resulting object of others' cognitive operations	(d3)		(d4) (d5)	(d4) (d5)	(d4) (d5)
	Representation of others' cognitive process	(d3)		(d4) (d5)	(d4) (d5)	(d4) (d5)
	Resulting object of one's own cognitive operation	(d3)	(d4) (d6)			
	Representation of resulting object of one's own cognitive operation	(d3)		(d4)(d6)(d7)	(d4)(d6)(d8)	(d4) (d6)
	One's own cognitive operation process	(d3)	(d4) (d6)			
	Representation of one's own cognitive operation process	(d3)		(d4)(d6)(d7)	(d4)(d6)(d8)	(d4) (d6)

d1: Segmentation of process
d2: Invisibility
d3: Simultaneous processing with other activities
d4: Simultaneous processing with rehearsal
d5: Cognitive operation (inference)
d6: A two-layer WM
d7: Acquisition of criteria for cognitive activity
d8: Influence on virtual application at a lower layer

targets are, difficulties exist in performing cognitive activities to some extent. First, we illustrate the relative difficulties in performing cognitive activities. Because *selection* is performed simultaneously with *rehearsal*, it is more difficult than either *observation* or *evaluation*. Because *virtual application* is performed with *rehearsal* simultaneously and is repeated until finding appropriate operators, it is more difficult than *selection*.

Table 1 shows that targets of a cognitive activity are classifiable into two types: the outside world and representation. A cognitive activity that targets the outside world includes only *observation*. Generally speaking, observing a process is more difficult than observing an object because extraction of a process is essentially more difficult than extraction of an object (d1). For instance, a motor skill such as typing using a keyboard is a pre-packaged sequence of actions. It is difficult to extract a part of the action from it. In any case, *observation* of the outside world is the easiest.

By observing LTM and retrieving information such as operators, a representation of what is retrieved is created in WM. Observing LTM is more difficult than observing the outside world because it requires synchronous processing with *rehearsal* (d4) of elements in WM. The other four cognitive activities for a representation, which is created by observing LTM, present similar difficulty as cognitive activities for a representation, which is created by observing the outside world. For that reason, we omit them from Table 1.

By observing ordinary objects or processes of the outside world, corresponding representations are created: "representation of an ordinary object of the outside world" and "representation of an ordinary process of the outside world." They can become the target of *rehearsal*, *evaluation*, *virtual application*, and *selection*. Regarding them, one factor of difficulty in performing each kind of activities is synchronous processing (d4).

Because other persons' cognitive operations are invisible (d2), representations concerning others' cognitive operations, which a learner creates in WM by observing others' cognitive operations, becomes incomplete. The learner may supplement them with her inference. Therefore, cognitive activities for representations concerning others' cognitive operations are more difficult than representations of ordinary objects (or processes) of the outside world. Whatever the targets are, the difficulty encountered in performing *rehearsal* is the same. As Table 1 shows, factors of difficulty in performing cognitive activity for representations concerning others' cognitive operations include the synchronous processing of rehearsal (d4) and cognitive operations (inference) (d5).

As described in 3.1, when one observes "one's own cognitive operation", the inner world in which ordinary cognitive activities are executed becomes another outside world, and WM is made to be two-layered. Considering the two-layer WM, synchronous processing is essential, that is, one performs cognitive activity for elements at the upper-layer while maintaining elements at a lower-layer. As the factors of difficulty in performing cognitive activities for "one's own cognitive operation", we identify synchronous processing (d4) and a two-layered WM (d6). In addition, *evaluation* has a special factor of difficulty: acquisition of "criteria for cognitive activity (d7)" at the upper layer. A learner can learn by evaluating elements at the lower layer and by solving common problems that are often encountered if a learner needs to acquire only "criteria for states" at the lower layer. However, such is not the case. A learner needs to learn "criteria for cognitive activity" as well and he rarely has a chance to learn "criteria for cognitive activity", which causes acquisition of "criteria for cognitive activity (d7)" to become more difficult. *Virtual application* of an operator at the upper layer affects virtual application of an operator at the lower layer (d8), which must be resolved during processing at the upper layer. Therefore, virtual application at the upper layer is the most difficult in cognitive activities. It causes *selection* of an appropriate operator to become difficult (d9) at the upper layer.

4. Organization of Existing Computer-based Support Systems and Methods Based on Our Framework

Using our framework, we analyze existing computer-based support systems and methods to clarify the correspondence between them and factors of difficulty and to specify their targets. According to the correspondence, we categorize factors of difficulty into two from a unified viewpoint: those which some support systems already intend to eliminate and those which no systems intend to eliminate. The categorization can reveal what factors remain without support.

Although we have analyzed some representative support systems: MIRA [11], Algebraland Computer System [5, 7], Geometry Tutor [1], Interactive History [14], Intelligent Novice Tutor [25], and Error Based Simulation [13], we describe only three examples because of space limitations in this paper. ASK to THINK – TEL WHY is an inquiry-based tutoring model. A tutor guides learners by asking a question using a given template of five kinds of questions. Tutees only answer questions. King claims that tutees become aware of metacognitive activity in answering self-regulation questions (SR-Qs) [21]. Asking SR-Qs is training also for the tutor to observe *others' cognitive operation process* because he must determine the timing of asking an SR-Q. Ideally, a tutor should observe *his own cognitive operation process*, but factors of difficulty exist (d4 and d6 in Table 1). The target of observation is shifted from *one's own cognitive operation process* to *others' cognitive operation processes* to eliminate these factors. The tutor's SR-Qs induce tutees to observe *their own cognitive operation processes*. The other four questions by a tutor allow tutees to observe *resulting objects of one's own cognitive operations*. Tutors' questions reduce tutees' cognitive loads of cognitive activity at the upper layer. Tutees' answers of these questions also allow the tutor to evaluate tutees' results of cognitive operation. It also means to shift the target of evaluation from one's own cognitive operation to others for eliminating difficulty.

In Reciprocal Teaching [4, 27], learners in a small group take turns playing the discussion leader role and a monitoring role for the goal of understanding a text. For a discussion leader role, a learner externalizes his comprehension, such as in a summary. It is training for observing or evaluating results of his own cognitive operation; it incurs a heavy cognitive load. For that reason, the method allows a teacher to advise a discussion leader if

Table 2. Correspondence between Difficulties and Supports

Target	Cognitive Activity	Existing support methods and support systems	
		Support that reduces difficulty	Other support
Resulting object of one's own cognitive operation	Observation		ASK-the other-Q (tutees) Reciprocal-summary (leader)
Representation of resulting object of one's own cognitive operation	Evaluation	ASK-tutees' answers of the other-Qs (tutor)	Reciprocal-evaluation (leader)
	Virtual Application		
	Selection		
One's own cognitive process	Observation	[Elimination of d4,d6 by shifting a target] ASK-SR-Q (tutor) Reciprocal (monitors) Our method (monitors) [Elimination of d4,d6 by externalizing] Kitchen-third (learners) Algebraland (Search Space Window) Geometry Tutor IH (navigation window) Our method (externalization tool)	ASK -SR-Q (tutees) Reciprocal-others' advice (leader) Kitchen-third (teacher) Kitchen-fourth (learners) Geometry Tutor (complete proof) MIRA (pre&post reflection) IH (notation) EBS (simulation)
Representation of one's own cognitive process	Evaluation	[Elimination of d4,d6 by shifting a target] ASK-SR-Q-evaluation (tutor) Reciprocal-advice (others) Our method (monitors) [Elimination of d7] Our method-a template of Q (monitors)	Reciprocal-others'advice (leader) Kitchen-fourth (learners) Our method-monitors' Q (solver)
	Virtual Application		
	Selection		

necessary. The method also provides an opportunity for other learners to observe and evaluate the discussion leader's summary. It is training that monitors observe and evaluate *others' cognitive operation process*. However Palincsar et al. seems not to have understood such an effect, that is, Reciprocal Teaching eliminates factors of difficulty (d4, d6) by shifting the target from *one's own cognitive operation* to *others' cognitive operations*, exactly as observed in ASK to THINK – TEL WHY.

Shoenfeld describes the "Kitchen Sink" approach as "four classroom techniques that focus on metacognition" [30]. The "Kitchen Sink" approach reduces a learner's cognitive load by dividing a learning process into two or more sequential stages. The first and second techniques show the problem solving process of a novice and an expert. They pull the trigger at an awareness of metacognitive activity and get learners motivated to master it. The third technique is a practical demonstration of metacognitive activity by an expert and externalizes the *learners' own cognitive operation processes*. The fourth technique gives an opportunity to perform metacognitive activity by asking a question. In summary, Kitchen Sink does not try to eliminate difficulties associated with learning of metacognitive activity.

Through these analyses, we clarify the correspondence between the difficulty in performing metacognitive activity and existing support systems and methods. We find that most of the support systems and methods help eliminate factors of difficulty (d4, d6). In addition, some of these reduce the difficulty of evaluating *one's own cognitive operation* by shifting the target from it to *others' cognitive operation*. Nevertheless, no systems and methods exist that help a learner acquire the criteria for cognitive activity (d7) and master virtual application (d8) and selection of appropriate operators (d9) at the upper layer of WM.

We have designed our support method by eliminating the difficulties (d4, d6 and d7) including the adoption of those effective ways in the existing support systems and methods with explicit explanation of what difficulty we are going to eliminate and how to realize it. Furthermore, our method has been designed to gradually increase individual cognitive load [15, 17, 18, 19].

5. Conclusion

We have tried to uncover the correspondence between existing systems for supporting learning of metacognitive activity and factors of its difficulty based on the framework we have developed. The correspondence indicates that existing support methods and systems address different targets with the same goal of helping learners acquire metacognitive activity. Our framework can also contribute to a shared understanding of research on assisted learning of metacognitive activity and accumulation of the research results.

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