Nourishing Problem Solving Skills by Performing HCI Tasks
Relationships between the Methods of Problem Solving (Retrieval, Discovery, or Search) and the Kinds of Acquired Problem Solving Skills

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Abstract: There are three methods for deriving a solution for a problem with which a person is facing, which are 1) retrieval of an existing solution from his/her own memory or from available external resources including human resources, digital resources, and so on, 2) clarifying the constraints to meet and discovering a solution that should satisfy them by exploring the problem space, or 3) deriving a solution by applying inference rules successively until the goal state is achieved. This paper describes the distinctive cognitive processes that respective methods should use when deriving a solution. On the assumption that the ultimately needed problem solving skill would be the one which makes a person solve any problem by himself or herself without reliance on any external resources other than himself/herself, i.e., adaptive problem solving, this paper discusses the implications of the respective methods of problem solving to acquiring the required problem solving skill.

1 INTRODUCTION

Problems are part of daily life. A problem can be defined as a situation in which people cannot immediately achieve their goals using routinely performed procedures. In order for them to solve their problems, people have to understand what the problem is, to find adequate resources, to undertake adequate actions, and to monitor the situation until the goal is reached, getting around impasses and other unexpected obstacles and undertaking corrective actions when necessary.

Following GPS (General Problem Solver) by Newell and Simon (1972), problem solving is defined by a sequence of the following processes:

1. Recognize and represent the current state, or generate a representation of the current state. When the current state is the state to start a problem solving activity, it is called “initial state”,
2. Imagine and represent the states to achieve, or generate a representation including the top-level goal and intermediate subgoal states,
3. Select an action to move the current state to the next, which replaces the current state if the move is done successfully, and
4. Repeat until the top-level goal state is achieved.

In order for a person to carry out a PS (Problem Solving) activity by applying these PS processes, the following conditions have to be satisfied:

1. Be aware of the existence of goals to achieve and represent them unambiguously and precisely at an appropriate grain size,
2. Represent the current state as the initial state unambiguously and precisely at an appropriate grain size,
3. Have a repertoire of operators for transforming one state to another, and
4. Have a consistent set of criteria for selecting an appropriate operator among competing ones, which can be applied to the current state and cause transitions to different states.

A PS task requires a problem solver to execute appropriate PCM (Perceptual-Cognitive-Motor) processes that are expected to be effective for accomplishing the PS task. Figure 1 illustrates how PS activities happen at the interface between tasks and PCM processes. They could become diverse depending on the nature of tasks (including ICT tasks), and how people carry out PCM processes. External tasks impose time constraints on people’s PS activities and people’s PCM processes are carried out under the

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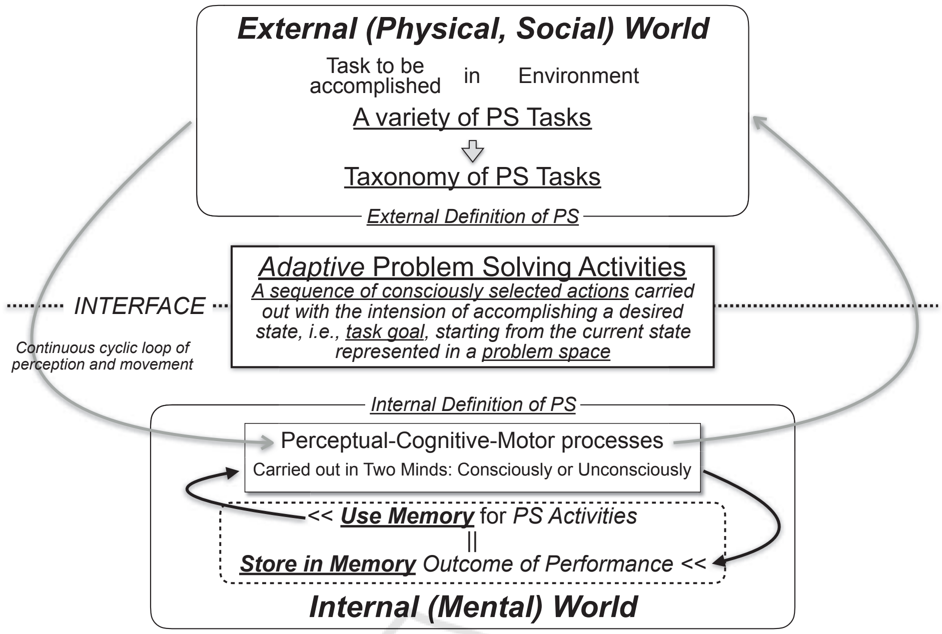

Figure 1: Adaptive problem solving activities.

limitations (or possible ranges) of PCM capabilities. Therefore, PS activities are necessarily adaptive to the tasks people have to deal with. Adaptation is carried out within the range of PCM capabilities. As pointed out by Greiff et al. (2017), APS (Adaptive Problem Solving) skill is one of critical competencies people must have in order to achieve well-being in the current networked, diverse, and heterogeneous society.

The interactions between the tasks that people have encountered and the PCM processes that people have actually carried out to accomplish the tasks have significant influence on people's development of PS performances (Kitajima, 2016). Therefore, people's experiences do significantly affect the actual action sequences for solving problems that are observed when some tasks are given to them.

In our external environments of the 21st century, there are an abundant number of artificial objects. Any objects people interact with should have effect on the memory that is directly associated with the objects, and some portions of memory that are indirectly related with the objects. As people live in diverse cultures and societies, a same object should be used differently in terms of use of memory at the time of using an object, and formation of memory after having used an object. PS activities should occur in the process of object use. After successful PS activities that deal with any single object, it is differently associated with each person's memory, and socio-cultural ecology should be a primary factor.

Interactions with novel artificial objects for accomplishing some goal inevitably involve APS activities because the number of artifacts that surround a person becomes larger and they should influence his/her primary task in unpredictable ways to force him/her to manage the situation by carrying out problem solving adaptively. The increase of the number of surrounding artifacts results in the increase of the number of dimensions to deal with for a person to live satisfactorily in the 21st century.

The purpose of this paper is to give a characterization of PS activities in general and APS in particular from the viewpoint of well-definedness of problem, to provide a detailed analysis of respective PS activities by using a cognitive architecture, MHP/RT (Model Human Processor with Realtime Constraints), and discusses the nature of PS and APS skills, required and potentially acquired, as a function of the degree of well-definedness of the problems, and to suggest the kinds of HCI tasks that could be accomplished by performing the cycles shown in Figure 1 to nourish APS skills, one of critical skills required in the 21st century.

2 PROBLEM SOLVING ACTIVITIES

2.1 Problem-Solving in Well-Defined Problem Spaces

A problem space is defined by an initial state, a goal state, a set of intermediate states, and operators to move from one state to another if a set of conditions to move is satisfied. *A problem space is well-defined* if the initial state, the goal state, and the intermediate states are represented unambiguously and precisely, and the conditions for move are defined appropriately. A person who solves a problem in a well-defined problem space (or if he/she is able to represent the problem as an instance of a well-defined problem space) would show a deterministic PS behavior for a given goal, i.e., he/she solves a problem to achieve the given goal starting from a specific initial state by successively applying a fixed sequence of operators, which may be most efficient in terms of, e.g., time, energy consumption, etc.

2.1.1 GOMS Models

Card et al. (1983) suggests that the knowledge that a person acquires for carrying out routine goal-oriented tasks defined by well-defined problem spaces consists of Goal, Operators, Methods, and Selection rules (GOMS). Goal is represented as a rigid hierarchical goal structure, in which a goal is satisfied if and only if all of its subordinate sub-goals are satisfied. Method is defined by a specific fixed-ordered sequence of operators to accomplish a specific goal. Hierarchically, operators reside at the bottom layer of the goal structure, and methods are just above the operator-layer, each of which is considered as a label to identify a distinct sequence of operators, and associated with a goal at that level of hierarchy, in such a way as "goal G is accomplished by applying method M." Selection rule specifies a consistent rule to select a method among competing methods applicable for the current state. An operator's performance such as execution time is required to be independent of states in order for an operator to be qualified as operator of GOMS. With these features, GOMS models are able to predict performance times of skilled users in carrying out routine goal-oriented tasks (Gray et al., 1993; Haunold and Kuhn, 1994).

2.1.2 Production System

If a person has a well-defined problem space for a given goal, his/her operator sequence is predictable. Models developed under ACT-R cognitive architecture (Anderson, 2007; Anderson and Lebiere, 1998), Production Systems, can simulate cognitive processes involved in accomplishing goals by focussing on single goals successively and searching for production-rules defined by a set of pairs of conditions and actions (equivalent to operators in this context). They are stored in procedural memory and those that match the conditions concerning the currently focussed goal and the existence of required knowledge stored in declarative memory are possible to fire in the next cycle. A person who becomes an expert level of a domain can be viewed as one who has constructed an efficient set of production rules, called "routine expertise" (Holyoak, 1991). GOMS model lies at one extreme of a well-defined problem space, where the strong condition for operator qualification is applied, i.e., an operator has to be independent of context, or an operator's performance has to be indifferent to which state it is applied, and due to this feature, it can predict performance times of a specific kind of problem solver. For those who can use a well-defined problem space when he/she needs to accomplish a goal, it reduces just to cognitive activities to traverse the problem space. It is very different cognitive activities than those that require adaptive skills. It may require, however, times for representing current states, searching for the next operators that match the conditions to move with the current state, selecting the most appropriate one among a set of competing operators, and actually carrying out the selected operator.

2.2 Problem-Solving in Ill-Defined Problem Spaces

A well-defined problem space can degrade to ill-defined problem spaces easily due to several reasons. One may have the abilities to transform an initially ill-defined problem space to a less ill-defined one. Once an ill-defined problem space is transformed to a well-defined one, one may traverse the well-defined problem space by successively firing production rules as modeled by the ACT-R cognitive architecture. Holyoak (1991) names this class of expertise as "adaptive expertise", who is good at generate appropriate decoupling of the condition-action pairs of the production rules flexibly in the given situation to produce appropriate actions. Procedural knowledge represented as production rules are for traversing in a well-defined problem space. Given a top-level goal, one is required to find in his/her knowledge a well-defined problem space or somehow generate one. Once it is defined, PS activities can be considered as the activities for traversing in the problem space. PS skills should involve the skills necessary for transforming an ill-defined one to well-defined, or less ill-defined ones, which is APS skill.

2.3 Turning Well-Defined Problem into Ill-Defined Ones

The following subsections describe how well-defined problem may turn into ill-defined ones, and point out necessary cognitive skills for changing ill-defined one to well-defined one.

Imagining Goals is not Trivial: One may have difficulty in imagining a set of goals to achieve the top-level goal. For example, a foreign traveler stands in front of a ticketing machine with unfamiliar and strange interface to him/her by which he/she believes he/she is supposed to buy a train ticket. He/she is unable to generate intermediate goals to achieve the top-level goal, i.e., "he/she has a necessary ticket in his/her hand." This is the issue of mental models:

- the variety of mental models one has in the domain in question (mental model),
- the ability to switch from one mental model to another if the current one is estimated as ineffective (switching skill), and
- the ability to create effective mental models from experience (model creation through experience).

Recognizing and Representing State is not Trivial: In traversing a well-defined problem space, it is obvious where to attend to in the current state one has reached, and how to represent it because every state has already been represented unambiguously and precisely at the required level for selecting next operators. However, when goals are underspecified, one may find difficulty in controlling where to attend because a goal for the current state should provide the semantic context that helps him/her to parse the current state of the scene where he/she is in and comprehend it.

Comprehension requires background knowledge which is different from person to person. In addition, the ability to filter out the relevant objects from irrelevant ones may differ from person to person. Kitajima and Toyota (2012) demonstrated that elderly participants who had inappropriate functioning of attention had difficulty in acquiring relevant information from rather complicated sign boards while performing a way-finding task. This evidence shows that even if one has a well-defined problem space in his/her long-term memory, it might be difficult for him/her to activate it for use in the PS activity. No effective retrieval cue is represented in working memory to activate task relevant well-defined problem space.

At this stage, an ill-defined problem space might change to a well-defined or less ill-defined one if one has the following:

- background knowledge to make him/her possible to represent objects in the current state appropriately for the given goal (background knowledge and comprehension skill),
- the ability to use the representation for defining to-be-searched-for objects (target objects) or evaluating the degree of relevance of attended objects (searching skill), and
- the ability to pay attention to the relevant objects in the current state (attention skill).

Selecting Next Action is not Trivial: In traversing a well-defined problem space, next actions are selected by evaluating expected cost to be expended moving from the current state to the final goal state. Means-ends analysis or the hill climbing strategy is applied for this purpose. This is only possible when the problem space is strictly defined and one is able to manipulate it as a whole. In reality, it is not possible if the size of problem space is large. One cannot foresee the entire problem space. In addition, one cannot fully specify the current situation. Under these conditions, one's action selection should not be rational but is controlled by the bounded rationality principle and the satisficing principle uncovered by Simon (1956) and further studied by Kahneman (2003) in generating situated next actions.

However, the farther one can foresee in the problem space, the lesser ill-defined the current problem space becomes. Kitajima and Toyota (2012) demonstrated that elderly participants who had inappropriate functioning of planning had difficulty in estimating relevance of the acquired "right" information from sign boards to the current goal while performing a way-finding task because the current goal is underspecified. This evidence shows that even if one is able to attend to a right object, it might be difficult for him/her to estimate it as relevant for accomplishing the current goal which is not detailed enough to be matched with the representation of the right object.

An ill-defined problem space might change to a well- or less ill-defined one if one has the following:

- the ability to foresee the future states by performing mental simulation (planning ability), and
- background knowledge to be used in the planning activity (mental model).

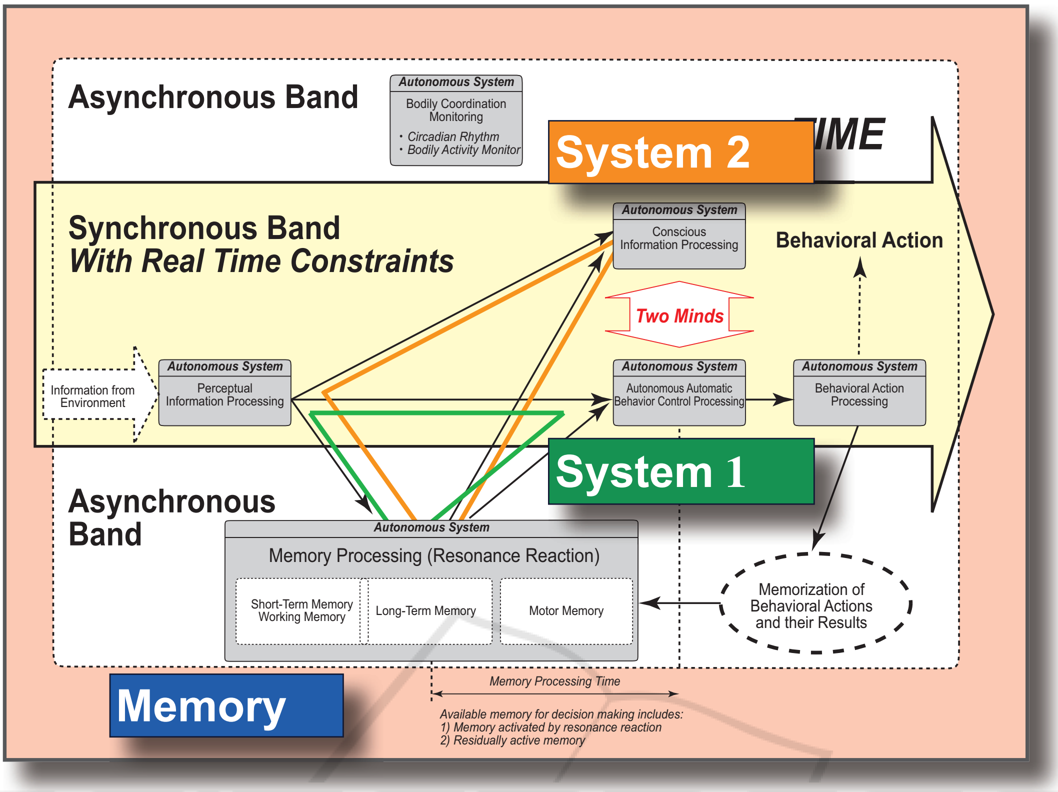

Figure 2: MHP/RT: Model Human Processor with Realtime Constraints.

3 A CLOSER LOOK AT SELECTING NEXT ACTION

This section introduces a cognitive architecture, MHP/RT (Model Human Processor with Realtime Constraints) proposed by Kitajima and Toyota (2013, 2012), that is capable of simulating action selection processes in *any* problem solving situations, which have been described in the previous section phenomenologically. MHP/RT consists of memory and action selection processes, and describes in detail not only how action selections are carried out and which action will be performed but also how the results of action selections are stored in memory (see Kitajima (2016) for a full description of the architecture and its applications).

3.1 Cyclic Processes of Action Selection and Memorization

Action selection and memorization is a cyclic process which works while one lives in the world. As one interacts with the environment, memory is gradually structured as multi-dimensional memory frames (see the bottom part of Figure 1 for a schematic illustration). Constraints on behavioral processing are imposed by conscious and unconscious processes, System 2 and System 1 of Two Minds, respectively, and behavior must be synchronized with the ever-changing external and internal environments, which is a form of self-organization. As one grows while carrying out the cyclic processes of action selection and memorization, he/she develops his/her memory and shows distinct behavioral characteristics (Kitajima and Toyota, 2014, 2015).

3.2 MHP/RT: Model Human Processor with Realtime Constraints

Figure 2 illustrates MHP/RT (Kitajima and Toyota, 2012, 2013), which consists of five autonomous subsystems. MHP/RT is an extension of a version of dual processing theories, Two Minds, proposed by Kahneman (2003, 2011). Two Minds consists of unconscious processes, System 1, and conscious processes, System 2. System 1 is a fast feed-forward control process driven by the cerebellum and oriented toward immediate action. In contrast, System 2 is a very slow feedback control process driven by the cerebrum and oriented toward future action.

MHP/RT focuses on synchronization between System 1 and System 2 in the information flow from the perceptual system from the environment at the left end to the motor system at the right end. Output from the perceptual system is diverted into three paths, one path leads to the conscious process of System 2, the other leads to the unconscious process of System 1, and the last one leads to the memory system. Information in memory activated by the input from the environment is become available to System 1 and 2. System 1 and 2 work in synchronous with each other but the memory process works asynchronously with System 1 and 2. The dotted oval shows the process of memorization of output from the motor process. These interactions between System 1 and 2, and memory are not seriously considered in the original Karhneman's Two Minds. Processes associated with unconscious System 1 are indicated by green lines. And those associated with conscious System 2 are indicated in orange lines.

3.3 MHP/RT's Four-Processes: Use and Modification of Memory

MHP/RT works in one of four different modes when one looks at it from a particular event that occurred at the absolute time T. Two are before the event in which MHP/RT uses memory and the other two are after the event in which it modifies memory:

- **System 2 Before Mode:** MHP/RT consciously uses memory before the event for anticipating the future event which takes relatively long time ($T -$ some amount of time).
- **System 1 Before Mode:** MHP/RT unconsciously uses memory just before the event, say 100 milli seconds before the event for automatic preparation for the future event ($T -$ a few hundreds mill seconds).
- **System 1 After Mode:** MHP/RT unconsciously tunes the current network connections related to the past event for better performance for the same event in the future ($T +$ a few hundreds mill seconds).
- **System 2 After Mode:** MHP/RT consciously reflects on the past event resulting in structural changes in memory ($T +$ some amount of time).

4 PROBLEM SOLVING ACTIVITIES VIEWED FROM MHP/RT

This section discusses how PS activities are described from the viewpoint of MHP/RT's action selection processes and memory processes. There are three methods for deriving a solution for a problem with which a person is facing; retrieval, inference, and exploration. In the following subsections, each method is elaborated by combining the description in Section 2 and Section 3.

4.1 Solving a Problem by Retrieval

Solving a well-defined problem: Given a problem statement, irrespective of whether it is generated internally or provided externally, a person represents both the goal state to achieve and the initial state that he/she is in unambiguously and precisely enough to retrieve the description of the action sequences that should intervene the both ends of the states *from his/her memory*. Therefore, this problem is considered as a well-defined problem.

For solving the problem, he/she is required to just carry out the retrieved sequence of actions. This practice should strengthen the retrieved memory trace that connects the representation of the initial state and the goal state. System 2 Before Mode is used when retrieving the sequences of actions, and System 1 Before Mode is used to actually solve the problem. System 1 or 2 After Mode strengthen the memory that has used in the activity. In this way, he/she actually learns from the PS practice to strengthen the memory traces of successful performance.

Problem solved *without* problem solving activities: Given a problem statement, a person uses *external memory* to retrieve solutions. The description of the problem statement is used literally as it is, and he/she expects to reach any "solutions" that someone has already created for the problem. Since the solution is external, he/she is required to follow consciously the sequences of actions as the solution specifies. In other words, the problem is solved by borrowing the others' thinking processes, and he/she just perceives the state of the problem and moves eyeballs and hands as the description of what to do in the perceived situation.

He/she could use System 1 After Mode for tuning neural networks to just finished activities or deliberate reflection in System 2 After Mode. Only when he/she does them, he/she can learn from the practice, otherwise he/she just memorizes the episode, "the problem was given, and successfully solved by retrieving solutions from the Web.” The link between the problem and the solution may or may not be established. The problem may not be solved by using his/her memory when encountered it again in the future. Learning is very limited compared with the former case.

4.2 Solving a Problem by Inference

Given a problem statement, irrespective of whether it is generated internally or provided externally, one represents both the goal state and the initial state that he/she is in unambiguously and precisely enough to retrieve the inference rules, i.e., procedural knowledge, to carry out the necessary state transitions. This is the way of problem solving modeled as production systems like ACT-R (Anderson, 2007; Anderson and Lebiere, 1998) or Soar (Newell, 1990; Laird et al., 1987).

In this case, it is assumed that a person has procedural memory, which connects *perceptual* multi-dimensional memory frame with *behavior* multi-dimensional memory frame with the help of *relation* multi-dimensional memory frame, which are associated with perceptual, System 1, and System 2 processes, respectively. The inference rules are successively applied to transform the current state to the next until the goal state is achieved. System 2 Before Mode is used for planning and System 1 Before Mode is used to execute individual production rules. System 1 After Mode is used to strengthen the successfully applied production rules in behavior multi-dimensional memory frame and declarative memory in relation multi-dimensional memory frame. System 2 After Mode might be used to create a new set of production rules that are expected to function more efficiently for the kinds of situations defined by the just solved problem. Ultimately, the person will have the ability to carry out the same task more and more efficiently, very fast without error; it is said that he/she has acquired routine expertise for the kinds of tasks executable by applying well-learned procedural knowledge (Holyoak, 1991).

The states that appear while solving the problem are represented unambiguously and precisely enough to retrieve production rules from procedural memory (behavior multi-dimensional memory frame), and factual knowledge from declarative memory (relation multi-dimensional memory frame), triggered by perceptual multi-dimensional memory frame that is activated by external perceptual stimuli. *Therefore, the performance of PS activity would depend on the contents of memory and the functioning of perceptual sensors.* These should be influenced by the kinds of experiences one has had from his/her birth. This is obviously affected by the culture and the circumstances one is in in everyday life while one grows up. This suggests the external environment should be of crucial importance for nourishing this kind of PS skill.

4.3 Solving a Problem by Exploration

Given a problem statement, a person can only represent both the goal state and the initial state vaguely, and therefore it is not possible for him/her to retrieve anything directly relevant to solve the problem. This is the case where he/she is faced with an ill-defined problem as described in Section 2. He/she needs to create effective retrieval cues to find any action that should move the current state to another along the unknown successful path to the goal, whose representation should become less vague as one proceeds. This is equivalent to make the initial vague representation of the goal clearer; to convert the ill-defined problem to a less ill-defined or hopefully a well-defined one.

The notion of resonance is relevant for this to happen. Memory system in MHP/RT is regarded as an autonomous system, which means that memory should not be a passive database system to return data on request from the action selection process. The MHP/RT’s memory system receives input from the autonomous perceptual system and resonates with the other autonomous systems, i.e., conscious system (System 2 of Two Minds) and unconscious system (System 1 of Two Minds) to make available the currently activated portion of memory. The mechanism of resonance is used to make available any relevant portion of behavior multi-dimensional memory frame to the action selection process of MHP/RT. System 2 Before Mode and System 1 Before Mode use this resonance mechanism to select plan and next action.

The selected action may succeed or fail, or result in uncertain outcome to fall into an impasse.The processes are totally exploratory but the memory traces of the executed actions will be created with the flag of success/failure. The memory trace with successful performance will be strengthened because it is associated with rewards. Ultimately, the person will have the ability to handle the same situation flexibly with less ineffective search; it is said that he/she has acquired adaptive expertise (Holyoak, 1991) for the kinds of ill-defined tasks with a variety of well-developed behavior and motion multi-dimensional memory frames available through resonance with perceptual multi-dimensional memory frame.

Development of flexible and rich memory is necessary for acquiring adaptive expertise through a variety of experience with reality (not virtual). It is often felt that a solutions for an ill-defined problem is discovered suddenly or the solution emerges spontaneously. It is because the critical process underlying the discovery is memory resonance. However, the richness of memory should affect the possibility of successful discovery should happen; construction of memory structure that integrates perception and body movement with high reality is important, and again a variety of experience with reality is important for nourishing this problem solving skill.

5 CONCLUSIONS

This paper suggested that when faced with a problem, either it is given externally or generated internally, it could be carried out either by retrieval, search, or discovery method, each of which is associated with distinct cognitive processes for action selection and memorization. Respective methods should have different implications to development of PS skills. Retrieval method would be effective when his/her own memory is used; search method is effective for advancing efficient use of inference rules; discovery method is crucial for turning ill-defined problem to well-defined one which should be critical for APS skill development.

The importance of experience was emphasized for nourishing PS skills. Some aspects of experience needs to be carefully designed in education, society, or wherever a person carries out some activity for the purpose of nourishing PS skills by considering the distinct features in terms of cognitive processes involved in the different kinds of PS activities.

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