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The Effects of Mental Capacity and Size of Chunk of Problem Solver and Mental Demand of Problem on Science Problem Solving

Soo-Young Ahn

(Gyeong Nam Science High School)

ABSTRACT

The development of cognitive psychology provides us a theoretical base from which we can obtain information about human problem solving. One purpose of this study was to investigate the effects of cognitive psychological factors on the problem solving of the two kinds of tasks (content free, content specific). And the other purpose was to find out the existence of critical situation in problem solving process. Even the items of tasks with the same logical structure and content knowledge could have different sizes of mental demand.

The results were as follows. The mental demand of the problem, and the problem solver's mental capacity, might be the main factors in problem solving. Critical situation of both a group and an individual existed in the tasks that need content free knowledge (FIT 752 task). But the critical situation of a group was completely different from that of the individual in the tasks that need content specific knowledge (electric circuit task). According to the analysis of achievement for each individual in the task that need content specific knowledge, the critical situation of an individual existed in problem solving, but the critical situation of a group was not existed by were summed up the individual results.

Key words: mental capacity, mental demand, chunking.

I. Introduction

Problem solving is a process of interaction between a problem solver and the problem environment (task). Therefore research on problem solving mainly consists of factors related to the problem solver and the problem environment. Traditional researches have been concentrated on the problem solving factors of problem representation, problem solving strategy, and solvers knowledge base.

Today the development of cognitive psychology provides us a theoretical base from which we can obtain information about human problem solving. In the theory of Pascual-Leone (Neo-

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Piagetian theory) and the information-processing theory, it is considered that short term memory can play an important role as a structural factor of cognitive development (Chapman, 1990). In particular, Pascual-Leone insisted that the results of problem solving could be dependent on both mental capacity, which corresponds to the information-processing ability of children's short term memory, and mental demand which is involved in the problem (Pascual-Leone, 1987; Niaz, 1989; Johnstone, 1993).

According to Chi (1978) and Simon (1974), another cognitive factor in problem solving is the size of chunk related to knowledge base of the problem solver. Since the size of chunk is related to the differences of the amount of information needed to solve the problem, the differences in knowledge base between novice and expert result in that the novice recognizes a part of a problem as a composite of individual bits of information, while the expert recognizes it as a chunk.

The recent development of cognition theory made it possible to take into account the problem solvers procedural aspects such as problem solving strategies, problem representation, problem solving procedure, the structural aspect related to cognitive ability, and problem environment as important variables in research on problem solving (Nias, 1989: Johnstone, 1993; Rutherford, 1997; Tsaparlis, 1998; Roth, 2000).

Studies based on Neo-Piagetian theories showed that the mental demand of the problem and the problem solver's mental capacity might be the main factors in problem solving. However, on the role of the critical situation and chunk size, there have been no consistent results.

One purpose of this study is to investigate the effects of these cognitive psychological factors (mental capacity, mental demand, chunking) in problem solving of the two kinds of tasks requiring content free knowledge and content specific knowledge in relation to electric circuits in physics. The other purpose is to find out the existence of critical situation in problem solving process.

Ⅱ. Key Words

• Mental capacity (M-capacity)

It is the capacity of process information in short-term memory. It is related to age. According to Pascual-Leone, mental capacity is a structural and functional capacity. Structural capacity is the capacity increased due to organic factor by age. Functional capacity is the problem solvers ability to process as a much information as possible in a problem solving situation. Mental capacity in this study is the functional capacity.

• Mental demand (M-demand)

Mental demand of a problem means the number of variables and/or procedures to be processed simultaneously in short-term memory to solve the problem. Therefore, researchers consider this demand to be determined by the problem itself. The more complex and/ or difficult the problem is, the higher the mental demand will be. How many variables and/or procedures you need, however, is dependent on whether you are an expert or not: a novice student may need more procedures to solve a problem than an expert.

• Chunk and chunking effect

Chunking is grouping of separated information into a unit of information that may themselves be considered as a unit. A chunk of information in short-term memory is processed as a unit. The size of chunk is dependent on the problem solver's knowledge base. When familiarity with the problem has been gained through practice, and when chunking of the problem into familiar chunks is achieved, the subjects may be successful, despite the M-demand being greater than their M-Capacity.

Ⅲ. Method

1. Subjects

Subjects consisted of 102 girl students enrolled in the second-year of a Korean high school. 92 of the 1021 students were selected according to the result of the pretest on the basic knowledge of electric circuits. They participated in this study.

2. Instrument

Two types of test were used: Figural Intersection Test 752 (FIT 752, J. M. Johnson, 1982), and Electric Circuit Test.

1) FIT 752 test

FIT was used as the tool for measuring mental capacity of problem solver. This test consisted of seven groups (from value of mental demand 1 to value of mental demand 7), and each group consisted of 5 items. All items of each group had the same number of figures but a different shape. For example, the items of first group had 2 kinds of figures; the items of second group had 3 kinds of figure, and so on.

In each item, two types of figure sets were presented. One type is a set of figures separated from each other on the right of the page. In the left of the page, the other type was the figures into which the right presented figures were intersected. Students found out and then marked a dot on the intersected common area of all of the figures. Therefore, the more the number of the figures would be increased, the more mental capacity of solver would be needed (Table 1).

Mental capacity of the subjects were determined by the FIT 752 test procedure suggested by Johnson(1982). The test time was limited to 13mins, to measure the mental capacity needed in the process of the problem solving.

Table 1. Item of FIT 752

	Exercise	Group							
		1st	2nd	3rd	4th	5th	6th	7th	Total
No. of items	5	5	5	6	5	5	5	5	36
Value of mental demand		1	2	3	4	5	6	7	

FIT 752 test tool was used not only as the tool measuring the mental capacity of the subjects, but also as tasks requiring content free knowledge.

2) Electric circuit test

Three (1st, 2nd, 3rd) electric circuit tests were developed to investigate the relation between mental capacity and mental demand in problem solving of the task needing domain-specific knowledge. In the electric circuit tests, the developed items were used as tasks requiring domain specific knowledge. The test consisted of seven items according to mental demand. The items satisfied the following conditions.

1. Each item must have the same content knowledge and logical structure.
2. Each item must require the least knowledge-related to problem solving.
3. Each item must require distinctly different mental demand.

The items satisfied the above condition as a content specific test. Regardless of the simplicity or complexity of the circuit, knowledge for measuring the current and voltage at the specific part demands the same amount of knowledge. Adding circuit elements, such as a resistance connection, can increase the mental demand for each item. Finally each test completed by considering the above conditions consisted of seven items, from mental demand two to mental demand eight.

For example, item 6 of first test is in Figure 1.

A circuit consisted of four resistors and a battery, as follows. What is the potential difference across the 30 Ω resistor?

According to the review of literature, the steps of solution by the experts and novices are different. Actually, in this study, most novices and experts solved the problem in the following steps.

Novice : [Serial connection equivalent resistance(R_{ab}) → Parallel connection equivalent resistance(R_{cd}) → Total equivalent resistance(R_{ed})] → Total current → Potential difference on the 12 Ω resistance → Potential difference on the parallel connection circuit → Current on the 30 Ω resistance → Potential difference on the 30 Ω resistance.

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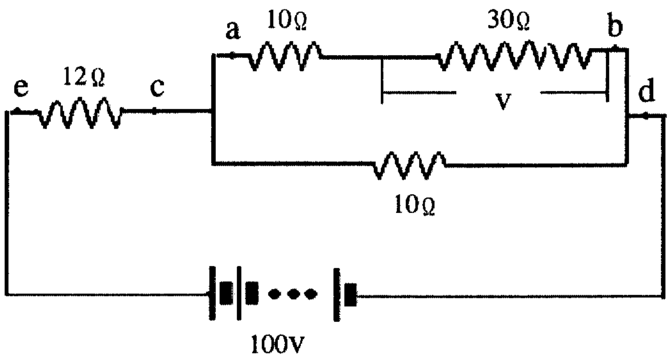

Fig. 1. Example of item 6th

Expert : Total equivalent resistance(R_{ed}) → Potential difference on the parallel connection circuit → Potential difference on the 30Ω resistance.

The mental demand for each item is different according to the problem solver's knowledge level. We determined the value of mental demand of the item on the basis of the novices problem solving process. The novice has schemata that exist independently in the problem solving process.

3. Procedure

1) Pretesting Phase

This stage was designed to select those students who held the basic knowledge of electric circuits. We gave to the 102 subjects the pretest that consisted of seven items about the basic knowledge of electric circuits. Among the 102 subject given the pretest, 92 subjects were selected for this study. All subjects had more than an 80% success rate on the pretest.

2) Figural Intersection Testing & Electric Circuit Testing (1st) Phase

In this stage, two types of tests were used: Figural Intersection Test (FIT) 752 and Electric Circuit Test. At first, to investigate the relation between mental capacity and mental demand in problem solving of the task needing content free knowledge, we presented the FIT 752 test to the subjects. Following the FIT 752 test guide (Johnson, 1982), mental capacities of the subjects were determined. Second, to investigate the relation between mental capacity and mental demand in problem solving of the task needing domain specific knowledge, we administered the electric circuit test to the subjects for 50min.

3) Instruction & Electric Circuit Testing Phase

This stage was designed to find out the chunking effect on the problem solving process. In this stage, the electric circuit test was conducted two times after first electric circuit test. The second and third test items had the same logical structures as the first test items, but different voltage and resistance on the circuit. To find out the chunking effect on the problem solving process, the second test was given after instruction(training) on the process of finding the equivalent resistance (sizes of mental demand 2~3) following the first test. The purpose of the instruction (training) was only to chunk the process of finding the equivalent resistance, and so, during the instruction, any new problem solving process or algorithm was not to be presented to the students. In item 6th, the novice goes through three steps to find out the total equivalent resistance. The purpose of the researcher in this problem lies in chunking the procedures of finding the total equivalent resistance into a single process through instruction (training).

Specifically, the instruction (training) on the process of finding out the equivalent resistance was performed at the circuit (Fig. 2).

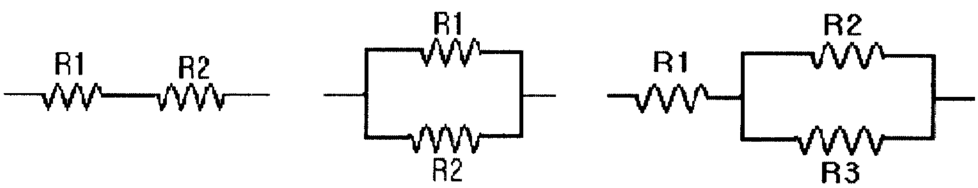

Fig. 2. The examples used in the instruction training

Before the third test, the other instruction (training) was given to students under the same conditions only to chunk the process of finding out the partial current and the entire current, the partial voltage and the entire voltage in the electric circuits.

The correct answer was scored one point, and the wrong answer was scored zero point. The quality of the solving process was ignored.

Ⅳ. Test Results

1. Mental capacity and mental demand

1) Tasks requiring content free knowledge- FIT 752 tasks

FIT 752 task is not only a test for measuring the mental capacity of the subjects, but also a proper task of solving problems requiring content free knowledge. FIT test result showed the average mental capacity of 5.83. The subjects were sorted into 4 groups from mental demand 4 to 7, according to the mental capacity.

The success rates for each item group regarding FIT task in each mental demand class are shown in Figure 3. As mental demand of the items increased, the task solving success rates decreased in all groups. Especially, up to mental demand 4 items, the success rates showed no

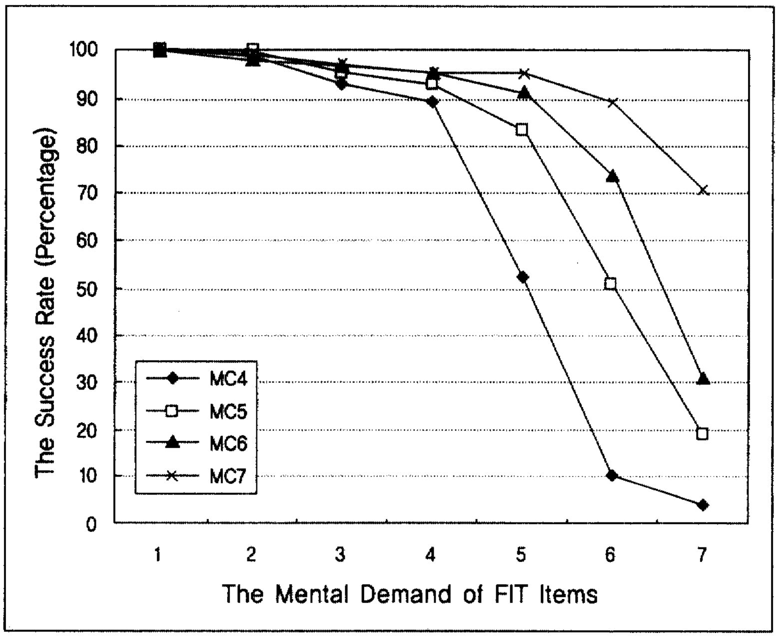

Fig. 3. The students' success rate by mental demand of FIT items

significant decrease, but from mental demand 5, showed rapid decrease. This result proved that the size of mental demand of tasks might be a factor affecting problem solving.

To find out the effect of mental capacity on problem solving, the success rates of groups sorted by mental capacity were compared (see Fig. 3). Up to mental demand 4 items, the success rates were high, but no significant differences among groups. However, for the mental demand 5 items, the success rate of the mental capacity 4 group was low, while the other groups still showed high success rates. In the items of mental demand 6 and 7, the differences on success rates among groups were significant. The ANOVA analysis of each group showed significant differences ($p<0.01$) among the groups on the items of mental demand 5. These results confirm that the problem solver's mental capacity is a factor affecting the problem solving in tasks that require more than a certain mental demand.

2) Tasks requiring domain specific knowledge - Electric Circuit Tasks

The success rates of the groups with different mental capacities on the electric circuit tasks are shown in Figure 4. As mental demand of the items increased, the success rates of the groups all decreased. Unlike for the FIT 752 tasks, the success rates showed differences among groups on the items of mental demand 3. The results of ANOVA analysis on success rates among groups with different mental capacities showed significant differences on the items of mental demand 3. This means that the problem solver with larger mental capacity is superior to the problem solver

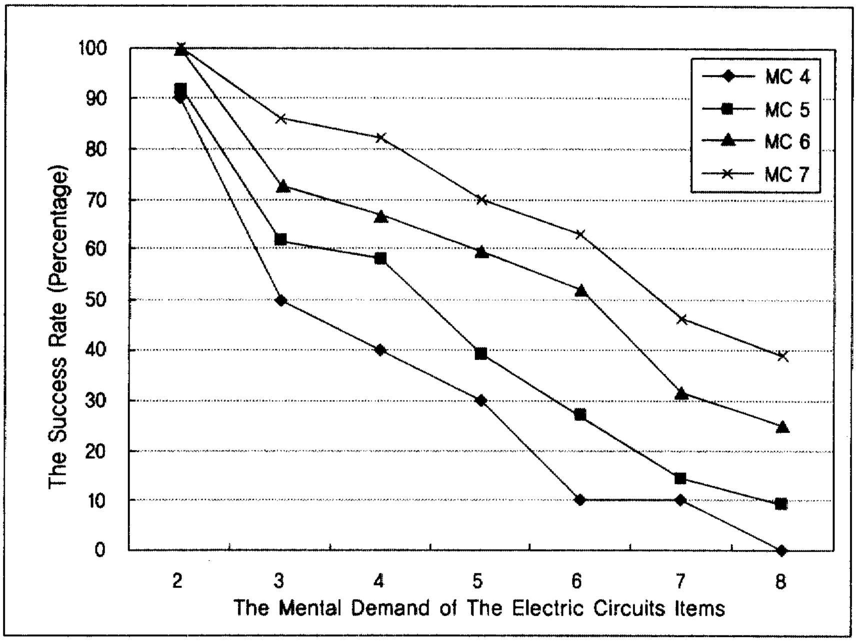

Fig. 4. The students' success rate by the mental demand of the electric circuits items (1st test)

with smaller mental capacity in the electric circuit tasks. As shown in Figure 4, there were no significant differences on the items of mental demand 2, which was so easy that every group could solve the problem successfully.

2. Chunk size and the chunking effect

Independent unit information can be chunked as a single chunk of information if repeatedly experienced in treatments or instruction (training). The information that can be operated at one time in short term memory is treated as a unit chunk. Content free knowledge is mainly required in the cognitive tasks such as FIT tasks. In contrast, domain specific knowledge is required in the tasks such as electric circuit test. The tasks requiring content free knowledge are processed in the short-term memory as an independent unit of information. On the other hand, the tasks requiring domain specific knowledge may be processed by unit chunks based on the problem solver's base knowledge.

In this study, one partial process of the problem solving in the 2nd and 3rd test on the electric circuit tasks was treated to be chunked. The test results for the 1st, 2nd, and 3rd are shown in Figure 5. According to the graphs in figure 5, the success rates for each item in the 1st, 2nd and 3rd test increased along with the tests. The change of success rates as the increase of mental demand showed similar trend among tests. The results of ANOVA are presented in Table 2.

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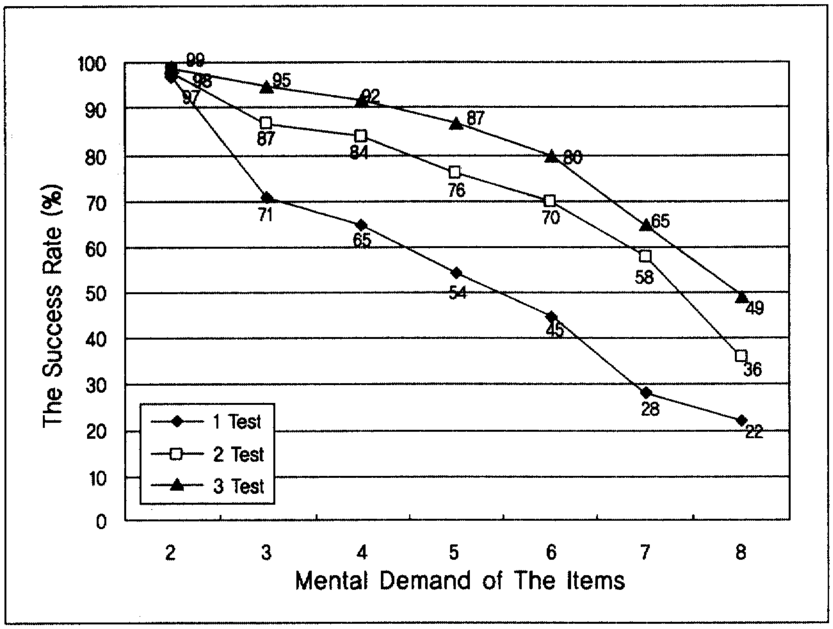

Fig. 5. The tests (1st, 2nd, 3rd test) results about the electric circuits task

Table 2. The results of ANOVA each item between tests

Mental demands	2	3	4	5	6	7	8	Total
F values	0.51	10.95*	12.13*	13.85*	14.99*	15.43*	7.76*	21.49

*$p < .001$

The results of the ANOVA analysis showed that the success rates for each item, excluding item 2, changed significantly among the tests. The significant differences of the success rates for each item among the tests resulted from the chunking effect by training. In other words, due to the instruction (training), the knowledge related to the electric circuit items was chunked within the problem solver's cognitive structure. As a result of chunking effect, the mental demand of the items decreases in the problem solvers cognitive structure.

3. Critical situations

Considering the cognitive psychological relation between the problem solver's mental capacity, and mental demand of the problem, successful problem solving requires larger mental capacity than the size of mental demand, or at least the same level of mental capacity. If the mental demand of a task is larger than the problem solver's mental capacity, critical situation where the success rate on the task rapidly decreases may appear.

The existence of the critical situations during the process of problem solving is a matter of concern from the cognitive psychological perspective. Previous studies have not yet clearly demonstrated on the possibility of the existence of critical situations. Most studies have mentioned the possibility vaguely, without any efforts to prove its existence. For the similar variations of the success rates, some researchers (Johnstone *et al.*, 1993) affirmed the existence of the critical situation, arguing the rapid decrease of success rates. On the other hand, other researchers (Opdennacker *et al.*, 1990) argued there was no rapid decrease.

In the FIT 752 task needing content free knowledge shown in Figure 3, the changes of success rates in each group sorted by mental capacity were examined. Mental capacity 4 group showed rapid decrease of the success rate on the item with mental demand 5. Mental capacity 5 group in the mental demand 6, and mental capacity 6 group in the mental demand 7, represented the typical characteristics of the critical situation as theoretically expected.

In the first test of the electric circuit requiring domain specific knowledge shown in Figure 4, the changes of success rates among groups showed different style from figure 3. According to Figure 4, the changes of success rates in each group showed gradual decrease, so that the critical situation, rapid decrease of success rates from for the items of a certain mental demand, was not clearly apparent.

The explanation for the different test results of the critical situation according to the tasks is as follows. The problem solver's mental capacity and chunk size within the cognitive structure, and mental demand of the problem, should be precisely determined before examining the existence of the critical situation. Especially, the chunk size and the mental demand of the problem depend on the knowledge in relation to the tasks.

The tasks requiring content free knowledge such as FIT 752 test remain usually unchunked within problem solver's cognitive structure. Therefore, the success of problem solving is determined by the correlation between the problem solver's mental capacity and the mental demand of the problem, not by the chunk size. The critical situation may be easily showed where simply the mental capacity and mental demand affect problem solving.

For the items requiring domain specific knowledge to solve them, like electric circuit task, the chunk sizes are likely to be different from individual to individual. So, according to the size of chunk, the mental demand that a problem solver actually recognizes would be different, even in the same test item. Therefore, there could be individual differences in the sizes of mental demand that show the critical situation to start to appear. To prove this, we analyzed the result of the problem solving in the 1st electric circuit task by individuals. The result of analysis is shown in Figure 6. A string of lines in figure 6 represents the result of an individual's problem solving.

The horizontal line on the upper side means success in the problem solving, while the horizontal line on the lower side means failure. The horizontal axis indicates different mental demand. From the upper-left success area to the lower-right failure area, the oblique lines indicate success in the previous items, and then failure in the next items, with larger mental

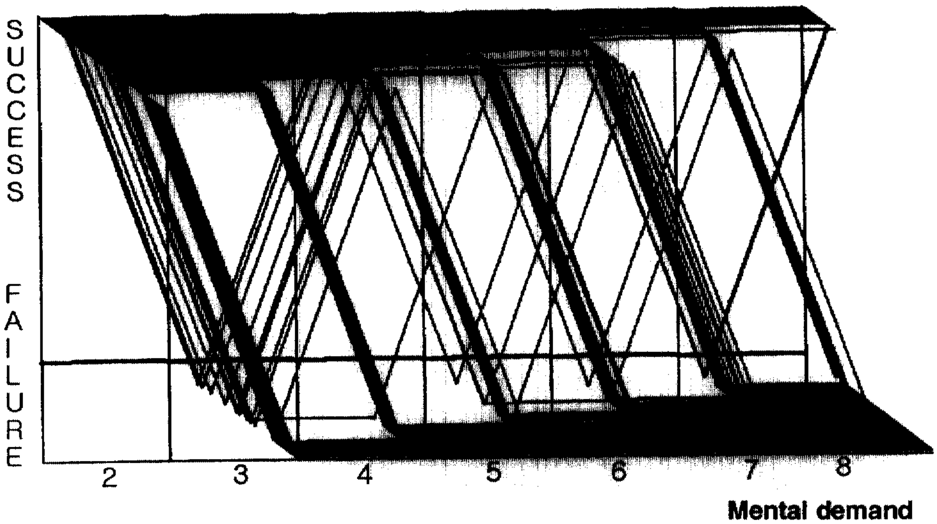

Fig. 6. Individual problem solving in the electric circuit tasks

demands. The long horizontal line in the upper area means continuous success, while that in the lower area is continuous failure.

The oblique lines from upper area to lower area show that one succeeded in the test items with low mental demand and failed in the test item with high mental demand. These downward oblique lines indicate the existence of critical situations. The oblique lines from lower to higher area means that one failed in the test items with low mental demand, and succeeded in the items with high mental demand. These upward oblique lines are not expected by the theory, and are considered to come from inaccuracy of the measurement.

Figure 6 showed that most of the students experienced critical situations, but the mental demand under the critical situation was significantly different with each individual. Despite a critical situation existing for a problem solver, if all individual results were summed up to find the effect of the critical situation for a group, they would not show any critical situation due to the difference of mental demands for the individuals.

V. Discussion and Conclusion

One purpose of this study was to investigate the effects of these cognitive psychological factors on the problem solving of the two kinds of tasks (content free, content specific). And the other purpose was to find out the existence of critical situation in problem solving tasks that each items of tasks with the same logical structure and content knowledge could have different sizes of mental demand.

The results were as follows.

Mental demand seemed to be one of the major factors affecting problem solving. Even when the logical structure and content knowledge of a problem were the same, students had more difficulties in the problem with large mental demand. These results suggest to us educational implications for judging the degree of difficulty of the test items on the basis of more quantitative criteria.

Even for a single problem solver, the success rate for the electric circuit items in relation to domain specific knowledge increased along with the sequence of the 1st, 2nd and 3rd test. Considering the training for the chunking before the 2nd and 3rd test, we can explain that the learning effect resulted from repeated instructionb (training) in the tasks that require the same logical structure as necessary for the school class. Since knowledge in relation to the items is chunked by the repeated training, mental demand of the items decreases.

The analysis of the achievements (the success rates) for each mental demand in both FIT 752 task and the electric circuit task showed that the group with larger mental capacity had higher achievement. That confirmed the mental capacity was a factor affecting the problem solving.

Considering cognitive characteristics of mental capacity and critical situation, the rapid decrease of the success rate, may appear in the items with a specific mental demand. The existence of critical situation seemed to be affected by task characteristics. There were critical situation of both a group and an individual in problem solving of FIT 752 test requiring content free knowledge. But the critical situation of a group was not appeared in problem solving task that need content specific knowledge(electric circuit test).

The analysis of achievement for each individual in the task that need content specific knowledge showed the existence of critical situation. Since mental demand of an item is different from individual to individual, the point where the critical situation appears will be different from individual to individual. Therefore, if all the individual results were summed up, the critical situation for a group would disappear as a result.

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