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The influence of metacognition on problem-solving performance

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The aim of the study was to determine the impact of metacognition on problem solving performance. For that purpose four experiments were conducted. In the first two the technique of feeling-of-warmth ratings was used to investigate the differences on metacognition between able and poor problem solvers. In our third experiment the technique of feeling-of-warmth ratings was combined with thinking aloud methodology. In the last experiment an attempt was made at the manipulation of metacognition by the use of instructions, based on the findings obtained in experiments 1 to 3. The main findings are as follows: (1) The pattern of feeling-of-warmth ratings of able problem solvers differs in relation to the problem type, (2) no such differences were obtained for the groups of average and low problem solvers. (3) Able problem solvers are more successful in classifying problems according to the solution approach used than are poorer problem solvers. (4) The feeling-of-warmth ratings of able problem solvers accurately reflect the solution processes expressed in the thinking aloud protocols. With poorer problem solvers no such congruency was found. (5) Metacognitive instructions were found to have an equalizing effect on performance of well - and ill - defined problems.

Metacognition refers to „knowledge and cognition about cognitive phenomena“ (Flawell,1979; p. 906). It includes knowledge of general cognitive strategies along with their monitoring, evaluation and regulation, as well as the beliefs about factors that affect cognitive strategies. From a theoretical viewpoint, metacognition seems to be an important aspect of cognition which can affect problem-solving performance (Doerner, 1974; Sternberg, 1982; Schoenfeld, 1983); empirical studies have, however, failed to give undivided support to the hypothesis. The main difficulty related to this kind of research is the assessment of metacognition in the individual's cognitive process while solving a problem. The most frequently used approach is thinking aloud method, where the respondents are asked to verbalize their thoughts as they work on a problem. Although there is evidence to suggest that the instruction to think aloud does not alter the sequence of cognitive process significantly (Ericsson & Simon, 1984), the method has its limitations: verbal protocols include only the events and operations of which the subject is aware at the time; additionally, they are sensitive only to sequential operations. It seems that these methodological shortcomings above all affect research into metacognition. Metacognitive processes occur rather infrequently in thinking aloud protocols. In his study of the processes involved in solving logical problems Doerner (1974) identified only .8% statements of respondents which could be classified as meta-components. Similarly low was the frequency of metacognitive statements in the study by Jaušovec (1988), who investigated different well and ill-defined literature problems. Although both studies have shown that the amount of overt metacognitive statements relates positively to problem-solving performance, it is difficult to draw conclusions about the relationship between metacognition and problem-solving performance because of the scarcity of the statements that can be classified as metacomponents. Similarly inconsistent are the comparative analyses of expert-novice differences in metacognitive knowledge. The research of Simon & Simon (1978) indicated that the experts in physics give fewer metacognitive statements than novices, the explanation being a more automatic process among the experts. On the other hand Schoenfeld (1983) describes some of the strategic misfunctions of college students engaged in mathematical problem solving as failures of goal setting, monitoring, and the evaluation of plans, which is the essence of metacognitive proficiency. The majority of students so engaged embark on a course of action that can be described as „read a problem, pick a direction, and then work on it until you run out of time“ (Schoenfeld, 1985, p. 366). Experts, by contrast, have metacognitive knowledge that leads them to ask themselves, and to answer, three kinds of questions: (a) what (precisely) are you doing, (b) what is the reason for doing it, and (c) how will the result be used later in the solution.

Metcalfe (1986a; 1986b; Metcalfe & Wiebe, 1987) has recently introduced a different method for investigating the individual's metacognitions during problem solving. The technique requires the subjects to make judgments about how close they feel to be to the solution of problems - called feeling-of-warmth (FOW) judgments - repeatedly during the

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course of problem solving. These judgments are called „warmth" judgments after the searching game in which one person hides an object and then directs others to where the object is by telling them that they are getting warmer-closer to the object, or colder-farther away. Subjects are asked to indicate how near they believe to be to the solution. Metcalfe (1986b) used the „feeling of warmth" procedure to examine the subjective phenomenology of different problems. She was able to show that the patterns-of-warmth ratings differed for insight and noninsight problems. Noninsight problems were characterized by more incremental pattern in the course of their solving in comparison to insight problems.

In our study we used the technique of FOWs to investigate differences in metacognition between good and poor problem solvers. According to Metcalfe's (1986a) findings we expected that able problem solvers - because of their higher abilities at estimating their closeness to the solution and using these abilities to decide the next steps in the cognitive activity - will differ in their FOW patterns when solving different problem types. On the other hand, poorer problem solvers, being less sensitive to the potential effectiveness of their problem solving approach, will not differ in their FOW ratings when solving different problem types.

In our first experiment we compared warmth ratings of successful and unsuccessful solvers of different well-defined and insight problems. In experiment 2 instead of insight problems we used ill-defined problems with goal characteristics which were not so rigorously defined. The aim of our third experiment was to investigate further the relationship between problem solving performance and metacognition. For that purpose we used the technique of FOW ratings in combination with thinking aloud methodology. In the last experiment manipulation of metacognition was attempted by the use of different instructions, based on the findings obtained in experiment 1 to 3. The main hypothesis was that these instructions would affect problem solving performance.

EXPERIMENT 1

The hypothesis was that able problem solvers, because of their higher monitoring abilities, will differ in their FOW patterns when solving different insight and well-defined problems.

METHOD

Subjects

One-hundred-seventy-six University of Maribor students attending an introductory course in psychology participated in the experiment. One-hundred-forty-nine subjects produced the data that could be used for our analysis. According to their problem-solving performance they were divided into 5 performance groups (0, 1, 2, 3, and 4-6 problems solved).

Materials

Six problems were given in random order to the subjects for solution, one at a time. Half of the problems were well-defined and half were insight problems. The well-defined problems were designated as such because they have clearly defined given states, goal states and operators; past literature has labelled them as multistep problems (Hayes & Simon, 1977; Simon, 1979). The insight problems are considered as such according to Metcalfe's (1986a, 1986b) definitions. The characteristic of insight problems is that the operators which are needed to transform the given state of the problem into the goal state are not clearly defined and must be elaborated by the problem solver (Doerner, 1979). As shown by Metcalfe & Wiebe (1987) the phenomenology of insight-problem solution is characterized by a sudden, unforeseen flash of illumination.

Procedure

The subjects were told that they would have to solve 6 problems. The time available for each problem was limited to 10 minutes. While working on a problem, subjects were asked to provide warmth ratings to indicate their closeness nearness to the solution. These ratings were marked with a slash on a 3-cm visual analogue scale on which the far left end was "cold", the far right end was „hot", and the intermediate degrees of warmth were to be indicated by slashes in the middle range. There were 40 lines that could be slashed for each problem, arranged vertically on the answer sheet. The subjects were told to put their first rating at the far left end of the scale and to make a slash on the far right end of the scale when they thought that they had solved the problem. Subjects then worked their way down the sheet marking warmth ratings at 15-sec intervals, indicated by an electronic clock.

RESULTS

Only those problems were analyzed in which the last warmth rating indicated that the subject thought that he/she had solved the problem (a slash on the far right end of the scale). For each problem the final presolution rating (i.e. the rating made on the trial prior to the far right rating that had to accompany the solution) was determined. According to this warmth rating the problems were rank ordered from greatest to least, for each person. Then a Goodman & Kruskal (Nelson, 1984) gamma (G) correlation between the rank orderings of the increment in warmth (going from the most incremental to least) and problem type was computed. These gammas were treated as summary data scores for each subject. A positive correlation indicates that the well-defined problems tended to have more incremental warmth protocols than did the insight problems.

Table 1.
Means and standard deviations of Gamma (G) correlations for the five performance groups solving inside and well-defined problems

	Groups - number of solved problems				
	0	1	2	3	4-6
n	19	32	55	26	17
M	-.16	.12	.18	.31	.61
SD	.46	.50	.52	.58	.54

A one-way analysis of variance showed that the five performance groups differed significantly in the amount of G correlation (F (4,144)=4.58, p <.005). A Newman-Keuls post test indicated that the average G correlation of the group of students who solved 4-6 problems was significantly higher than the average G of the other four groups (p <.01). The group of students who solved 3 problems differed significantly only from the group of students who solved none of the problems (p <.05). Moreover, it was found that the overall G correlations of the groups of students who solved none of the problems or only one problem, did not differ significantly from zero, whereas the overall correlations of the groups who solved 2, 3 and 4-6 problems differed significantly from zero (p <.01).

The results indicate that able problem solvers differ in their FOW patterns when solving insight and well-defined problems, whereas poorer problem solvers do not differ in their FOW ratings when solving different problem types. This is precisely what was expected given the hypothesis that high performers are more sensitive to the potential effectiveness of their problem solving approach than are poorer problem solvers.

EXPERIMENT 2

The hypothesis was that able problem solvers, because of their higher monitoring abilities, will differ in their FOW patterns when solving different ill-defined and well-defined problems.

METHOD

Subjects

The subjects were 112 students at the University of Maribor who took part in the experiment during their introductory course in psychology. According to their problem solving performance they were subdivided into 5 performance groups (0, 1, 2, 3, and 4-6 problems solved). Twelve subjects failed to give warmth ratings during problem solving, so they were excluded from the analyses.

Materials

The three well-defined problems were the same as in experiment 1. The ill-defined problems were designated as such because their goal states were only vaguely defined. Doerner (1983) considers the first step in solving this kind of problems to be the redefinition of open goals into more precise ones. The process then continues with testing the appropriateness of the reformulated goal. Such a strategy is called hypothesis testing and is considered to be of a dialectic nature (Reitman, 1965).

Procedure

The procedure in experiment 2 was the same as in experiment 1.

RESULTS AND DISCUSSION

The commonly used strategy in solving the ill-defined problems is hypothesis testing (Doerner, 1979; Reitman, 1965). The strategy involves a dialectic process, a continuous digression from and approximation towards the solution. It was expected that FOW ratings would show a similar pattern of coming closer and moving away from the right end of the scale. For the purpose of classifying such a pattern the visual-analogue scale was converted into a numerical one in such a way that the 3-cm rating lines were divided into 6 equal regions. A slash occurring anywhere within one of these regions was given the appropriate numerical warmth rating. For each problem the number of ratings which were preceded and followed by a rating lower by more than 1 unit on the numerical scale was determined. Such a rating was called a spike. Problems were then rank ordered according to the number of spikes and a gamma correlation was computed between problem types and rank orderings, for each person. These gammas were treated as summary data scores for each subject. A positive correlation indicates that ill-defined problems tended to have more spikes in their warmth protocols than well-defined problems.

Table 2.
Means and standard deviations of Gamma (G) correlations for the five performance groups solving ill-defined and well-defined problems.

	Groups - number of solved problems				
	0	1	2	3	4-6
n	17	37	21	13	12
M	-.07	.05	.13	.25	.62
SD	.33	.39	.57	.54	.48

A one-way analysis of variance indicated that the five performance groups differed significantly in the amount of G correlations (F (4, 95) = 4.78; p <.005). A Newman-Keuls post test indicated that the overall G correlation of the group of students who solved 4-6 problems was significantly higher (p <.01) than the G correlations of the other four groups. It was also found that only the G correlation of the group of students who solved 4-6 problems differed significantly from zero (p <.01).

The results of both experiments show that able problem solvers differ in their FOW ratings when solving different problem types. These differences are less pronounced for average problem solvers (Exp. 1) or are insignificant (Exp. 2). For low problem solvers no such differences were obtained. These findings confirm our hypothesis that the able problem solvers have higher abilities of estimating their closeness to the solution and they use them for deciding on the next steps in cognitive activity.

A second reason for the obtained greater variability of FOW-ratings in high performers could be a more flexible use of strategy (i.e. a change in strategy related to the problem type). On the other hand, an equal FOW-pattern for different problem types obtained with poor problem solvers could be indicative of a more rigid use of strategy. In our third experiment we tried to clarify this ambiguity using the technique of FOW-ratings in combination with thinking aloud method.

EXPERIMENT 3

METHOD

Subjects

One hundred and sixteen University of Maribor students participated in this experiment, each solving 10 problems. According to their problem solving performance 2 groups were subsequently selected: a high performance group (7 students who solved 8 and more problems), and a low performance group (7 students who solved none of the 10 problems).

Materials

In the first part of the experiment ten problems were given in random order to the subjects for solution, one at a time. Three problems were insight problems, 5 were well-defined problems and 2 were ill-defined. In the second part of the experiment we used one insight and one well-defined problem. The insight problem was the Coin problem used in experiment 1. The subject had to show how to arrange 10 coins in 5 rows (strait lines) of 4 coins in each row. (Dreistadt, 1969). The well-defined problem was the Cannibals and missionaries problem (Ernst & Newell, 1969). The subject had to figure out how to transport three missionaries and three cannibals across a river in a boat holding only two people at a time. An additional requirement was that the number of cannibals on either side of the river must not exceed the number of missionaries.

Procedure

The subjects were told that they would have to solve 10 problems. The time available for each problem was limited to 10 minutes. After testing, subjects were asked to classify the 10 solved problems according to the way they had solved them into a maximum of 3 categories, and to explain their classification.

In the second part of the experiment subjects were told that they would have to solve two problems. The time available for each problem was 15 minutes. While working on a problem subjects were asked to provide warmth ratings to indicate their perceived closeness to the solution. Respondents were also asked to think aloud while working on the problem. Taped protocols were later on typed verbatim.

RESULTS AND DISCUSSION

For each person the number of correctly solved problems and the number of correctly classified problems was determined. The respondents were, according to the number of the problems solved divided into 4 groups (solved 0-1, 2-3, 4-5 and more than 6 problems). A one-way analysis of variance indicated that the four performance groups differed significantly in the amount of correctly classified problems (F (3, 112)=30.74; p <.001). A subsequent Newman-Keuls test indicated that all the differences between means were significant on a .01 level. Kendall's Tau correlation coefficient between problem solving performance and the number of correctly classified problems (Tau = .61; p <.01) also proved to be significant. The results confirm our hypothesis that able problem solvers, because of their higher abilities in monitoring their own cognitive processes, are more successful in classifying problems according to the solution approach than the poorer problem solvers. These results are similar to the findings obtained by Maki & Berry (1984) who studied predictions of future test performance. They found that subjects who had the above-average test performance were more accurate in the predictions of their test performance than the subjects who scored below the average on that test.

A greater knowledge about cognitive phenomena in high performers was also documented by the comparison between the classification explanations given by high and low performers.

As shown in Figure 1 the explanations given by able problem solvers are more abstract, and reflect a ceratin amount of knowledge on the cognitive strategies involved in the solution process. In contrast, poorer problem solvers are more oriented toward concrete features of the solved problems in their explanation (e.g. the modality of the problem, whether the problem was difficult etc.) Similar differences are reported for procedural knowledge among experts and novices in different domains (Rohwer & Thomas, 1989). The procedural knowledge of novices appears to be clustered around concrete phenomena. In contrast, the procedural knowledge of experts is organized around higher-order principles.

Person A (Solved problems = 8; Classification score = 10)

Category 1 (classified all well-defined problems):
The approach to these problems is systematic and step-wise, involving logical thinking.

Category 2 (classified all ill-defined problems):
The problems in this category are solved with imagination. You need a lot of ideas and time to produce an acceptable solution.

Category 3 (classified all insight problems):
These problems are sometimes solved immediately, only by looking at them; or never.

Person B (Solved problems = 1; Classification score = 3)

Category 1 (classified 2 well-defined and 1 insight problem):
I solved these problems at once.

Category 2 (classified 1 well-defined problem):
These problems require more thinking.

Category 3 (classified 2 ill-defined, 2 well-defined and 2 insight problems):
These problems I couldn't solve. I had no idea.

Person C (Solved problems = 0; Classification score = 0)

Category 1 (classified 2 ill-defined and 2 well-defined problems):
These problems require writing.

Category 2 (classified 2 well-defined and 2 insight problems):
These problems require drawing.

Category 3 (classified 1 well-defined and 1 insight problem):
These problems are solved by calculation.

Person D (Solved problems = 1; Classification score = 2)

Category 1 (classified 3 well-defined and 2 insight problems):
The instruction provided a picture.
Category 2 (classified 2 well- and 2 ill-defined problems and 1 insight problem):
No picture was provided, only text.

Figure 1. Examples of classification explanations of able and poor problem solvers.

In the second part of the experiment the visual analogue scale was converted to a numerical one in the same way as in experiment 2. For each problem and person the final presolution rating was determined. A one-way analysis of variance was plotted in order to determine the differences in warmth ratings between the two performance groups for each problem type. No significant differences were found for insight ($F(1, 12)=1.66$) and well-defined problems ($F(1, 12)=4.09$). On the other hand, a two-way analysis of variance for repeated measures on one factor indicated a significant group problem-type interaction ($F(1,12)=13.71$; $p < .005$). Subsequent t-tests indicated that the high performance group differed significantly in warmth ratings when solving the insight and the well-defined problem ($t(6)= 9.02$; $p < .001$). For the low performance group the differences in FOW-ratings were insignificant ($t(6)=2.12$). The results are similar to those obtained in experiment 1.

The comparison of FOW-ratings and thinking aloud protocols between the two performance groups indicated that the able problem solvers have higher abilities of estimating their closeness to the solution than the poorer problem solvers.

As shown in Figure 2 the feeling of warmth ratings of able problem solvers reflected the solution processes expressed in the thinking aloud protocols precisely. With poorer problem solvers no such congruency was found. For example: Person A started again the solution process from the beginning because of a perceived mistake. This change is also documented in the FOW ratings, changing them from 3 to 1. In contrast, even though person C started the solution process from the beginning several times, the FOW ratings show a continuous incremental pattern. Similarly unrelated are the thinking aloud statements and FOW-ratings for person D. On the other hand, the thinking aloud protocol of person E shows a step-wise solution approach which is not accompanied by an adequate change in FOW-ratings.

EXPERIMENT 4

The basic aim of experiment 4 was to influence problem solving performance with instructions aimed at metacognition. The main hypothesis was that instructions would affect problem solving, thus confirming the role of metacognition in intellectual performance.

METHOD

Materials and procedures

Thirty-six students from the University of Maribor participated in the experiment. They were randomly divided into two groups, one control and one experimental. The respondents solved 6 problems, 3 well- and 3 ill-defined. For each problem the number of correct answers was determined and transformed into T scores which were summarized and divided by three to obtain the average T score for each person's performance of well-defined and ill-defined problems.

The respondents in the experimental group received instructions during problem solving. Before the experiment began the respondents received a one-hour introductory lesson on problem solving processes. Each subject received written materials (6 pages) outlining the differences between problem types and different solution strategies. The respon-

Person A (Solved problems = 8)

TA protocol for problem Cannibals:	FOW-rating	Time in sec.
(sighing) one M goes back ... we have on the right two C, o... (sighing) and then ... on the	3	120
left we have three C, one M goes to the ...No, here we have two C ... wrong Let's start again (erases the written answers) First we have one C and one M	1	140

(The pattern of FOW-ratings is then incremental up to the solution.)

Person B (Solved problems = 8)

TA protocol for problem Cannibals:	FOW-rating	Time in sec.
Boat, cannibal, cannibal, the missionary goes back and takes one cannibal, cannibal, missionary, missionary, cannibal, missionary...	2	140
Cannibal, boat ... That's wrong! Cannibal, cannibal, missionary ... That's all wrong... (Erases the answers) We have here ...	1	160
two cannibals and two missionaries ... and here ...		

(The pattern of FOW-ratings is then incremental up to the solution.)

Person C (Solved problems = 0)

TA protocol for problem Cannibals:	FOW-rating	Time in sec.
First I'll take one cannibal and one missionary ...	1	80
(Reading the problem instruction) First I'll take two cannibals, one, two they go across the river ...	2	180
(Reading the problem instruction) First I'll take ... one cannibal ... We have here on the left then one C and three M	3	220
(Reading the problem instruction) OK., first I'll take one cannibal and one missionary ...	5	340

Person D (Solved problems = 0)

TA protocol for problem Coins:	FOW-rating	Time in sec.
(Reading the problem instruction) In each row four coins	1	160
One... (counting to ten) Reading the problem instruction) In each row four coins ... One, two, three, four ...	2	180
(Reading the problem instruction) One... (counting to ten) In each row four coins ... How?	3	200

(The pattern of FOW-ratings is incremental up to the rating given with the solution.)

Person E (Solved problems = 0)

TA protocol for problem Cannibals:	FOW-rating	Time in sec.
Two cannibals go ashore, on the right. Here there are one M and one C ... OK.	1	160
(Reading the problem instruction) One C goes back ... now we have two ... three ... Two missionaries on this side	1	180
and one to the other ... one cannibal and then on the left one cannibal, so, one M must go on the other side, the boat is ...	1	200
here ... One M goes back, takes one M ... (pause) Two missionaries, and one cannibal go to the left ... On the left we have now one C and one M, one C is in the boat ...	1	220
This one goes to the right ... two M ... One C is still here, he disembarks ... we go back for another missionary, OK. this is OK.	1	240

(The last rating indicates that the person has reached the solution.

Figure 2. Examples of thinking aloud protocols and FOW-ratings of able and poor problem solvers.

dents were told to study the materials because they will have to use them during the problem solving. First, the respondent read the problem. Then he/she was asked to designate the problem either as well- or an ill-defined one and to suggest the solution strategy to be used. The experimenter then asked the respondent to think of his/her cognitive processes while solving the problem, for the solution strategies will be discussed at the end of the session.

The respondents of the control group received no instructions. For both groups the time available for solving each problem and for the instructions was limited to 20 minutes.

RESULTS AND DISCUSSION

The influence of metacognitive instructions on problem solving performance was determined by two one-way analyses of variance for each problem type. The analysis of variance has shown a significant effect of the instruction on performance of well-defined problems ($F(1, 34) = 35.6$; $p <.001$) and on performance of ill-defined problems ($F(1, 34) = 14.2$; $p < .001$). Furthermore, the results indicate that metacognitive instructions have an equalizing effect on performance of well- and ill-defined problems. The correlation between the performance on well-defined and ill-defined problems in the control group was found to be insignificant ($r = -.18$) while in the experimental group it proved to be significant ($r = .65$; p <.01). Such influence of metacognitive instructions may be explained by the fact that individuals, when solving problems, usually use similar solution strategies regardless of the problem type. This is the suggestion put forward by the results of experiments 2 and 3. Even though the combination of FOW-ratings with TA protocols in experiment 4 did not show significant differences in the strategies used by gifted and poor problem solvers, the results indicate that the gifted problem solvers are more efficient in monitoring and evaluating their cognitive process than the poor ones. One can assume that such processes result in a change in the solution approach in gifted problem solvers, and a rigid pursuance of the selected direction in poor problem solvers.

CONCLUSION

The study was designed to investigate the influence of metacognition on problem-solving performance. The cumulative results indicate that metacognition is an important factor in problem-solving performance, equally important in solving closed and more creative, open ended problems. Able problem solvers seem to have higher abilities of estimating their closeness to the solution and they use them in deciding on the consecutive steps in cognitive activity. As shown in experiment 3, capable students seem to know much more about general cognitive strategies - how and when to apply them - than less capable individuals do. Poor problem solvers are also less efficient in monitoring their own cognitive process during problem solving than the able ones, and therefore use a more rigid solution approach.

A second important finding of the present study is that it proved the FOW („feeling of warmth")-ratings to be an efficient method for studying metacognition. Moreover, experiment 2 proved that the comparison of the number of spikes could (in addition to slope and increment) represent an efficient way of analyzing the FOW ratings. This analysis proved to be especially useful for the group of ill-defined problems. However, there are still some open questions. For instance, what do FOW-ratings exactly mean to the respondent? Experiment 3 indicated that able problem solvers are more accurate in establishing their closeness to the solution. This could be indicative of a better monitoring process in able problem solvers. On the other hand, the different FOW-ratings given by gifted problem solvers when solving different problem types and equal FOW-ratings given by average students, could also point to a more flexible versus rigid strategy use in the respective ability groups. Even though these two assumptions are not mutually exclusive, further research is needed to clarify this ambiguity.

The findings that individual differences in problem solving are related to metacognition, and that rather simple instructions about metacognition can significantly affect problem solving have important educational implications. Instruction should be designated to explicitly assist students in acquiring metacognitive knowledge of how to plan their problem-solving efforts, how to set goals and subgoals for these efforts, and how to monitor their progress towards those goals.

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