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Title	Cognitive variables in problem solving in stoichiometry
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Source	National Association for Research in Science Teaching (NARST) 2001 Annual Conference, 25-28 March 2001, USA

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Citation: Lee, K. -W. L., Tang, W. -U., Goh, N. -K., & Chia, L. -S. (2001, April 25-28). *Cognitive variables in problem solving in stoichiometry*. Paper presented at the National Association for Research in Science Teaching (NARST) 2001 Annual Conference, 25-28 March 2001, USA.

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## COGNITIVE VARIABLES IN PROBLEM SOLVING IN STOICHIOMETRY\*

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### Abstract

The purpose of this study is to investigate if the cognitive variables that have been found to be important predictors of problem solving performance in the earlier studies are valid across different topics and levels. The topic for the two previous studies was Electrochemistry at the Grade 12 level whereas the topic for this study was Stoichiometry at the Grade 9 level. One hundred and fifteen Grade 9 chemistry students (aged ranging between 13 and 16 years old) from three classes in the government boys' secondary school were involved in this study. The validation was done by designing and administering tests to the students to assess their problem-solving performance and the related problem-solving ability and skills in Stoichiometry. The results of this study and the comparison of the results between this study and the two previous studies are presented in the paper.

### Background of the Study

Lee (1985) did a study in Australia to investigate cognitive variables that affect problem-solving performance in electrochemistry at Grade 12 level. She found that successful problem solving is related to several important cognitive variables which can be grouped as block variables, namely *Prior Knowledge (Specific Knowledge and Non-Specific but Relevant Knowledge)*, *Linkage skills (Concept Relatedness and Idea Association)*, and *Problem Recognition Skills (Problem Translating Skill and Prior Problem Solving Experience)*. These block variables consist of predictor variables as shown in the above brackets. It was also found that the influence of these predictor variables on the success of problem solving varies with the familiarity of the problems. The meanings of these cognitive variables have been discussed and reported in details in the previous paper (Lee, Goh, Chia & Chin, 1996) and are now briefly described.

*Prior Knowledge* variable which concerns the problem solver's knowledge base required for solving a problem, consists of two types, one is specific knowledge directly related to the problem and the other is nonspecific but relevant knowledge to the subject area of the problem. *Linkage* variable which concerns the integrating and assimilating effect of the cognitive structure in problem solving, consists of two types, one is *Concept Relatedness* and the other is *Idea Association*. *Concept Relatedness* is a measure of the relatedness between concepts that are involved in problem solving. *Idea Association*, on the other hand, measures the ability to associate ideas, concepts, words, diagrams, or equations through the use of cues which occur in the statements of the problems. *Idea Association* involves the retrieval of information from the existing cognitive structure and the linkage between the retrieved information and the external cues. *Problem Recognition Skill* which concerns the problem solver's information processing skills, consists of *Problem Translating Skill* and *Prior Problem Solving Experience*. *Problem Translating Skill* measures the problem solver's ability in comprehending, analyzing, interpreting and defining a given problem. *Prior Problem Solving Experience* measures the problem solver's prior experience in solving the similar problems.

The same study was replicated in Singapore to determine if the same cognitive variables had the same influence in problem-solving success, when time and culture were different (Lee, *et al.* 1996). The results of the study were consistent with the Australian study. All the cognitive variables, except *Concept Relatedness*, are significant determining variables of problem-solving performance.

\* Paper presented at the National Association for Research in Science Teaching (NARST) 2001 Annual Conference, USA, 25-28 March 2001.

*Idea Association* and *Problem Translating Skill* are the more important predictors for solving the familiar problem. The five cognitive variables: *Idea Association*, *Problem Translating Skill*, *Prior Problem Solving Experience*, *Specific Knowledge* and *Non-Specific Knowledge but Relevant*, are all significant predictors of problem solving performance on solving partially familiar problems. Among them, *Idea Association* is the most influential predictor. *Problem Translating Skill* is a significant predictor for unfamiliar problems. Lee *et al.* (1996) have concluded that acquisition of knowledge alone does not guarantee problem-solving success. Certain problem solving skills such as linkage and problem translating skill must be learned. This formed the basis of the present study, which is an extension of the two studies done earlier (Lee, 1985; Lee *et al.*, 1996).

This present study was designed to verify the importance of the cognitive variables to problem solving in Chemistry across topics and levels. The topic for the two previous studies was Electrochemistry at the Grade 12 level whereas the topic for this study was Stoichiometry at Grade 9 level. The variable of *Prior Problem Solving Experience* was not included in this study because this variable is not a teachable variable and also the topic of Stoichiometry was a completely new content area to the students. Stoichiometry is chosen for this study because research has shown that many students find it difficult to understand the concepts involved and to apply the concepts to solve Stoichiometry problems (BouJaoude and Barakat, 2000). It is important to find out what cognitive variables determine the success of problem solving in Stoichiometry so that teachers can emphasize their teaching in these cognitive variables to enhance problem-solving performance. The validation was done by designing and administering tests to the students to assess their problem-solving ability and skills in solving problems in Stoichiometry. The comparison of the results of the three studies is also presented in the paper.

### Methodology

One hundred and fifteen Grade 9 chemistry students aged ranging between 13 and 16 years old from three classes in the government boys' secondary school were involved in this study. Five instruments testing the six variables, including the dependent variable, namely Problem Solving Performance (PSP); and five independent (cognitive) variables, namely *Specific Knowledge (SK)*, *Non-Specific but Relevant Knowledge (NSRK)*, *Concept Relatedness (CR)*, *Idea Association (IA)* and *Problem Translating Skill (PTS)* were designed and administered as post-tests to the students after teaching the topic of Stoichiometry.

Of the five instruments, two were traditional types of tests (multiple-choice questions and problem-solving test) while the rest were non-traditional, open-ended type of tests. All the five instruments were designed on the content of Stoichiometry, but their formats were modeled upon similar instruments used in Lee's (1985) study done in Australia. The six variables, five instruments and the types of instruments are summarized in TABLE 1.

Problem Solving Test for Students (PSTS) was designed to measure the dependent variable of *Problem solving Performance (PSP)*. It consisted of six problems in Stoichiometry. The teacher of these students (second author of this paper) was invited to classify the familiarity level of these problems based on the definitions provided. "Familiar problems" refer to the problems which are similar to the questions that have been set in O-level examinations or used in the textbooks. "Partially familiar problems" refer to the problems which are in part similar to the questions having been set in O-level examinations or used in the textbooks. "Unfamiliar problems" refer to the problems which have not appeared either in O-level examinations or in the textbooks. The teacher classified four of the six problems as familiar problems (Problems 1, 3, 4 and 6) whereas the other two problems (Problems 2 and 5) as partially familiar problems.

**TABLE 1: Problem-solving variables and instruments**

Variables	Instruments	Type of Instruments
Concept Relatedness (CR)	Concept Relatedness Test (CRT)	Non-traditional
Idea Association (IA)	Association Test (AT)	Non-traditional
Specific Knowledge (SK)	Verbal Knowledge / Intellectual Skill Test (Section A) (VKIST)	Multiple-Choice Questions
Non-Specific but Relevant Knowledge (NSRK)	Verbal Knowledge / Intellectual Skill Test (Section B) (VKIST)	Multiple-Choice Questions
Problem Translating Skill (PTS)	Problem Translating Test (PTT)	Non-traditional
Problem Solving Performance (PSP)	Problem Solving Test for Students (PSTS)	Traditional Problem Solving

### Results

The Cronbach  $\Delta$  reliabilities were calculated for all the five instruments. Correlation analyses were done to determine the relationships among the variables (five predictor variables and one dependent variable). In addition, multiple regression analyses were conducted for the overall problem in the PSTS with respect to the three block predictor variables and the five individual predictor variables. This was done to determine whether all the block predictor variables and the individual predictor variables contribute significantly to successful problem solving.

### Reliability of the instruments

The Cronbach  $\Delta$  reliabilities of all the five instruments are presented in TABLE 2. The scoring systems used for scoring all the five instruments, involved a number of scoring items. The numbers of the items involved in the scoring systems for all the instruments are also shown in TABLE 2.

**TABLE 2: Reliabilities of the instruments**

	Instrument	Variable	Cronbach $\Delta$	No. of items
1.	CRT (Overall)	CR	0.93	30
2.	AT (Overall)	IA	0.81	13
3.	VKIST (Section A)	NSRK	0.39	10
4.	VKIST (Section B)	SK	0.44	10
5.	PTT (Overall)	PTS	0.69	12
6.	PSTS (Overall)	PSP	0.82	18

### Correlation analyses

The Pearson correlation coefficients among the five predictor variables and the performance variable for the overall *problem solving performance (PSP)* are shown in TABLE 3.

**TABLE 3: Correlation between predictor variables and performance variable on the overall problem**

Variable	PSP	CR	IA	NSRK	SK	PTS
PSP	1.00					
CR	0.17*	1.00				
IA	0.60**	0.06	1.00			
NSRK	0.45**	0.10	0.38**	1.00		
SK	0.46**	0.03	0.22*	0.43**	1.00	
PTS	0.54**	0.04	0.54**	0.44**	0.34**	1.00

\*Correlation is significant at the 0.05 confidence level (2-tailed).

\*\*Correlation is significant at the 0.01 confidence level (2-tailed).

From TABLE 3, it is shown that all the predictor variables were moderately and significantly correlated to the performance variable for the *overall problem solving performance (PSP)*, except for *Concept Relatedness (CR)*, which correlated weakly but significantly. The scores for the six cognitive variables reflected theoretical expectations with respect to relationships among the variables. All the other predictor variables correlated significantly with each other at a confidence level of either 0.01 or 0.05 using two-tailed tests. *Concept Relatedness (CR)* correlated least with the other predictor variables. This trend was also observed to be the case in two similar studies done earlier (Lee, 1985; Lee *et al.*, 1996). A possible explanation for this observation can be that *Concept Relatedness (CR)* is less reflective in the process of problem solving as compared to the *Idea Association (IA)*.

#### Multiple regression analyses

The best-fit model for problem-solving performance in this study was first examined by checking statistically the effect of interaction of all the five cognitive variables on the problem solving performance. The results show that the effect of the interactions was insignificant (TABLE 4). The best-fit model for problem-solving performance for this study is therefore the additive model of five predictor variables, excluding the interactions (see "Predictor Variables").

#### Block predictor variables

The variance contributions of the individual block predictor variables to the problem-solving performance were given by the differences in the variances of Model 1 (TABLE 4) and each of these other models, Models 3, 4 and 5 (TABLE 4). Model 3 contained the two block predictor variables, namely: *Linkage (L)* and *Prior Knowledge (PK)*, while Model 4 contained the two block predictor variables, namely: *Linkage (L)* and *Problem Recognition Skill (PRS)*. Model 5, on the other hand, contained the two block predictor variables, namely: *Prior Knowledge (PK)* and *Problem Recognition Skill (PRS)*. The variances of problem-solving performance contributed by each of the block predictor variables are shown in TABLE 5.

For the overall problem, about 48% of the variance of problem-solving performance was accounted for by the five predictor variables (TABLE 4, Model 1) and a total of about 19% by the block predictor variables (TABLE 5). All the three block predictor variables were found to be statistically significant in predicting the overall problem-solving performance, with *Linkage (L)* being the most significant.

**TABLE 4: Variances of Models 1 - 5**

Model	Variable	Overall
1	5 Predictor Variables	0.481
2	5 Predictor Variables & Interactions	0.492
3	Component Variables of L & PK	0.456
4	Component Variables of L & PRS	0.442
5	Component Variables of PK & PRS	0.358

**TABLE 5: Variances of Problem-Solving Performance Accounted for by the Block Predictor Variables**

Variable	Overall
PRS	0.025*
PK	0.039*
L	0.123***

\* P&lt;0.05

\*\*\* P&lt;0.001

*Predictor variables*

The variances of problem-solving performance accounted for by each of five predictor variables for the overall problem were computed in a similar manner as in the case of the block predictor variables. The contributions of the overall problem are shown in TABLE 6.

**TABLE 6: Variances of problem-solving performance accounted for by the five constituent predictor variables**

Variable	Overall
PTS	0.025*
NSRk	0.004
SK	0.029*
CR	0.021*
IA	0.101***

\* P&lt;0.05

\*\*\* P&lt;0.001

Four out of the five cognitive variables investigated, namely: *Concept Relatedness (CR)*, *Idea Association (IA)*, *Specific Knowledge (SK)* and *Problem Translating Skill (PTS)* (except for *Non-Specific but Relevant Knowledge, NSRK*), were significant in determining the overall problem-solving performance in Stoichiometry (TABLE 6). *Idea Association* was found to be the most important predictor for the success of solving stoichiometry problems.

One point to note, although statistically the *NSRK* variable was not significant in accounting for the overall problem-solving performance, conceptually it was an important background knowledge

required for understanding and solving stoichiometry problems. In addition, *NSRK* was significantly contributing to problem-solving performance in Problem 3 and Problem 5 respectively. Based on the above reasons, *NSRK* was not removed from the model. As a result, Model 1 (TABLE 4) consisted of five predictor variables.

### Interpretation of the Results

The above results seem to imply that the 'linkage' variable was the utmost important predictors for the success of solving Stoichiometry problems, ranging between the familiar and partially familiar types. Three aspects of linkage in learning process in science include: "(1) internal linkage in a cognitive structure, (2) activation of a particular part of cognitive structure for learning, and (3) external linkage between an existing cognitive structure and the new learning content." (Lee *et al.*, 1996, page 693). In problem solving, *CR* is a measure of the relatedness between concepts that are involved in problem solving which is closely related to the first aspect of linkage that involves the linkage among the known concepts. *IA* measures the ability to associate ideas, concepts, words, diagrams, or equations through the use of cues that occur in the statements of the problems. It is related to the second and third aspects of linkage mentioned above. In this study, *IA* has greater influence than *CR* in problem-solving performance that this result is consistent with the earlier studies. Once again, this result confirms the earlier finding that the linkage process that involves eliciting information from the existing cognitive structure by the external cues is more significantly influential than that which involves cross-linking between concepts in the existing cognitive structure.

For the 'prior knowledge' variable, although many students scored reasonably high for both the *NSRK* variable (Mean is 78%), and *SK* variable (Mean is 76%), it was found that except for the specific knowledge, the general knowledge of the problems did not seem to have much effect on the problem-solving performance. This could probably be explained by the familiarity of the six problems. If the students are familiar with the problems, the correct knowledge they possess, especially *NSRK*, would not be crucial in solving them, unless the knowledge has been meaningfully learnt before it could be effectively used for problem solving (Ausubel, Novak and Hanesian, 1978).

For the 'problem recognition skill' variable, or 'problem translating skill, *PTS*' (the only constituent variable in this study), was also important in solving Stoichiometry problems. Its influential level was about the same as *Specific Knowledge (SK)* of the 'prior knowledge' variable, however, was much less influential than *Idea Association* of 'linkage' variable. We could explain this, again, by the familiarity level of the problems. Since many students were familiar or partially familiar with the six problems, the translation of the statements including the goals of the problems would not be too difficult for many of them. The success of problem solving in this case would then depend greatly on how relevant one can retrieve the appropriate information from the existing cognitive structure, and how effective one can link the information retrieved and the information in the problem statements so that a solution sequence is possible. It is therefore that 'linkage' variable is a more significant predictor than 'prior knowledge' and 'problem recognition skill' variables.

### Comparisons Between the Electrochemistry and Stoichiometry Studies

In comparison between this study (Stoichiometry Study) and the previous studies (Electrochemistry Studies), some consistent results emerge. The overall results of Stoichiometry Study based on a mixture of six problems ranging between familiar and partially familiar problems and the results of Electrochemistry Studies on the three respective problems of different familiarity (familiar, partially familiar and unfamiliar problems) were compared. The relationships between the effects of cognitive variables on problem-solving performance and the familiarity level of the problems for both topical studies (Electrochemistry studies and Stoichiometry study) are summarized in TABLE 7. From TABLE 7, it is shown that the importance of block predictor variables in problem-solving performance in the Stoichiometry Study appears to have the same pattern as the results of partially familiar problem in the Electrochemistry Studies. Apart from some slight difference in the relative importance of the various individual predictor variables in the two topical studies, *IA*, *SK* and *PTS* variables are consistent in their contribution to problem-solving performance regardless the different topics and levels. The Stoichiometry Study confirms the Electrochemistry

Studies in that all the cognitive variables, especially *IA*, *SK* and *PTS* are important in solving chemistry problems. The importance of *CR* and *NSRK* to problem solving in terms of statistical evidence varies from one study to another that their significance in problem solving is not conclusive at this stage. Nevertheless, the results of the three studies provide consistent evidence of the importance of the cognitive variables to problem solving in chemistry and their influence is evidently affected by the familiarity of the problems instead of the topic and level.

TABLE 7: Comparison of the results of Electrochemistry Studies and Stoichiometry Study

Electrochemistry Studies				Stoichiometry Study			
Familiar Problem	L (IA)	> (slightly)	PRS (PTS)	Problems ranging between familiar and partially familiar problems			
Partially Familiar Problem	L (IA)	>	PRS (*PPSE>PTS)	≈	PK (SK≈NSRK)	≈	PRS (PTS)
Unfamiliar Problem	PRS (PTS)			Overall Results: L > PK ≈ PRS (IA > CR) (SK) (PTS)			

\* *PPSE* - *Prior Problem Solving Experience* variable, a constituent variable of *Problem Recognition Skills* block predictor variable, was not included in the Stoichiometry Study.

## CONCLUSION

The results of this study show that for a successful problem solving of a mixture of familiar and partially familiar problems in Stoichiometry, problem solvers must make relevant links between cues from the problem statement and the underlying knowledge base, possess correct specific knowledge and make adequate translation of the problem statements. However, if the problem solvers are unable to make the relevant links they may have difficulty in solving this type of problems even though they might have the required prior knowledge and might translate adequately the problem statements.

The results of the three studies seem to suggest that the difference in topics and levels appeared to have little effect on the relative importance of these variables on problem-solving performance. Instead, the familiarity of the problems is evidently influencing the relative importance of the cognitive variables both the block and the constituent predictor variables to problem solving.

This study confirms, once again, the findings of our earlier studies and what other researchers (e.g. Gabel & Bunce, 1994; Niaz, 1995; Heyworth, 1999) have stressed earlier that an effective problem solving requires the following problem-solving ability and skills:

- (1) A good understanding of and meaningfully learnt knowledge;
- (2) Appropriate problem-solving procedures which include the re-description of the original problem in a way facilitating the subsequent search for its solution;
- (3) Relevant linkages of information between the information of problem statements and the existing cognitive structure



Teachers may emphasise their instruction of problem solving on the above three aspects to improve students' problem solving performance in Chemistry.

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