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Chemistry Students' Competence throughout their BSc Course in some Problem-Solving Strategies

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ABSTRACT

The main objective of the study was to test chemistry students' competence, in the first, second and final years of their BSc course, in some basic problem-solving strategies. Five strategies were tested: clarification and clear representation of problems; focusing sharply on the goal; identification and use of relevant principles; use of equations for calculations and deductions and use of a step-by-step procedure. The study method used was the analysis of students' solutions to questions that were carefully designed to test competence in problem-solving strategies. The study showed that performance was poor in all the problem-solving strategies tested and that there was no improvement in performance as students progressed from year to year. About a half of the students tested (average performance in all of the 11 questions used for testing) had difficulty in answering the questions. Possible reasons for students' difficulties are identified and suggestions are made for rectifying the difficulties. It is suggested that difficulties with the use of cognitive strategies are often not due to students' inability to understand and use them but to insufficient emphasis being placed on them in their courses. Since an increase in competence in cognitive strategies and cognitive skills can be expected to lead to more efficient learning and problem-solving, not only in education courses but also throughout their lives, there is a need for training students in them until they become automatic and spontaneous mental operations. Such training should be integrated, throughout any course, with the teaching of content knowledge.

KEYWORDS

Cognitive strategies, thinking, problem solving, students' difficulties with problem solving.

1. Introduction

Cognitive skills and strategies[1–4] are the tools for all mental activities. Competence in them is hence essential for the effective learning and storage of knowledge in memory, and for the fluent retrieval and use of this stored knowledge, for example in problem solving[5–7], not only in education courses but also throughout our lives. It is also now generally believed that intelligence (Intelligence Quotient, IQ) depends not only on genetic inheritance but also on our level of competence in cognitive skills and strategies[8,9]. The development of students' competence in cognitive skills and strategies should therefore be an important objective of all education courses. They should be more competent in them at the end of any course than at its beginning.

Concerning research in cognitive strategies and skills, most of them have been done with curricula and students in schools[10,11], and the amount of work done with university students is somewhat limited[12,13]. In South Africa, some research has been done with first year university chemistry students[14–16] and with matric physical science teachers[17]. These studies indicated that their competence in cognitive skills and strategies was poor. No studies have been reported on testing students' cognitive abilities throughout the years of a university degree course. The main purpose of this research was to obtain information about students' competence in some basic cognitive skills and strategies throughout the years (first, second and final years) of a BSc course.

This study was restricted to strategies and skills needed for problem solving and it did not consider any learning aspects. This article discusses students' performance in the questions that tested competence in cognitive strategies. Their performance in the questions that tested cognitive skills will be reported in another paper.

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2. Cognitive Strategies Tested and Their Importance

Cognitive strategies have been defined in many different ways. Often they are stated broadly, for example[18] as 'Devise/choose solution plan', 'Execute the plan'. This ensures wide applicability of a strategy across many disciplines and areas. For the purpose of testing someones competence in strategies it would, however, be better to define them sharply. The cognitive strategies tested in this study have been defined more sharply and are:

- Clarification and clear representation of problems.
- Focusing sharply on the goal.
- Identification and use of relevant principles.
- Use of equations for calculations and deductions.
- Use of a step-by-step procedure for the solution.

These strategies were selected for the study because they are particularly important for the solutions of problems in the physical sciences. Because of the wide applicability of these strategies they have been incorporated into a general model for solving problems in chemistry[5].

Consider the first strategy: clarification and clear representation of problems. The use of this strategy will reduce memory overload and hence simplify problem solving and also help prevent careless errors. Many types of difficulties and errors of students during problem solving are due to their rushing into the

solutions, without initially clarifying the problems. This strategy is much broader than the other strategies tested in this paper and it includes, among others, the following:

- identification of all the data given and the goal and giving explicit symbols to them;
- representing symbolically all the relevant information (e.g. data, goal, processes) in a coordinated manner, for example as diagrams, graphs, tables or equations.

The second strategy stated above – focusing sharply on the goal – is of crucial importance for successful problem solving. Though this strategy is very easy to understand and use, many students do not use it. For example, to calculate some quantity (e.g. density), many students do not recognize that they must start the solution by focusing sharply on the defining equation for that quantity. Instead, they start the solution with the data and information given and the equations they remember[5]. This is not a logical approach.

The third strategy stated above must always be used during problem solving. Reasoning, calculations and deductions must always be based on explicitly identified principles. Non-use of this strategy will often cause errors and also will not help achieve one of the important objectives of problem solving in education courses which is to reinforce the learning of the principles of the subject studied[5].

The fourth strategy stated above is the use of equations for calculations and deductions. This strategy would sharpen problem solving because information in equations is concise and unambiguous. The alternative to the use of equations for calculations and deductions is verbal reasoning which is often cumbersome and error-prone. Many people have difficulty with verbal reasoning and the difficulty is probably associated with the need for processing *lengthy* information (information in statements is lengthy compared with those in equations) in working memory (short-term memory), which is limited in most people[19,20]. A good method for 'by-passing" verbal reasoning would be to translate all the relevant quantitative information given in verbal statements into equations and then use the equations for calculations and deductions. This strategy of using equations, however, needs ability to do the following operations: translate all quantitative information in verbal statements into equations; deduce the information organized in equations and combine different equations.

The last strategy stated above is the use of a step-by-step procedure (step-by-step reasoning) for the solution of problems. This strategy simplifies problem solving because it implies the breaking down of a complex problem into simpler problems, the solution of the simpler problems and the combination of the solutions to the simpler problems.

Competence in strategies is needed for the effective solutions of problems encountered by students not only in their science courses but also throughout their lives. There are two main types of difficulties associated with the use of strategies: (a) lack of awareness of the need and importance of the strategies; (b) lack of competence in the skills needed to execute the strategies.

3. Objectives and Method of Study

The main objectives of the study were:

- to highlight the importance of using cognitive strategies during problem solving;
- to test the competence of first, second and third year (final year) BSc Chemistry students at our university, during a particular year (2009), in some cognitive st rategies that are important for problem solving in chemistry;
- to compare the performance of students during the three years;
- to identify, by studying students' solutions to the questions, reasons for their difficulties with strategies and to suggest methods for rectifying them.

The study method used was the analysis of students' solutions to carefully designed questions. The criteria that must be satisfied by the questions were discussed in a previous paper[17]. Two of them are: (a) difficulty in answering a question must be due *only* to incompetence in the use of a strategy; (b) solution to the question must not be known to the students.

4. Question Paper and its Administration to Students

The question paper had questions that tested competence in both cognitive strategies and skills. 11 questions tested strategies and these are given in Table 1. Fifty first year, 42 second year and 27 third year students, from the BSc courses in 2009, answered the question paper. Students wrote the solutions in the spaces provided below each question. A broad column, labelled 'space for rough work" was also given in the question paper for doing rough work. No time limit was set for answering the question paper. Most of the students submitted their answer scripts before two hours. Five instructions were given in the question paper, three of which that are relevant to academic aspects are:

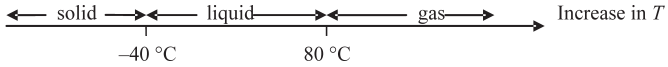
1. Some questions may appear to be difficult but they are not. If you reason logically, you will be able to answer them quickly. Note also that some of the data and information given in a question may not be necessary to answer the question.
2. Show all the steps in your reasoning. Also do all the rough work in the space provided adjoining each question, because the main objective of this test is to probe into your thinking processes, and how you set-about the solution of the problem.
3. All the principles and equations needed to answer a question are given in the question paper.

The 11 questions used for testing cognitive strategies are given in Table 1 and they have been classified into five types of strategies.

5. Results and Discussion

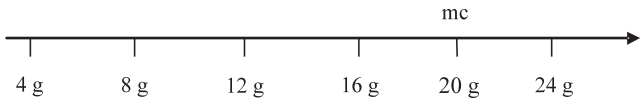
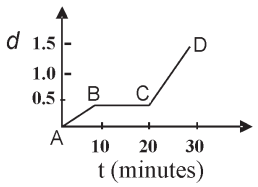
Students' performance in the 11 questions used for testing cognitive strategies is shown in Table 1, where columns 2, 3 and 4 show respectively the percentages of first year (yr.1), second year (yr. 2) and third year (yr. 3) students who answered correctly. The results show that performance of all groups of students tested was poor. The percentages (average for all the questions used) of first year, second year and third year students who answered the questions correctly were respectively 46 %, 48 % and 48 % which shows that there is no significant difference between the performance of the three groups of students. Unless otherwise stated, the performance discussed hereafter will be the average performance of all the students tested.

Questions 1–3 test whether students use the important strategy of representing all the relevant information concerning the problem in a clear, concise and coordinated manner, as the first step towards its solution. *Question 1* is easy to solve if all the relevant information given in the problem statement is first coordinated together in one place, for example on a line diagram as shown below:



This diagram shows clearly that the substance will be a liquid at 50 °C, a gas at 90 °C and a solid at –50 °C. No reasoning is needed

Table 1 The questions used for testing cognitive strategies. n = number of students tested; Note: density = mass /volume

Questions	% Correct			
	Yr.1 (n = 50)	Yr.2 (n = 42)	Yr.3 (n = 27)	Average (n = 119)
Representation of problems clearly				
1. A solid substance melts at –40°C to form a liquid and the liquid boils at 80°C to form a gas. Will the substance be a solid, liquid or gas when its tempaerature is:(a) 50°C; (b) 90°C or (c) –50°C?	54	60	52	55
2. The mass of A (symbol, m_A) is larger than the mass of B (symbol, m_B) by 6 g but is smaller than the mass of C (symbol, m_C) by 8 g. The mass of C is 20 g. The mass of C (i.e. m_C) has been represented on the line below. Similarly, represent the masses of A and B on this line. 	88	64	67	75
3. 5.0 grams of a gaseous substance A is present initially in a closed 2.0-litre vessel at 20 °C. When heated to 300°C, it *partially* breaks down to give 1.0 grams of a gas B and 0.80 grams of a gas C. Which one of the following correctly represents the substances present in the vessel at 300 °C? (i) A only (ii) A, B and C (iii) B and C only (iv) B only	44	52	59	50
Focusing sharply on the goal				
4. If the density of a gas present in a closed vessel is x at a temperature T, which one of the following will be its density if the temperature is doubled to $2T$? Volume is kept constant. (a) 0.5 x (b) x (c) $2x$ (d) $4x$ (e) x^2	16	19	19	18
5. 5.0 grams of gaseous N_2O_4 is present in a closed 2.0-litre vessel at 20 °C. When heated to 300 °C, with the volume of the vessel being kept constant, 2.0 grams of N_2O_4 dissociates into NO_2 according to the equation $N_2O_4(g) \rightleftharpoons 2NO_2(g)$. Calculate the density of the gas mixture present in the vessel at 300 °C. (density = mass/volume)	20	17	15	18
6. The graph below shows the total distance (d) walked by a man plotted against time (t) (Note : the defining equation for speed (s) is $s = d/t$)  During the first ten minutes (see line AB) does the man's speed increase, decrease or remain unchanged?	22	31	34	28
Identification and use of relevant principles				
7. A closed vessel contains a mixture of two gases A and B at a temperature T and pressure p. The mass of A is 1.2 grams and the total mass of A and B is 2.0 grams. The gases do not react with each other. What will be the mass of A present in the vessel if the pressure is doubled from p to $2p$?	28	26	37	29
Use of equations for calculations and deductions				
8. Will the density of a liquid increase, decrease or remain unchanged if its temperature is increased? (note : the volume of a liquid always increases when its temperature is increased)	66	76	63	69
9. 5.0 grams of a gaseous substance A is present in a closed 2.0-litre vessel at 20 °C. When heated to 300 °C, it partially breaks down to give 1.0 gram of a gas B and 0.80 gram of a gas C. Calculate the mass of A present in the vessel at 300 °C by applying the law of conservation of mass which states that the total mass of all substances present before a chemical reaction is equal to the total mass after the reaction.	50	57	63	55
10. A gas obeys the equation $pV = kT$ where k is a constant. If the temperature of this gas is increased, at constant m and p, will its density d increase, decrease or remain unchanged? (note: $d = m/V$, where m = mass and T = temperature)	56	57	63	58
Use of a step-by-step procedure				
11. Use the equation $t = k/N$ (where N = number of men employed to do some task, t = time needed to do the task, k = a constant) to calculate the time needed by four men to do some task if three men need 12 hours to do the same task.	58	64	56	60

to solve this problem. Despite the simplicity of the problem, about 45 % of the students tested (column 4 in Table 1) did not solve it correctly. Students' answer scripts showed that none of the erring students tried to use the strategy of representing the data given in a coordinated manner. They did not recognize the importance of using this strategy. *Question 2,* unlike question 1, tests only ability to *execute* the strategy of representing some information on a line diagram and it was surprising that 25 % of the students tested could not do it. Since the skills needed to perform this task are very simple, one would have expected all university students to be able to do this. This study, however, shows that they should be trained.

In *question 3* too, students' performance was poor even though the solution to the problem does not need any reasoning. About a half of the students tested did not recognize that if a substance A breaks down *partially* (this word was emphasized by giving it in italics) to give substances B and C, there will be unreacted A in the vessel, in addition to the products B and C. Most of the erring students thought that only B and C will be present in the vessel. The poor performance of students may be attributed to their not clarifying the problem by representing the partial decomposition by the equation $A \rightleftharpoons B + C$, which would have alerted them to the fact that there will be unreacted A in the vessel because only a part of A decomposes.

Questions 4–6 mainly test whether students use the very important strategy of starting the solution of a problem by focusing sharply on the goal. The goal in questions 4 and 5 is the calculation of density (d) whose defining equation $d = m/V$ shows that d depends *only* on m and V. In question 4 , since m and V do not change, d will not change and in question 5 the value of d is easily calculated since m and V were given ($m = 5.0$ g, $V = 2.0$ l). Despite the solutions being very easy, about 80 % of students had difficulty. Most of their difficulties were due to their not starting the solution with the defining equation. Instead, they tried to use verbal reasoning for answering question 4 and to manipulate the irrelevant data given (the equation for the dissociation) and the ideal gas equation for answering question 5. For question 6, about 70 % of students thought, because distance travelled increases with time, that speed also will increase with time. This error was probably caused by students rushing into the solution without focusing on the defining equation for the relevant quantity (speed) to answer the question.

Question 7 mainly tests whether students recognize that deductions and calculations have always to be based on principles. Mass (m) is a basic physical quantity and hence does not depend on any other quantity. Mass will therefore not change when pressure is changed. About 70 % of students, however, thought incorrectly that mass will change (either double or halve) when pressure is doubled, despite this conclusion contradicting familiar experience. This error suggests that most students did not recognize that to deduce how one quantity varies with another quantity it is necessary to make use of a relationship that exists between the two quantities.

Questions 8–10 tested whether equations are used, rather than statements, for doing calculations and making deductions. In *question 8,* the required deduction is easy if it is based on the equation $d = m/V$. This equation shows that an increase in temperature, because it increases V, will decrease d. About 30 % of students did not solve this problem correctly. Their answer scripts indicated that their difficulty was mainly associated with their using verbal reasoning, instead of the equation $d = m/V$, to deduce the answer.

Question 9 needs the application of the law of conservation of mass. Though this is a simple law, about 45 % of students had difficulty in applying it. Their answer scripts indicated that their difficulty was mainly associated with the use of verbal reasoning to do the needed calculation. A better method would be to translate the information given in the question, by applying the law of conservation of mass, into the equation

$$m_A \text{ (at 20°C)} = m_A \text{ (at 300 °C)} + m_B \text{ (at 300 °C)} + m_C \text{ (at 300 °C)}$$

and then use this equation to calculate the required mass, m_A (at 300 °C).

Though *question 10* involves a qualitative deduction, the best strategy for answering it would be to first derive the equation that relates the relevant quantities (density d and temperature T) and then use this equation for making the required deduction. The equation that relates d and T can be obtained by combining the two given equations ($d = m/V$ and $pV = kT$) and is $d = mp/kT$. This equation shows that an increase in T will decrease d. About 40 % of students were not able to make this deduction. Their answer scripts indicated that they tried to deduce the answer by verbal reasoning, which is very difficult for this problem.

Question 11 mainly tests whether students use the important strategy of proceeding step-by-step, using step-by-step reasoning, for the solution of a problem. To calculate the time (t) needed by four men (i.e. $n = 4$) to do some task, using the equation $t = k/n$, the unknown in this equation (k) must first be calculated. This can be done by substituting the given data ($t = 12$ h, $N = 3$ men) into the given equation: 12 h = k/3 men. The k value obtained can then be used to do the required calculation. Despite the fact that this type of calculation, where an equation has to be applied twice, occurs in many sections of their chemistry and physics courses, about 40 % of students had difficulty. Their answer scripts indicated that the main reason for their difficulty was their attempting to do the calculation in one step.

6. Conclusion

This study, which mainly tested the competence of students throughout a BSc course (first year, second year and final year) in five important problem-solving strategies, showed that their competence was poor. The percentages (average for all the questions used for testing) of students who answered correctly were 46 % for first year students, 48 % for second year students and 48 % for final year students. Some examples of poor performance of final year students are:

- About 85 % were distracted by irrelevant information given in a problem and did not use the important strategy of focusing on the defining equation ($d = m/V$) to calculate density;
- About 60 % implicitly assumed, even though no principle relates mass and pressure, that the mass of a gas would change when pressure is changed;
- About 40 % did not initially get a picture of a problem and hence could not deduce that if a substance A breaks down partially there will be unreacted A in the vessel;
- About 35 % were unable to apply a simple law (the law of conservation of mass) which was given as a verbal statement to do a simple calculation;
- About 35 % did not know that the best strategy for answering the question 'how does gas density depend on pressure?' would be to first derive the equation that relates gas density and pressure and then use it for making the required deduction.

The study also showed that there was no significant improvement in students' competence in cognitive strategies as they progressed from year to year through their BSc course. This suggests that the strategies used by them (generally unconsciously) to solve problems in their university courses are not *transferred* to

solve the unfamiliar types of problems that were used in this study. Such transfer should, however, be an important objective of education courses because increased competence in cognitive strategies would increase students' intelligence[8] (Intelligence Quotient, IQ) and their self-confidence and also their ability to cope with problems encountered in their daily lives. There is ample research evidence that cognitive strategies learnt and used in one context are not automatically transferred to another context and that such transfer needs the satisfaction of many conditions[21,22]. For example, it needs the *explicit* identification of the strategies used and repeated training in them in a variety of contexts until they become automatic mental operations.

Even though students' competence in the use of strategies was poor, the strategies are not difficult to understand and use. Students' difficulties are not due to incapability in using them but to insufficient emphasis being placed on them in our courses. Since an increase in competence in cognitive strategies (and also cognitive skills) can be expected to lead to more efficient learning and problem solving, there is a need for continuously training students in them. There is research evidence that such training is best integrated with the teaching of subject content[23,24]. The aim of such training should be to ensure that the use of cognitive strategies becomes automatic and spontaneous habits of the mind[25,26].

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