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Students' Competence in Intellectual Strategies Needed for Solving Chemistry Problems

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ABSTRACT

Many students' difficulties in solving chemistry problems are due to lack of competence in a few widely applicable skills and strategies. The competence of 300 first year chemistry students at North-West University, South Africa, in four intellectual strategies (clarification and clear presentation of the problem; focussing on the goal and identifying a strategy for moving towards the goal; identification of the principles needed for solution; proceeding step by step) was investigated, over a period of four years, by comparing their performance in 'standard' questions and 'hint' questions. The 'standard' and the 'hint' questions were the same but the 'hint' questions, in addition, suggested the strategies which should be used to solve the problems. Performance in all test items was poor, but improved in the 'hint' questions. The results indicate that about 80 % of the students were unable to use the required strategies, and also that many students who have the competence to use the strategies did not recognize the necessity for doing so. The results also suggest negative attitudes and lack of self-confidence in problem solving. There is therefore a need for specific training of students in the use of intellectual strategies. This should be integrated with the learning of subject content.

KEY WORDS

Intellectual strategies, chemistry problem solving.

1. Introduction

Problem solving is an important part of most science courses. Most students have difficulties with problem solving, and many of these difficulties are due to students not being sufficiently competent in a few widely applicable intellectual skills and strategies.[1–3]

Intellectual strategies are often interlinked with intellectual skills. Intellectual skills are specific cognitive operations that can be considered to be the 'building blocks' of thinking. They are the mental activities needed for the functioning of the other dimensions of thinking (metacognition, creative thinking, critical thinking, thinking strategies).[4] Intellectual skills include focussing, information gathering, remembering, analysing, generating, integrating and evaluating. Intellectual strategies (or processes) can be defined as the plans of action intended to accomplish goals (such as problem solving). They generally involve a sequence of individual skills. Many intellectual skills are generally needed to perform a strategy. Different skills are used at various points in a strategy. Thus a problem solving strategy would require many skills.

A systematic four year research study has been carried out[5] to investigate, by carefully designed test items, the competence of first year university chemistry students in some of the intellectual strategies and skills that are important for learning chemistry effectively. This paper describes the results obtained concerning students' competence in intellectual strategies. Results concerning their competence in intellectual skills will be described in a subsequent paper.

Four types of intellectual strategies particularly important in solving chemistry problems are:

A. clarification and clear presentation of the problem;
B. focussing on the goal and identifying a strategy for moving towards the goal;
C. identification of the principles needed for solution;
D. proceeding step by step.

Clarification and clear presentation of the problem is an important initial strategy, often neglected by students.[6,7] This would help decrease the load on working memory.[8,9] Focussing on the goal helps distinguish between relevant and irrelevant information.[10] Identification of laws and principles sharpens our reasoning and avoids errors,[11] and proceeding step by step towards the goal would simplify problem solving.[12]

2. Method of Study

It is difficult to investigate students' competence in intellectual strategies because of the difficulty of isolating them from intellectual skills. A useful method for isolating and testing intellectual strategies has recently been suggested,[10] and it involves the comparison of students' performance in pairs of questions; in 'standard' questions and 'hint' questions. The standard and hint questions are the same, except for one difference. The hint question has a hint that suggests a strategy that should be used to solve the problem. The standard questions were given to the students in a test 1 question paper and the hint questions in a test 2 paper. The test 2 question paper was given immediately after collecting students' answer scripts to the test 1 paper. Since the only difference between a standard and hint question is in the strategy stated in the hint, any improvement in student performance in the hint question may be attributed to the influence of the strategy used. This method of using standard and hint questions was used in the present study to investigate students' competence in intellectual strategies.

Since the main objective of the study was the identification of difficulties associated with strategies, two important criteria

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must be satisfied in the test items. First, lack of knowledge of the required principles and concepts should not be the reason for any student's difficulty. To help ensure this, the principles and concepts needed for the solutions of the test items were given, and some of the items even used everyday concepts, not specifically related to chemistry. For the same reason, the simplest possible test items were designed; items that needed only a few fundamental principles and concepts for their solutions. The second criterion that must be satisfied is that the test items should not be familiar ones for which students already know the methods for their solutions. It would be difficult for a test item to satisfy both these criteria for each and every student tested: 'good' students may have come across similar test items and 'poor' students may have difficulties with the principles and concepts needed for the solutions.

3. Subjects of the Study and Administration of the Tests

Four groups of first year chemistry students at the University of North-West were tested between 1999 and 2001. All students were Tswana-speaking, and English was their second (or third) language. These students were selected for the study because they had recently passed the matriculation examination (the South African school-leaving and university entrance examination). These students should therefore be expected to have the skills and strategies necessary to study physical science at university level.

The total number of students tested was 301. The results, for test 1 and test 2, of the four groups of students tested were compared to see if there was any significant difference in their performance. For this purpose, two-way analyses of variance (ANOVA) were performed. The F-values obtained ($F = 4.31$ and $F = 5.14$) were less than the critical value ($F = 8.54$, $P > 0.05$). It can therefore be concluded that there was no significant difference in performance between the four groups of students tested, both in test 1 and in test 2. Hence all the groups will be considered together in this paper.

Students were tested at the beginning of the academic year, before they received significant teaching in chemistry beyond school level. Both test papers were given in the same session. Once test 1 paper was answered it was collected from the students, and test 2 paper was then given to them. All students finished both papers in two hours or less, except for thirty students who failed to complete test 2.

4. Test Items Used

The test items (questions) used in the test 2 question paper are given below. The same items were given in the test 1 paper, but without the hints. The test items have been categorized in terms of the four strategies tested in this research.

A. Clarification and Clear Presentation of the Problem

1. Atom A is heavier than atom B but is lighter than atom C. Atom D is lighter than atom A but is heavier than atom B. Atom B is heavier than atom E. Which atom is the heaviest?
   Hint: Use the information given in the data, to arrange the atoms in the order of increasing masses on the line given in Fig. 1, before answering the question. The first piece of information (atom A is heavier than atom B) has been indicated in this line.
2. A substance has a melting point of –25 °C and a boiling point of 85 °C. Is this substance a solid, a liquid or a gas at –10 °C? (Note: Any substance exists as a solid below its melting point and as a gas above its boiling point.)
   Hint: Use the diagram shown in Fig. 2 that indicates the melting point, boiling point and the different phases of the substance, to answer the question.

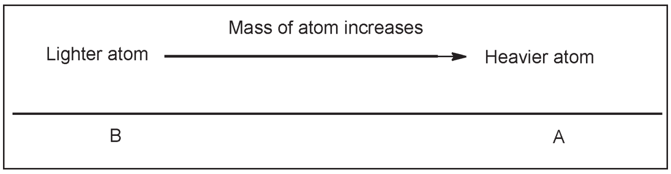

Figure 1.

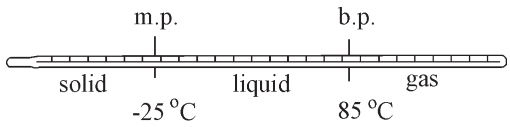

Figure 2.

3. Calculate the ratio of 2 m to 4 km.
   Hint: The quantities are given in different units. Convert them to the same unit before finding the ratio.
4. Arrange the following in the order of increasing time (i.e. start with the smallest time):
   microsecond (μs), picosecond (ps), femtosecond (fs), nanosecond (ns).
   given that: 1 μs = 10^{-6} s;1 ps = 10^{-6} μs;1 fs = 10^{-15} s;1 ns = 10^{6} fs.
   Hint: In the data, picosecond (ps) and nanosecond (ns) are not defined in terms of the second(s). First find the relationship between these quantities and the second(s), and then arrange the data in an *order*, before attempting to answer the question.

B. Focussing on the Goal and Identifying a Strategy for Moving Towards the Goal

5. 3.00 g of phosphorus pentachloride (vapour) are heated in a closed 1.00 dm^3 container at 300 °C. It then partially dissociates according to the equation
   $PCl_5\ (g) \rightleftharpoons PCl_3\ (g) + Cl_2\ (g)$,
   to give 0.50 g of Cl_2. Calculate the density of the *gaseous mixture* present in the vessel after dissociation.
   (*Note*: Density is defined as the mass per unit volume. P = 31.0; Cl = 35.5.)
   Hint: Calculate the density of the gaseous mixture ($d_{mixture}$) by using the equation
   $d_{mixture} = m_{mixture} / V_{mixture}$
   where $m_{mixture}$ and $V_{mixture}$ are respectively the mass of the mixture and the volume of the mixture.
6. The mole fraction of a gas A in a mixture of two gases A and B is 0.20 when the pressure is 200 kPa. What will be the mole fraction when the pressure is increased to 400 kPa?
   (*Note*: (a) the gases do not react with each other.
   (b) the mole fraction of A is, by definition, equal to the number of moles of A divided by the total number of moles.)
7. The density of 2.0 g of a *solid* is 4.6 g cm^{-3}. What will be the density of 4.0 g of the same solid, under the same conditions?
   Hint: Deduce the answer by using the defining equation for density (d), which is $d = m/V$, which shows that density depends not only on the mass m but also on the volume V. Recognize that V will also change when m changes from 2.0 g to 4.0 g.
8. 1.0 mol of ethanol (a liquid) is dissolved in 1.0 dm^3 of water. The concentration of ethanol in the solution then obtained will be
   (a) 1.0 mol dm^{-3}
   (b) less than 1.0 mol dm^{-3}

(c) greater than 1.0 mol dm^{-3}
(d) 0.50 mol dm^{-3}
Select the correct answer. Briefly indicate your reasoning.
Hint: Reason out your solution by starting with the defining equation for the required quantity, $c_{ethanol}$ which is:
$c_{ethanol} = n_{ethanol}/V_{solution}$
where $n_{ethanol}$ and $V_{solution}$ are respectively the amount (number of moles) of ethanol and the volume of the solution.

C. Identification of the Principles Needed for Solution

9. The volume of 1.00 kg of water (which is a *liquid*) is 1.00 dm^3 at a pressure of 100 kPa. When the pressure is doubled, its volume will be
(a) 0.50 dm^3
(b) 1.00 dm^3
(c) 2.00 dm^3
(d) the volume cannot be calculated from the given data.
Select the correct answer and briefly indicate your reasoning.
Hint: Decide first whether there is an equation that relates the volume of a *liquid* to the pressure. Is volume inversely proportional to pressure, for a *liquid*?
10. Gaseous N_2O_4 dissociates partially on heating, according to the following equation
$N_2O_4\ (g) \rightleftharpoons 2\ NO_2\ (g)$.
When 0.50 g of N_2O_4 is heated in a closed vessel, 0.20 g of NO_2 is formed. Calculate:
(a) the mass of N_2O_4 present in the vessel.
(b) the total mass of N_2O_4 and NO_2 present in the vessel.
Hint: Use the fact that mass does not change during a reaction.

D. Proceeding Step by Step

11. When travelling from Mafikeng to Johannesburg, Mpho drove for 1 hour at 120 km h^{-1} and for 2 hours at 90 km h^{-1}. What was her *average speed* for the whole trip?
Hint: Calculate the required quantity, the average speed, *s*, by using the defining equation $s = d/t$.
d = total distance travelled = ...
t = total time taken = ...
$\therefore s = d/t$ = ...
12. Gaseous N_2O_4 dissociates partially on heating, according to the following equation
$N_2O_4\ (g) \rightleftharpoons 2\ NO_2\ (g)$
When 0.50 mol of N_2O_4 is heated in a closed vessel, 0.20 mol of NO_2 is formed. Calculate:
(a) the number of moles of N_2O_4 present in the vessel.
(b) the total number of moles of N_2O_4 and NO_2 present in the vessel.
Hint: Recognize that three different quantities are associated with N_2O_4. These are:
(i) number of moles of N_2O_4 present initially, $n_{N_2O_4}$(initial)
(ii) number of moles of N_2O_4 that reacted, $n_{N_2O_4}$(reacted)
(iii) number of moles of N_2O_4 present after reaction, $n_{N_2O_4}$ (unreacted).
To calculate the required quantities, proceed step by step as follows:
(i) $n_{N_2O_4}$(initial) = ...
(ii) $n_{N_2O_4}$(reacted) = ...
(iii) $n_{N_2O_4}$(unreacted) = ...
(iv) $n_{total} = n_{N_2O_4}$(unreacted) + n_{NO_2} (formed) = ...

5. Results and Discussion

From students' answers, two types of information were obtained for each question. These are (a) the percentage of students who, on their own, used the required strategy and therefore successfully answered the question in the test 1 question paper, and (b) the percentage of students who were unable to answer the question in the test 1 paper but were able to do so using the strategy suggested in the test 2 question. This percentage was calculated using Hake's[13] formula for fraction of possible gain, *h*, where

h = (% correct in Test 2 – % correct in Test 1)/(100 – % correct in Test 1)

A few students seemed to be confused by the hints, and answered a test 2 question incorrectly, although they had answered the test 1 question correctly. This would have the effect of lowering *h*, and some of the test 2 improvements may therefore be slightly greater than reported.

In addition to obtaining the above data, information was also obtained from students' answers about their competence in some simple intellectual skills and also their attitudes and self-confidence.

The results are summarized in Table 1. Students were deemed to be successful in a problem if their reasoning was correct, even if they made errors in calculations.

The performance of students will now be discussed for the four strategies tested in this research study.

Table 1 Percentages of students successful in test 1 items and percentage improvement of unsuccessful students in test 2.

Test item	% Successful in test 1	% Improvement in test 2
1	60	25
2	38	32
3	40	27
4	19	8
5	29	24
6	8	–
7	6	5
8	12	3
9	26	20
10(a)	21	–
10(b)	19	14
11	16	20
12(a)	37	8
12(b)	10	30

A. Clarification and Clear Presentation of the Problem

A clear presentation of a problem always aids its solution, and some problems need clarification before they can be solved. Questions 1–4 test some aspects of the extent to which students' performance in problem solving is affected by their not clarifying and presenting the problem clearly.

Question 1 tests students' ability to compare five items of information to decide which atom is the heaviest. To store five items of information in our short-term memory and compare them mentally is a difficult task. The solution will be much easier if the items of information are coordinated together in a line diagram, as shown in Fig. 3. The answer may then be read directly from the line.

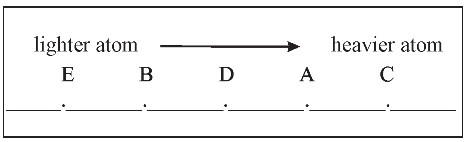

Figure 3 Items of information in question 1 arranged on a line.

In test 1, 60 % of the 300 students tested, over a period of four years, solved the problem. Of these, 27 % showed, in their answer scripts, the arrangement of the atoms in a diagram. Since it would be difficult to answer this question without some sort of arrangement that compares the data given, it is likely that the successful students arranged all the data in one place, though they did not show this on their answer scripts. In test 2, where the question had a *hint* suggesting the strategy of representing all the data on one line, there was a significant improvement in student performance. Of the students who failed in test 1, 25 % were able to answer the test 2 question correctly. This suggests that these students had the ability to represent the information given pictorially, but failed in test 1 because they did not recognize the necessity for doing this. Despite the suggestion in the hint to arrange all the data on one line, about 30 % of the students did not do so. These students may either have language difficulties that resulted in their being unable to carry out the simple instructions given or they lacked self-confidence which prevented them from even trying to proceed with the instructions. There is therefore a need for checking, and then ensuring, whether students are able to carry out simple instructions and tasks, without assuming that they can do so.

Question 2 also mainly checks whether students recognize the importance of a clear pictorial representation for successful problem solving. The solution to this problem is easy if we represent the melting point, boiling point and phases of the substance in a diagram, as shown in Fig. 4.

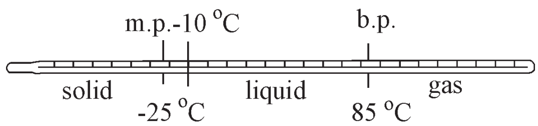

Figure 4 Phases of the substance in question 2 arranged in a diagram.

The diagram shows that the substance will be a liquid at –10 °C. In test 1, only 38 % of the students solved the problem correctly. In test 2, where students were asked to deduce the answer from a diagram relating the melting point, boiling point and phases of the substance, their performance was much better: 32 % of the students who gave incorrect answers in test 1 were successful in test 2. These students understood the diagram and were able to use it to deduce the correct answer. The other students were, however, unable to deduce the answer from the fairly simple diagram. This suggests that there is a need for the training of students in very basic intellectual abilities, such as how to obtain information from diagrams (particularly from diagrams that are unfamiliar) and on how to represent information as diagrams. This question did not test students' ability to draw a diagram from the data provided, which is a more difficult task. Training in these skills should build up the self-confidence of students.

Questions 3 and *4* test mainly whether students recognize that they must represent the data given in a *consistent* manner (i.e. in the same units) before they can solve the problem.

In *question 3,* the quantities given must first be converted into the same units before the ratio can be calculated. Since 4 km = 4000 m, the required ratio will be 2 m/4000 m = 1/2000. In test 1, only 40 % of the students made the units consistent and therefore calculated the ratio correctly. Student performance in test 2, where they were instructed to convert the quantities to the same units, was much better. Of the students who failed in test 1, 27 % were successful in test 2. These students therefore had the ability to interconvert units but did not recognize that the same units had to be used for the different quantities to calculate the required ratio. Despite the hint, many of the students were unable to calculate the correct ratio in test 2.

To answer *question 4,* all the times given must first be converted to the same unit (e.g. second) before they can be compared. The order, in increasing time, will be: femtosecond (fs, 10^{-15} s), picosecond (ps, 10^{-12} s), nanosecond (ns, 10^{-9} s), microsecond (μs, 10^{-6} s). Student performance was very poor. Only 20 % of the students arranged the times in the correct order in test 1. Most students' errors were due to their not converting all the units to the same unit before comparing them. Some students arranged the times in increasing order of the magnitude of the numbers, without considering the units. Concerning test 2, only 8 % of the students benefited from the hint; they converted all the units to seconds and arranged the times in the correct order. Most students did not know how to convert the units that were unfamiliar to them (e.g. femtosecond) into seconds, although the conversion factor was given in the data.

B. Focussing on the Goal and Identifying a Strategy for Moving Towards the Goal

A crucial step in problem solving is to start the solution by focussing on the goal, and on identifying a strategy for proceeding towards the goal. Many students, however, do not focus sharply on the goal and also do not appreciate fully the importance of identifying a strategy for proceeding towards the goal. This is illustrated in questions 5–8.

Question 5 tests whether students start the solution with the defining equation for the required quantity, $d_{\text{mixture}} = m_{\text{mixture}}/V$, where d_{mixture}, m_{mixture} and V are respectively the density, mass and volume of the mixture of gases in the vessel. Since, by the law of conservation of mass, mass does not change during any chemical reaction, m_{mixture} = 3.00 g. From the data V = 1.00 dm^3 and therefore d_{mixture} = 3.00 g/1.00 dm^3 = 3.00 g dm^{-3}. Although the solution is easy, only 29 % of the students answered the problem correctly in test 1. The answer scripts showed that about 30 % of the erring students used the defining equation for density for the calculation but they substituted incorrect masses: some substituted 0.50 g (the mass of Cl_2 given in the data), and some added or subtracted the masses (3.00 g and 0.50 g) given in the data. A few students even multiplied the mass of each gas by its molar mass. It appears from these answers that many students try to solve problems by merely manipulating the data given; they do not try to get a picture of the problem and identify the principles needed for the solution. Student performance in the hint question was much better; 24 % of the students who failed in test 1 were successful in test 2. These students' failure in test 1 may therefore be attributed to their not using the strategy of starting the solution with the defining equation for the required quantity.

Question 6 also tests whether students focus on the relevant defining equation for deductions. The defining equation shows that mole fraction depends *only* on the number of moles of substances present in the mixture. Since the numbers of moles of substances do not depend on pressure, mole fractions cannot depend on pressure. The mole fraction therefore will not change when pressure changes and its value will therefore be 0.20. Only 8 % of the students recognized that mole fraction does not depend on pressure. About 30 % of the students tested thought that mole fraction would be doubled (i.e. they implicitly assumed that mole fraction is directly proportional to pressure) and about 15 % thought that it would be halved. Since mole fraction is a concept that may be unfamiliar to students, its defining equation was included in test 1. This question was thus not given in test 2. Student performance in this question again illustrates that most of them do not focus on the goal to obtain the solution. Most students merely manipulate (add, subtract, multiply, divide) the data given, without much thought or understanding, in their attempt to obtain the solution. Often students seem to think incorrectly that two quantities always have to be either directly proportional or inversely proportional to each other.

Question 7 also tests whether students focus sharply on the goal and, in addition, also whether they recognize the importance of clarifying and getting a 'clear picture' of the problem. When the mass (m) of a solid increases, its volume (V) will also increase in the same proportion. The ratio m/V, which is equal to the density, will therefore not change. The density of the solid will therefore not change when the mass is doubled. Student performance was very poor. Only 6 % of the students recognized, in test 1, that the density of a solid will not change when its mass is changed. 52 % of the students thought incorrectly that the density would double to 9.2 g cm^{-3}; they implicitly assumed that density is directly proportional to mass, while 2 % assumed an inversely proportional relationship. 40 % of the students seem to have merely manipulated (divided, multiplied, added) the data given, without much thought, and obtained incorrect answers. Despite the hint in test 2, that V will also change when m changes, 90 % of the students did not recognize that density will not change. They made the same errors as in test 1. Since getting a clear picture of this problem does not seem to be a difficult task, it appears that students' difficulty may be due to their rushing into the solution without sufficient mental effort.

Question 8, as in question 7, tests whether students focus sharply on the goal and also whether they obtain a clear mental picture of the problem. When ethanol is added to 1.0 dm^3 of water, the volume of the solution obtained, $V_{solution}$, must evidently be greater than 1.0 dm^3. Since $n_{ethanol}$ is 1.0 mol and $V_{solution}$ is greater than 1.0 dm^3, $c_{ethanol}$ will be less than 1.0 mol dm^{-3} (apply equation $c_{ethanol} = n_{ethanol}/V_{solution}$). In test 1, only 12 % of the students chose the correct response. Most students (76 %) thought incorrectly that the concentration is 1.0 mol dm^{-3}. These students therefore incorrectly substituted the volume of water (1.0 dm^3) in the equation $c = n/V$. The hint, in test 2, did not improve student performance. 81 % of the students still thought incorrectly that the concentration is 1.0 mol dm^{-3}. Since it is not difficult to recognize (if one gives some thought to it) that the volume of a solution of two liquids would usually be assumed to be greater than the volume of solvent (water), it appears that these students rush into the solution without much thought, and without trying to get a clear picture of the problem.

C. Identification of the Principles Needed for Solution

To prevent some types of errors during problem solving we should identify the laws and principles used during the solution. Such identification would sharpen our reasoning, make problem solving easier and also help us to obtain greater insight and understanding of subject content. Many students, however, do not identify the principles or laws involved in each step during the solution. This may lead to errors. This is illustrated in questions 9 and 10.

Question 9 concerns the variation of the volume of a *liquid* with pressure. Since the volume of a liquid decreases slightly with increase in pressure, response (d) will be strictly correct. Response (b) was also taken as correct because the volume decrease is very small. In test 1, only 26 % of the students selected the correct response. Of the students who chose incorrect responses, about half of them thought that Boyle's law was applicable to liquids; they thought that volumes of liquids were inversely proportional to pressure. The other half of the students seem to have merely manipulated the data. Student performance in test 2 was much better: 20 % of the students who chose incorrect responses in test 1 chose the correct response in test 2. These students therefore recognized, when prompted to think about it in the hint, that Boyle's law is not applicable to liquids. Their error in test 1 was probably because they rushed into the solution without identifying the principles involved. The probing question in the hint 'Is volume inversely proportional to pressure for a liquid?' did not help most students. They did not make an attempt, or were unable, to identify the principles involved and apply them. They again seem to have merely manipulated the data given, without much thought and mental effort.

Question 10, just as question 9, also tests whether students use the strategy of first identifying, and then applying, the principles/laws that have to be used for the solution of a problem. It also tests their ability to apply a very simple law, the law of conservation of mass. According to this law, the total mass will not change during a reaction. The total mass (of N_2O_4 and NO_2) will therefore always be 0.50 g, and the mass of N_2O_4 present, which is equal to the total mass (0.50 g) minus the mass of NO_2 present (0.20 g), will be 0.30 g. Students' performance was very poor in test 1. Only about 20 % of them solved the problem correctly: 21 % in part (a) and 19 % in part (b). Most of them did not identify and apply the simple law to obtain the solution. In part (a), 11 % of the students thought that the mass of N_2O_4 present in the vessel would remain unchanged, 28 % of them tried to do some calculations using irrelevant equations (e.g. balanced equation for the dissociation, equation for molar mass), while the rest of the students manipulated (added, subtracted) the data given. In part (b), 19 % of the students used irrelevant equations, while the rest either manipulated the data (35 %) or did not answer the question (27 %). Student performance in the part (b) hint question was better; 14 % of the students who could not solve the problem in test 1 were able to do so in test 2. Despite the hint to solve the problem using the principle 'mass does not change during the reaction', 70 % of the students could not solve the problem. This is surprising because the principle is very simple. It appears therefore that many students have difficulty in applying even simple principles to solve problems that are unfamiliar to them. 10 % of the students still did not even attempt to solve the problem: they did not have self-confidence in their ability to do so.

D. Proceeding Step by Step

A very important strategy for successful problem solving is to proceed step by step. This strategy simplifies problem solving because we then solve many simpler problems. A step-by-step procedure implies that we break down a given problem into many simpler problems, solve these simper problems and then join together the solutions of the simpler problems to obtain the solution to the given problem.

Question 11 tests whether students proceed step by step with the solution and also whether they focus sharply on the goal. Three simple steps are needed for the solution, and they are the calculation of the total distance travelled (d), the total time taken (t) and the average speed (s), which is defined by the equation $s = d/t$.

Since $d = (1\ h \times 120\ km\ h^{-1}) + (2\ h \times 90\ km\ h^{-1}) = 300\ km$, and $t = (1\ h + 2\ h) = 3\ h$, the average speed (s) will be 300 km/3 h = 100 km h^{-1}. Though this is a fairly simple problem, only 16 % of the students solved it correctly in test 1. Most students calculated the total distance incorrectly (e.g. 120 km + 90 km) and many used incorrect expressions to calculate the average speed (e.g. $(120\ km\ h^{-1} + 90\ km\ h^{-1})/2 = 105\ km\ h^{-1}$; $(120\ km\ h^{-1} - 90\ km\ h^{-1})/2 = 15\ km\ h^{-1}$). Student performance in test 2 was much better: 20 % of the students who failed in test 1 were successful in test 2. Most students, however, repeated the calculations they did in test 1.

Question 12 tests whether students proceed with the solution in a step-by-step manner and also some other aspects. Although the form of this question is similar to that of question 10, the *principles* required for the solution are different. Three different quantities are associated with N_2O_4. These are: initial amount of N_2O_4, $n_{N_2O_4}$(initial); amount of N_2O_4 that reacted, $n_{N_2O_4}$(reacted); amount of N_2O_4 that remains unreacted, $n_{N_2O_4}$(unreacted). Many students' difficulties are due to their not distinguishing between these three quantities, not giving them different symbols and not knowing how they are related to one another.

(a) Since, by the law of conservation of matter, the relationship between these three quantities is $n_{N_2O_4}$(unreacted) = $n_{N_2O_4}$(initial) – $n_{N_2O_4}$(reacted), and since $n_{N_2O_4}$(reacted) is related, by the balanced equation for the dissociation, to the amount of NO_2 formed, n_{NO_2}, by the equation $n_{N_2O_4}$(reacted) = $\frac{1}{2}n_{NO_2}$, it follows that $n_{N_2O_4}$(unreacted) = $n_{N_2O_4}$(initial) – $\frac{1}{2}n_{NO_2}$ = 0.50 mol – ½ × 0.20 mol = 0.40 mol.

(b) The total number of moles, n_{total}, in the reaction mixture will be given by
n_{total} = $n_{N_2O_4}$(unreacted) + n_{NO_2} = 0.40 mol + 0.20 mol = 0.60 mol.

Student performance in test 1 was very poor. The percentages of students who answered correctly were only 37 % for part (a) and 10 % for part (b). Most students were unable to calculate $n_{N_2O_4}$(reacted) correctly, and many incorrectly equated $n_{N_2O_4}$(reacted) to the number of moles of N_2O_4 present in the vessel. Many students also merely manipulated (added, subtracted) the data given, without any reasoning, and some used the defining equation for molar mass to perform meaningless calculations. 40 % of the students did not even make an attempt to solve the problem. Student performance in test 2 was much better than in test 1. This is to be expected because each step in the solution was tested separately in test 2; the students had to answer four simpler questions.

The first question was to state the amount of N_2O_4 present initially in the vessel. Though this item of information was given in the problem statement, only 51 % of the students could identify it, and about 35 % did not even attempt to answer the question! These results are not only surprising but also revealing. They suggest that most students tested do not have much self-confidence and also that their focussing skills are very poor. Since inability to identify items of information given in problem statements is a very serious handicap for successful problem solving, it is important that training is provided to students in this aspect.

The second question was to calculate the amount of N_2O_4 reacted. Only 35 % of the students could do this. Nearly 40 % of them did not even attempt to solve the problem, and most students merely manipulated the data given without any reasoning.

For the third question, which corresponds to part (a) of the test 1 question, only 41 % of the students calculated the required quantity, $n_{N_2O_4}$(unreacted), correctly, an 8 % improvement. About 40 % of them manipulated, in various incorrect ways, the data given and 20 % did not even attempt to answer the question. Only 36 % of the students were able to use the hint to answer correctly the part (b) test question which involved the calculation of the total number of moles present in the vessel. 37 % of the students incorrectly manipulated the data given, and 27 % did not even attempt solution.

6. Conclusion

The main objective of this research was to study, using carefully designed questions, the competence of first year university chemistry students in four intellectual strategies that are particularly important for successful problem solving. The results show that student performance in all the questions was poor.

For the first four questions, which concern the strategy 'clarification and clear representation of the problem', only about 40 % (this is the *average* percentage for the four questions) of the students used this strategy on their own (in test 1) and were therefore able to solve the questions. The percentage of students who answered the questions correctly, however, increased significantly (by about 25 %) in test 2, where students were asked to use the strategies suggested in the *hint* to answer the questions. These students therefore had the competence to use the needed strategies but they failed in test 1 because they did not *recognize* the necessity for using these strategies. About 40 % of the students, however, were unable to use the suggested strategies to answer the questions.

Student performance in questions 5–8, which concern the strategy 'focus on the goal and identify a strategy for proceeding towards the goal' was very poor. Only about 15 % (average for the four questions) of the students tested used this strategy and were therefore able correctly to answer the questions in test 1. The percentage of students who were able to answer the questions, however, increased by about 15 % in the test 2 questions, where the strategy to be used to obtain the solution was stated in the hints. Similar results were obtained for student performance in the questions concerning the other two strategies.

From the results of this study we can conclude that only about 20 % of the students tested used, on their own, the needed strategies to solve the given test items, and that another 20 % were able to solve the test items only after they were asked to use certain strategies to obtain the solutions. We can therefore conclude, from the results of this study, that most of the students tested had difficulties with the application of even simple intellectual strategies.

In addition to providing information about students' competence in intellectual strategies, this study also provided some revealing information about their competence in some simple intellectual skills, their approach to problem solving and their self-confidence. The results show that most of the students tested were not sufficiently competent in intellectual skills, even very simple skills. For example, their focussing skills were very poor. About 50 % of students were unable to focus sharply to identify an item of information given in the problem statement (question 12(a), test 2). About 70 % of the students were also unable to apply the simple law 'mass does not change during a reaction,' which was given in the hint in question 10, to perform two simple calculations. It was found that about 40 % of the students could not deduce information from a diagram (given in the hint in question 2), and about 25 % of the students could not represent different items of related information on a line (given in the hint in question 1).

It was also revealing that about 30 % of the students did not even attempt to solve problems that were unfamiliar to them. This suggests avoidance of mental effort, lack of self-confidence and negative attitudes, which are probably related to their incompetence in simple intellectual skills and strategies. It also appears that most students try to solve problems by using, without much thought, standard procedures they have memorized. They do not use a logical, systematic and step-by-step approach. When confronted with unfamiliar problems they either give up or try to manipulate the data given and the equations they know, without much thought and understanding of the problem.

It has been shown that students who learn science in a second language may lose about 20 % of their capacity to reason and understand.[14] The language in the questions was made as simple as possible, but language may have caused some of the difficulty, because the students were not first language English speakers. This problem could be explored further in subsequent research.

This study provides strong empirical evidence that many first year university students do not have sufficient competence in the intellectual skills and strategies needed for the effective learning and use of chemical knowledge. This probably leads to lack of self-confidence and negative attitudes. There is therefore a need for the systematic training of students in intellectual skills and strategies.[2,15] Such training should be integrated with the learning of subject content,[16–19] and should be continued throughout all university courses.

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