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Intellectual Skills Needed for the Effective Learning and Application of Chemical Knowledge

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ABSTRACT

Many students' difficulties in learning and applying chemical knowledge are associated with their being incompetent in a few widely applicable intellectual skills and strategies. This paper discusses the results of a study that was done to test first year university students' competence in some types of intellectual skills that are important in chemistry. The skills tested include language skills, mathematical skills, graphical skills, three-dimensional visualization skills, information processing skills and reasoning skills. The study showed that the competence of most students in intellectual skills is very poor. This lack of competence could be expected to lead to negative attitudes and a lack of self-confidence that would seriously handicap their learning, and may also be an important reason for the observed high failure rate of students in science courses. The study also showed a significant correlation between success in first year university courses and competence in intellectual skills and strategies. It is strongly suggested that much greater emphasis should be placed in our courses on the development of students' intellectual skills and strategies. Such training should be integrated with the teaching of subject content.

KEYWORDS

Intellectual skills, learning and application of chemical knowledge, problem solving.

1. Introduction

Many types of intellectual skills and strategies are needed for the effective learning of any topic.[1,2] Lack of competence in some of these skills and strategies is one of the most important reasons for the difficulties of many students in learning chemistry.[3–7] The main objective of this paper is to discuss some of the results of a systematic study that was conducted, over a period of four years for a Ph.D. degree,[8] to test first year university students' competence in some of the most important types of intellectual skills and strategies that are important for learning and applying chemical knowledge. Students' performance in some of the questions used to test their competence in intellectual strategies was described and discussed in a previous paper published in this journal.[9] This paper will discuss their performance in some of the questions that were used for testing their competence in intellectual skills. Details concerning this study, such as the method of study, the principles used to design the test items and the administration of the test items, were published in the previous paper and will therefore not be given again here.

Intellectual skills are the 'building blocks' of thinking and they are involved in all types of thinking. In this study, the skills tested include language skills, mathematical skills, graphical skills, three-dimensional visualization skills, information-processing skills and reasoning skills.

2. Test Items Used

A representative sample of the test items (questions) used for testing students' competence in the various types of intellectual skills is given in Table 1. These questions have been classified into six types, based on the type of skill tested: language skills; mathematical skills; graphical skills; three-dimensional visualization skills; information-processing skills and reasoning skills.

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3. Results and Discussion

Students' performance in each of the sixteen questions given in Table 1 is shown in Table 2, where column 2 (heading: % correct) shows the percentages of students who answered each question correctly and column 3 (heading: % no attempt) shows the percentages of students who did not attempt to answer the question. The total number of students tested over the period of four years was 301. Some of the questions were tested for three years, some for two years and some of them for one year. The results in Table 2 show that students' competence in most of the intellectual skills tested is very poor.

Language skills are tested in Question 1, which tests students' understanding of two words (description, explanation) that are very important for learning science. Of the six statements given in the problem statement, only statement (b) is an explanation: it interprets pressure in terms of the properties (molecular motion) of the particles (molecules) present in the gas. The results in Table 2 show that student performance was very poor for part (f) of the question: about 90 % of the students thought incorrectly that the statement 'metals conduct electricity because they are electrical conductors' is an explanation. This error is probably due to the occurrence of the word *because* in the sentence. Student performance was also poor in questions 1(e) (70 % incorrect answers), and 1(a) (30 % incorrect answers). Both these statements, unlike the statements in the other parts of the question, involve relationships (volume and pressure in statement (a); rate of reaction and catalyst in statement (e)), and it may be that many students believe that statements that consider relationships are explanations. Students' performance in some other questions (not given in Table 1) also indicates that many of them think incorrectly that quantitative statements are explanations. Ability to distinguish between description and explanation is very important when learning science, and many students' failure in some examination questions is due to their giving a descriptive

Table 1 Some of the questions used for testing intellectual skills.

Language skills

1. State whether each of the following statements is a **description** or an **explanation**.
   (a) The volume of a gas is inversely proportional to the pressure.
   (b) A gas exerts pressure because its molecules constantly bombard the container walls.
   (c) An ideal gas obeys the equation $pV = nRT$.
   (d) Hydrogen molecules move faster than oxygen molecules.
   (e) The rate of a reaction is increased in the presence of a catalyst.
   (f) Metals conduct electricity because they are electrical conductors.

Mathematical skills

2. Calculate the following:
   (a) $(1.26 \times 10^{-3}\ \text{m}) - (1.86 \times 10^{-2}\ \text{m})$
   (b) $2 \times 20\ [1 - (6 - 15)]$
   (c) 12 km – 6 m
   (d) $(1.26 \times 10^{-3}\ \text{m}) - (1.86 \times 10^{-4}\ \text{km})$
   (e) $\dfrac{6 \times 10^{-2}\ \text{m}}{12 \times 10^{-2}\ \text{km}}$

3. The concentration of a solute in a solution is 1.20×10^{-6} mol cm^{-3}. Express this concentration in mol m^{-3} (1 cm = 10^{-2} m).

4. A *non-ideal* gas obeys the equation $p^2V = kmT^2$, where p, V, m and T represent respectively the pressure, volume, mass and temperature of the gas, and k is a constant. Which of the following statements are true for *this* gas?
   (a) At constant temperature, the volume of a fixed mass of the gas is inversely proportional to the pressure.
   (b) At constant pressure, if the temperature of the gas is doubled, the volume of the gas will be doubled.
   (c) At constant temperature, for a fixed mass of gas , pV = constant.
   (d) k is directly proportional to V.
   Briefly explain your answers.

5. 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? (Note: density is defined as the mass per unit volume.)

6. The rate of decomposition of a substance A is directly proportional to the square of its concentration (c_A). This information can be represented by the equation $rate = kc_A^2$.
   (a) If the rate is r at concentration c, the rate when the concentration is doubled to $2c$ will be: (tick (✓) the correct answer)
   (i) $4r$ (ii) $2r$ (iii) r (iv) $(½)r$ (v) $(¼)r$ (vi) none of the above
   (b) How will k change if the concentration of A is *doubled*?

7. The rate of a chemical reaction was measured at various concentrations of a reactant A.
   The following results were obtained:

concentration of A/mol dm^{-3}	0.10	0.30	0.50
rate of reaction/mol dm^{-3} s^{-1}	0.01	0.09	0.25

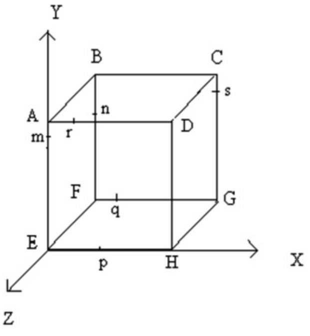
Write the equation relating the rate of reaction to the concentration of A.

Graphical skills

8. A non-ideal gas obeys the equation $p^{½}V = nRT^2$, where p = pressure, V = volume, n = amount (moles), R = gas constant and T = temperature. Draw a graph that will show how $p^{½}V$ will vary with p, at constant T.

Three-dimensional visualization skills

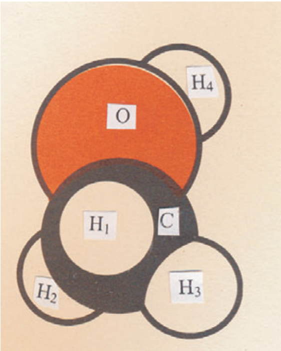
9. The diagram below represents a cubic box.



   (a) Which point (if either) is higher up in the box, in each case?
   (i) m or n
   (ii) p or q
   (iii) r or s.

(b) Which point (if either) is closer to point F, in each case?
(i) D or G
(ii) B or G
(iii) B or H
(c) In which plane (i.e. XY, XZ or YZ) is
(i) the face ABFE
(ii) the face EFGH
(iii) the face BCGF

10. Consider the following drawing of a methanol molecule, CH_3OH.
Which atom is closer to us, in each of the following cases?



(a) atom H_1 or atom H_2
(b) atom H_3 or atom H_4
(c) atom O or atom C

Information-processing skills

11. The rate of diffusion of a gas is directly proportional to the square of the temperature and is inversely proportional to the square root of its molar mass. Express this statement as an equation.

12. An item is bought and then sold at a thirty per cent profit. If the cost price of the item is 200 cents, what is its selling price?

Reasoning skills

13. Two men take 4 days to paint a house. How many days will be needed for 8 men to paint the same house? (Assume that men work at the same rate.)

14. 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.

15. 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?

(Note: average speed = total distance travelled/total time taken.)

16. Consider the following data:
(i) One mole of oxygen atoms (O) contains 6.022×10^{23} oxygen atoms.
(ii) An oxygen molecule (O_2) is built up by the combination of two oxygen atoms (O).
(iii) The mass of one mole of oxygen molecules is 32.00 g.
(iv) One mole of oxygen gas occupies 22.4 dm^3 at standard temperature and pressure.
Calculate the mass of 2.0×10^{10} oxygen atoms (O).

answer when they were asked to provide an explanatory answer.

Mathematical skills are tested by questions 2–7. Question 2 tests competence in basic mathematical operations (addition, subtraction, multiplication, division) with numbers and with physical quantities (which have both numbers and units). The results in Table 2 show that about 60 % of the students tested (average performance in questions 2(a) and 2(b)) were unable to perform basic mathematical operations correctly. Their performance in part (c) of the question showed that 30 % of the students did not recognize the fundamental principle that physical quantities in different units must be converted into the same unit before they can be subtracted (or added, multiplied, divided). The solutions to parts (d) and (e) of question 2 need more mathematical skills than that needed to solve part (c), and about 90 % of the students had difficulty with these two parts.

Question 3 tests ability to convert a physical quantity from one unit (mol cm^{-3}) to another (mol m^{-3}). This skill is needed in the study of many parts of the physical sciences. About 85 % of the students tested were not competent in this skill and this would certainly handicap their learning of science.

Questions 4 and 5 test whether students understand the information provided by equations. In question 4, the statements in all parts of the question are incorrect. Statements (a), (b) and (c) are true for the ideal gas equation (which students have learnt

Table 2 Percentages of students who answered correctly (% correct) and who did not attempt (% no attempt) to answer each question.

Question number	% correct	% no attempt
1(a)	71	1
1(b)	87	0
1(c)	84	1
1(d)	81	0
1(e)	29	0
1(f)	9	0
2(a)	6	14
2(b)	60	3
2(c)	70	8
2(d)	2	31
2(e)	19	25
3	11	21
4(a)	45	0
4(b)	55	0
4(c)	48	0
4(d)	55	0
5	6	6
6(a)	14	20
6(b)	43	17
7	7	28
8	3	42
9(a)(i)	72	5
9(a)(ii)	27	7
9(a)(iii)	75	8
9(b)(i)	79	5
9(b)(ii)	36	3
9(b)(iii)	88	8
9(c)(i)	72	8
9(c)(ii)	74	14
9(c)(iii)	56	11
10(a)	60	5
10(b)	56	6
10(c)	46	8
11	39	21
12	27	13
13	29	6
14(a)	21	19
14(b)	19	27
15	33	3
16	5	22

and may therefore remember) but are not true for the equation given in this question with which they are unfamiliar. About 50 % of the students thought that the statements were true. Question 5 tests the ability to interpret the defining equation for density ($d = m/V$) correctly. About 50 % of the students tested thought that the density (d) of a solid will be doubled when its mass (m) is doubled; that is, they thought density is directly proportional to mass. This is incorrect. From the equation $d = m/V$ we can conclude that d is directly proportional to m **only** if the volume V is kept constant. In the problem considered V is not constant, and when m is doubled V too will be doubled; hence d will not change.

Question 6 tests one of the most important uses of equations: their use for calculations. The results in Table 2 show that about 85 % of students were unable to use a simple equation ($r = kc_A{}^2$) to perform a calculation. The difficulty arises mainly because some reasoning is needed since the equation has to be applied twice: first to calculate the constant k using the given data and then to use this value of k to perform the required calculation. About 35 % of the erring students thought that r would be doubled when c is doubled. These students evidently did not know how to apply the equation twice for the calculation. They implicitly assumed that r would be doubled when c is doubled. This is a common type of error of many students: they implicitly assume, without any justification, that when some quantity is doubled another quantity (even a constant quantity!) will also be doubled. Since the understanding of the information provided by equations and their use for calculations is very important in all quantitative sciences, it is essential that students are trained so that they become competent in these skills.

Question 7 tests the ability to represent experimental data that show how two quantities vary with each other, as an equation. Less than 10 % of students were competent in this skill which is important for organizing data obtained by experiments.

Graphical skills are tested by question 8 which tests our understanding of the relationship between equations and linear graphs. The results in Table 2 show that more than 95 % of the students tested could not draw the correct graph showing how $p^{½}V$ will vary with p for the equation $p^{½}V = nRT^2$: more than 40 % of them did not even make an attempt to draw the graph.

Three-dimensional visualization skills are tested by questions 9 and 10. To answer question 9 correctly, we have to visualize three-dimensionally the drawing of a cube. About 35 % of the students tested were unable to do this. The same percentage of students had difficulty with question 10 which tests the ability to visualize three-dimensionally the various atoms in a 'space-filling' drawing of a methanol molecule (this drawing was taken from a matric text[10]). Since three-dimensional visualization of two-dimensional drawings (e.g. drawings of the structures of molecules and the internal structures of solids) is important for understanding many aspects of chemistry, students' lack of competence in this skill would certainly handicap their learning.

Information-processing skills are tested by questions 11 and 12. Question 11 tests students' ability to process the information given in a statement and give it as an equation. Processing includes the giving of symbols to the quantities involved (e.g. symbol r for the rate of diffusion, T for temperature, M for molar mass) and relating these quantities by using the mathematical expressions that correspond to the words 'directly proportional' and 'inversely proportional'. For example the statement 'r is directly proportional to T^2' means that r/T^2 is a constant. The equation corresponding to the statement in question 11 will be $r = kT^2/M^{½}$, where k is a constant. The results in Table 2 show that about 60 % of students were unable to convert the information given as a statement in question 11 into an equation. The conversion of statements into equations is a useful skill because it aids the solution of verbal problems involving calculations. Many students have difficulties with the use of verbal reasoning (reasoning using statements) for calculations and a useful method for 'by-passing' verbal reasoning would be first to represent the information provided by statements as equations and then use the equations for calculations.[5]

Question 12 is a type of problem encountered in our daily lives. Though it is a fairly simple and familiar problem, about 70 % of the students tested were unable to solve it correctly. Students' answers indicated that most of the erring students manipulated (multiplied, divided) the data given, without much thought or understanding. For example, about 20 % of the students calculated the answer by using the expression 200 cents × 100/30 while another 20 % used 200–30/100. A method for preventing students from merely manipulating the data given, without much thought to obtain some answer, would be to train them first to identify and relate the relevant quantities by an equation and then use the equation for the calculation. This would force them to think about the problem, clarify it and understand it. In question 12, the three relevant quantities involved are related by the following equation: selling price = cost price + (30/100) × cost price. The use of this equation to do the required calculation is fairly easy.

Reasoning skills and some other types of skills (e.g. focusing skills, organizing skills) are tested by questions 13–16. Question 13 mainly tests competence in inverse proportion reasoning. Though this question involves a relatively simple problem encountered in our daily lives, about 70 % of the students tested were unable to answer it correctly. Students' answers indicate, as in question 12, that most of them manipulate the data given without much understanding. For example, about 30 % of the students calculated the answer by using the expression 4 × 8/2 (which implies direct proportion reasoning) and gave the answer as 16 days, even though this answer is against our 'common sense' experience (8 men should not need more time (16 days) to paint a house than 2 men, who need 4 days). Since direct proportion reasoning and inverse proportion reasoning are of fundamental importance, not only in science but also in our daily lives, it is important that students are repeatedly trained to ensure that they become competent in them.

Question 14 tests ability to apply a simple law (the law of conservation of mass, which was given as a statement) to perform two simple calculations. Though the calculations are simple, about 80 % of the students tested were unable to do them and about 20 % did not even attempt to do the calculations. The answers indicated that most of the erring students tried to perform the required calculations by manipulating the data without first identifying the principles involved in the calculation. We suggest that the best approach for solving this problem would be first to relate the relevant quantities by an equation and then use the equation for the required calculations. The equation relating the relevant quantities, by the law of conservation of mass, is

$$m_{N_2O_4}(\mathit{before\ dissociation}) = m_{N_2O_4}(\mathit{after\ dissociation}) + m_{NO_2}.$$

Asking students first to relate the relevant quantities by an equation would force them to clarify the problem and understand it.

Question 15, which involves a situation encountered in our daily lives, was given to test whether students proceed step-by-step in a systematic manner when they solve problems. About 65 % of the students had difficulty. The difficulties of most students (about 40 %), however, were conceptual: they did not understand the meaning of 120 km h^{-1} and 90 km h^{-1} and they incorrectly calculated the total distance (d) travelled by adding these two speeds. That is, they thought that d = (120 + 90) km.

Question 16 was found to be very difficult by most of the students tested: only 5 % were able to perform the required calculation. The calculation needs, in addition to direct proportion reasoning, the ability to identify which of the information given in the problem statement is relevant (because some of the information given is irrelevant). Verbal reasoning is used by most people for performing calculations in some types of problems, such as this one. The use of verbal reasoning for calculations is, however, more difficult than the use of equations, particularly when many verbal reasoning steps have to be joined together. We suggest that equations should consistently be used for all calculations. This needs the ability to give the principles used for the calculations as equations and hence students should be trained to ensure that they are competent in this skill. The principle that has to be used for the calculation in question 16 is simple: it is the direct proportionality relationship between the mass of N atoms (symbol, m_N) and the number of atoms N. That is, $m_N \propto N$ or $m_N = kN$, where k is the constant of proportionality. This equation, $m_N = kN$, has to be used twice to do the required calculation. First it has to be used to calculate the value of k using the data given in the problem statement: when $N = 6.022 \times 10^{23}$, m_N = molar mass (M_o) of O atoms = 16 g and therefore $k = m_N/N = M_o/6.022 \times 10^{23} = 16\ g/6.022 \times 10^{23}$. Using this value of k we can calculate m_N when $N = 2.0 \times 10^{10}$, using the same equation, $m_N = kN$.

4. Conclusion

The main objective of this research was to study, using carefully designed questions, the competence of first year university chemistry students in some of the important types of intellectual skills that are required for learning chemistry: language skills, mathematical skills, graphical skills, three-dimensional visualization skills, information processing skills and reasoning skills.

The results show that a majority of the students tested were not competent in most of the intellectual skills that are essential for the effective learning of science. The study showed, for example, that for the students tested about:

- half of them were unable to distinguish between descriptive and explanatory statements;
- 70 % were unable to perform basic mathematical operations on numbers given in scientific notation;
- 85 % could not convert a physical quantity from one unit into another (mol cm^{-3} to mol dm^{-3});
- 50 % were unable to interpret and deduce correctly the information provided by equations;
- 85 % were unable to use a simple equation ($r = kc^2$), which however had to be applied twice, to do a calculation;
- 95 % could not correlate correctly the relationship between an equation ($p^{1/2}V = nRT^2$) and linear graphs;
- 35 % had difficulty in visualizing three-dimensionally the drawing of a cube and the arrangement of the atoms in a simple molecule;
- 60 % were unable to convert the information provided by a statement into an equation;
- 70 % were unable to solve the following two simple problems encountered in their daily lives: (i) An item is bought and then sold at a 30 % profit. If the cost price of the item is 200 cents, what is its selling price?; (ii) Two men take 4 days to paint a house. How many days will be needed for 8 men to paint the same house?
- 80 % were unable to apply a simple law (law of conservation of mass) to perform two calculations.

Students' lack of competence in intellectual skills and strategies can be expected seriously to handicap their learning throughout their university courses.

Lack of competence in intellectual skills and strategies could be expected to lead to a lack of self-confidence and negative attitudes. This would lead to students not even attempting to solve unfamiliar problems. About 20 % of the students tested did not attempt to solve problems that were unfamiliar to them. Many students try to solve problems by using 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.

Emphasis in most educational courses in South Africa (this may also be true elsewhere) is on the teaching of knowledge and not on the development of students' intellectual skills and strategies. This is undesirable.[11] The subject matter learnt is often forgotten but the improvement in intellectual abilities will be more permanent.[12] We suggest that much greater emphasis should be placed on the systematic training of students in intellectual skills and strategies. Such training should be integrated with the learning of subject content,[13–18] and should be continued throughout all university courses.

A subsidiary aim of the study was to ascertain whether a test of students' competence in skills could be used to predict their success in studying chemistry at university level. For this purpose two Pearson product correlation coefficients[19] were calculated:

- to investigate correlation between students' success in their first year university chemistry course (a first semester introductory general chemistry course was used) and their competence in skills;
- to investigate correlation between students' success in the same introductory chemistry course and their results in their matric (university entrance) examination.

The first year university course results were given as percentages, and each student's score for the skills test was also converted to a percentage. Symbols obtained in the matric examination were converted to an interval scale.

The analysis showed that there is significant positive correlation ($P < 0.01$) between the results students obtain in their first year university course, and both their matric results, and their competence in skills. Therefore both could be of value in predicting success at university. The correlation is far stronger ($r = 0.465$) between first year university results and the results of the skills test used in this study than between first year university and matric results ($r = 0.289$). This indicates that performance in the skills test is a better indicator than matric performance of success at university level. This is in agreement with several other studies which have found high school examinations to be poorer predictors of success than factors such as mathematical ability and logical thinking ability.[20–25] A test such as the one used in this study could therefore help to select students for admission into science courses. It could also be used by educators, during a course of study, to identify students who are likely to fail, so that remedial instruction could be given.

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