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Students' Competence in some Problem Solving Skills throughout their B.Sc. Course

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ABSTRACT

The main objective of the study was to test students' competence, throughout all their years (first, second and final years) of a B.Sc. course, in five important types of problem solving skills: information processing skills; skills concerning equations; graphical skills; three-dimensional visualization skills and inverse proportion reasoning skills. The study method used was the analysis of students' solutions to carefully designed questions. Students' performance was found to be poor for most of the skills tested. For example, more than half of all the students tested could not deduce information organized in equations, transform quantitative information in statements into equations and use inverse-proportion reasoning to do a calculation; and about a quarter of the students could not combine two equations and also could not visualize three-dimensionally the drawing of a cube. The study also showed that there wasn't much improvement in cognitive skills as students progressed from year to year. This suggests insufficient emphasis being placed on training students in cognitive skills in their courses. Since the development of students' competence in cognitive abilities should be an important objective of education courses, there is a need for explicitly identifying important cognitive skills and strategies and training students in them. Such training should be integrated with the teaching of content knowledge.

KEYWORDS

Cognitive skills, thinking skills, problem solving, students' difficulties with cognitive skills.

1. Introduction

Cognitive abilities are the tools for all mental activities[1–4] and this includes perception, judgment, selection, processing and storage of information in memory, and the retrieval and use of this stored information, for example in problem solving[5,6]. Competence in cognitive abilities is hence essential for success not only in academic courses but also in 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 abilities[7,8]. The development of students' cognitive abilities should therefore be one of the most important objectives of all academic courses.

Hundreds of cognitive (mental) abilities have been identified and they have been classified in many different ways and at different levels of detail[1,2]. A very broad classification of them is as cognitive skills and cognitive strategies. Cognitive skills are the basic building blocks of all mental activities and cognitive strategies are plans of action for controlling and executing mental tasks.

Most research concerning cognitive abilities has been done with curricula and students in schools[4,9] and the amount of work with university students is somewhat limited[10,11]. In South Africa, some research has been done with first year university chemistry students[12–14] and matric physical science teachers[15]. These studies showed that their competence was poor in the cognitive skills and strategies needed for efficient problem solving.

The main purpose of this study was to extend this research to test first, second and final year B.Sc. students at our university. Since the study was done during one year (2009), it cannot strictly be used to obtain reliable information on the development of students' cognitive abilities from year to year. This is because cognitive abilities of first year students in 2007 (who were third year students in 2009) and in 2008 (who were second year students in 2009) cannot be expected to be the same as those in 2009, who followed a new high school curriculum (curriculum 2005/NCS). The study should not therefore be considered to be a developmental study of the students.

The study tested competence in both cognitive skills and strategies. This article discusses students' performance in the questions that tested competence in cognitive skills. Their performance in the questions that tested cognitive strategies was reported in an earlier paper[16].

2. Objectives and Method of Study

The main objectives of the study were:

- to identify some of the most important cognitive skills that are important for problem solving in physical science;
- to test the competence of first, second and third year (final year) B.Sc. Chemistry students at our university, during a particular year (2009), in these cognitive skills;
- to compare the performance of the students during the three years;
- to identify, by studying students' solutions to the questions, reasons for their difficulties and to suggest methods for rectifying them.

The study method used was the analysis of students' solutions

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to carefully designed questions. The criteria that must be satisfied by the questions were discussed in the previous paper[16]. Two of them are: (a) difficulty in answering a question must be due *only* to incompetence in the use of a skill; (b) the solution to a question must not be known to the students. To satisfy criterion (a), all the principles and equations needed to answer the questions were given in the question paper and questions were designed that need only very simple principles for their solutions.

3. Cognitive Skills Tested

The cognitive skills tested in this study were restricted to those that are particularly important for problem solving in physical science at high school and tertiary education levels. Five skills were tested:

- Information processing skills
- Skills for dealing with equations
- Graphical skills
- Three-dimensional visualization skills
- Inverse-proportion reasoning skills

4. Question Paper and its Administration to Students

50 first year, 42 second year and 27 third year students, from the B.Sc. courses in 2009, were tested during the early part of their courses. Students wrote the solutions to the questions in the spaces provided below each question. No time limit was set for answering the paper. Most students submitted their answer scripts within two hours. Five instructions were given in the question paper, two 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.

The 10 questions used for testing cognitive skills are given in Table 1. Six of them had parts and the total number of parts was 19. The questions have been classified into the five types of skills tested.

5. Results and Discussion

Students' performance in the questions used for testing competence in cognitive skills is shown in Table 1. Columns 2, 3 and 4 show respectively the percentages of first, second and final year students who answered the questions correctly and column 5 shows the percentages for all the students tested.

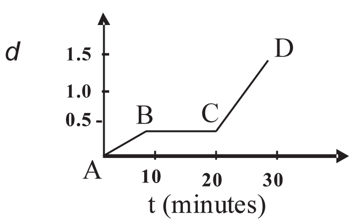
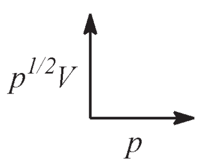
The results show that performance of all groups of students was poor in most of the skills tested. The average percentages (for all the 10 questions) for first, second and final year students who answered correctly were respectively 41 %, 42 % and 49 %, which suggests that there is only a slight improvement in students' performance as they progress from year to year in their B.Sc. course. In the discussions below what will be considered, unless otherwise stated, is the performance for all the students tested.

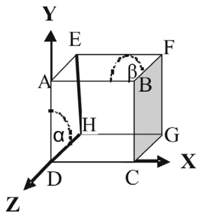
Questions 1 and 2 mainly test ability to process information: to translate or transform quantitative information in verbal statements into equations. About 60 % of students could not transform the simple statement 'the mass of A (give symbol m_A) is smaller than the mass of C (symbol, m_C) by 8 g' into an equation (which is $m_A = m_C - 8$) and the same percentage of students were unable to write the equation that relates the total mass of the substances before a reaction to the total mass after reaction, despite the symbols for the different quantities being given in the question. The ability to transform quantitative information in verbal statements into equations is very important for the successful solution of many types of problems. This is because equations are much better than verbal statements (and verbal reasoning) for doing calculations and also for making some types of deductions. Verbal reasoning is often difficult and error-prone, particularly when many variables are involved, and this seems to be mainly associated with the need for processing *lengthy* information (information in statements is lengthy compared with that in equations) in our limited working- memory (short-term memory)[17,18]. It is my experience that many students' difficulties with calculations involving fractions, percentages, direct proportion reasoning, inverse proportion reasoning, balanced equations for reactions and word problems are due to their using verbal reasoning, instead of equations, for calculations. Without using verbal reasoning, a much better method would be to transform all quantitative information in verbal statements into equations and then use the equations for calculations. To illustrate this statement, consider the solution to the following 'word problem' from MENSA[19]: 'A cup and a saucer together weigh 10 ounces. The cup weighs twice as much as the saucer. How much does the saucer weigh?' Though this is a fairly simple word problem (many word problems are more difficult than this), its solution is difficult using verbal reasoning but easy if the given information is transformed into equations which are then solved.

Questions 3–5 concern some important cognitive skills needed for using equations in science courses. Equations organize quantitative knowledge concisely, unambiguously and efficiently and hence should be used, consciously and deliberately, as fundamental frameworks for storing (in memory) and using knowledge. To do this, however, needs competence in the skills to do the following operations: interpret and deduce information organized in equations; transform quantitative information in statements into equations; rearrange and combine equations; use equations for calculations and deductions. Questions 3–5 were designed to test whether students are competent in these operations.

Questions 3 and 4 mainly test ability to interpret equations and deduce information organized in them. *Question 3* involves the interpretation of the equation $d = m/V$. Though this is a simple and familiar equation, most of the students tested were unable to interpret it correctly. About 90 % of them thought incorrectly that density (d) of a solid will double when its mass (m) is doubled. From the equation $d = m/V$ it may appear that d is directly proportional to m, but this is true only if V is constant. In this problem V is not kept constant. When the mass of a solid is doubled, its volume too will be doubled and therefore m/V, and hence d, will not change. For part (b) of the question, about 80 % of students thought incorrectly that density will change (either double or halve) when T is doubled. If the equation $d = m/V$ is used for deducing the answer it should be clear, because m and V are kept constant, that d will not change. *Question 4* tests ability to deduce information organized in the equation $p^{1/2}V = kT^2$. This equation shows that when T is constant kT^2 will be constant and hence $p^{1/2}V$ (and not pV) will be constant. About 85 % of students, however, thought that pV will be constant. These students did not use the equation $p^{1/2}V = kT^2$ to deduce the answer: the strategy they probably used for answering was recall of information they

Table 1 The questions used for testing cognitive skills. (N = number of students tested.)

Questions	% Correct			
	Year 1 (N = 50)	Year 2 (N = 42)	Year 3 (N = 27)	Total (N = 119)
Information processing skills				
1. The mass of A (give 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. Write the equation that relates m_A and m_c.	36	31	48	37
2. 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 gram of a gas B and 0.80 gram of a gas C. Write the equation that relates the following quantities by applying the law of conservation of mass: m_A (at 20°C); m_A (at 300°C); m_B (at 300°C) ; m_C (at 300°C). where m_A (at 20°C) is the mass of A at 20°C, and m_A (at 300°C), m_B (at 300°C) and m_c (at 300°C) are respectively the masses of A, B and C at 300°C. (Note: The law of conservation of mass states that the total mass before a reaction is equal to the total mass after the reaction)	32	41	63	42
Skills for equations				
3. The questions below concern density *(d)* which is defined by the equation $d = m/V$, where m=mass and V= volume. Give reasons for your answers.				
(a) If the density of 1g of a solid substance is x, which one of the following will be the density of 2 g of this solid? (i) (1/2) x (ii) x (iii) 2 x (iv) 4 x (v) x^2	10	03	08	07
(b) If the density of a gas present in a closed vessel is x at a temperature *T*, which one of the following would be its density if the temperature is doubled to 2*T*? Volume is kept constant. (i) (1/2) x (ii) x (iii) 2 x (iv) 4 x (v) x^2	16	19	19	18
4. For a non-ideal gas, the variable physical quantities *V*, *p* and *T* are related by the equation $p^{1/2}$ V $=kT^2$ where *k* is a constant. For this gas at constant *T*, will *pV* be a constant? Explain	24	10	08	15
5. A gas obeys the equation $pV=kT$. Derive the equation that shows the relationship between the density *d* of this gas and pressure *p* and temperature *T*. (note: $d = m/V$)	50	57	85	71
Graphical skills				
6. Use the graph given below, which shows the total distance in kilometers (*d*) walked by a man plotted against time *(t)* to answer the following questions (Note: the defining equation for speed (*s*) is $s = d/t$.)				
(a) Find the distance walked between 20 and 30 minutes	46	46	63	50
(b) During the first 10 minutes (see line AB) does the man's speed increase, decrease or remain unchanged?	22	31	34	28
				
7. For a non ideal gas, the variable physical quantities *V*, *p* and *T* are related by the equation $p^{1/2}V = kT^2$ where *k* is a constant.				
(a) At constant *p*, will a plot of *V* against *T* give a linear graph? (The equation for a linear graph is $y = mx + c$, where *y* and *x* are variables and *m* and *c* are constants).	06	12	11	09
(b) Show graphically how $p^{1/2}$V will vary with *p*, at constant *T*	22	08	11	14
				

Questions	% Correct			
	Year 1 (N = 50)	Year 2 (N = 42)	Year 3 (N = 27)	Total (N = 119)
8. **Three-dimensional visualization skills**				
The questions concern the figure given, where the arrowed lines represent the *x*, *y* and *z* axes and the box is a cubic box.				
				
(a) Is point F at a higher level, same level or lower level than point A?	84	91	63	82
(b) Which face of the cube is opposite to face HGCD?	94	100	85	94
(c) Will the angle ADH (α) be 90°, less than 90° or greater than 90°?	62	74	71	68
(d) Will the angle ABF (β) be 90°, less than 90° or greater than 90°?	58	65	60	61
Inverse-proportion reasoning skills				
9. Consider the relationship between the time *(t)* needed to do some task and the number of men *(N)* employed to do the task.				
(a) If the number of men employed is increased, will the time needed to do the task increase, decrease or remain unchanged?	92	100	93	95
(b) Which one of the following is the correct relationship between the variables in this question?				
(i) directly proportional (ii) inversely proportional (iii) exponential (iv) logarithmic *(v)* linear	82	91	78	84
(c) Which one of the following is the correct equation that relates the time needed (*t*) and the number of men *(N)* employed? *k* is a constant.				
(i) $t = kN$ (ii) $t = k/N$ (iii) $t = kN^2$	70	88	67	76
(iv) $t = kN^{1/2}$ (v) $t = k \log N$				
10. Three men need 12 hours to tile the floor of a house. How many hours will be needed by 4 men, working at the same rate, to tile the floor of the house?	46	46	52	47

had learnt for ideal gases, which however is not appropriate for the given question. Insufficient competence in the ability to deduce information organized in equations will seriously handicap the learning of quantitative knowledge in physical science.

Question 5 tests ability to combine the equations $d = m/V$ and $pV = kT$ so as to obtain the equation that shows how d is related to p and T. About 30 % of the students tested could not do this. The ability to combine equations is often needed for the solution of quantitative problems (problems involving calculations)[5] and lack of this ability will therefore seriously hinder problem solving.

Questions 6 and 7 mainly test competence in some graphical skills that are needed for studying physical science. *Question 6*(a) mainly tests ability to deduce information given in a simple graph: a graph of distance travelled plotted against time. Though this is not a difficult task, about a half of the students tested could not deduce from this graph the distance travelled between two times. Some of the erring students tried to calculate the distance travelled using the equation $s = d/t$. They did not focus on the question asked (which was to use the graph to answer the question) but tried to manipulate the equations they knew. Part (b) of the question is more difficult than part (a) because it also needs, in addition to the interpretation of the graph, the understanding of the equation $s = d/t$ (this equation was given in the question) that relates speed and distance travelled. About 70 % of students had difficulty with this part.

Question 7 tests ability to correlate information in linear graphs and equations. The equation in this question, $p^{1/2}V = kT,^2$ shows that:

(a) at constant p, V is directly proportional to T^2 (and not to T) and hence a linear graph will be obtained when V is plotted against T^2 and not when V is plotted against T;

(b) at constant T, $p^{1/2}$ V will be constant and hence a plot of $p^{1/2}V$ against any variable (e.g. p, V) will give a horizontal line.

Both parts of the question were very poorly answered. About 85 % of students had difficulty.

Question 8 tests ability to visualize three-dimensionally a drawing of a cube. Though the cube is a simple and familiar structure, about a quarter (average performance in all four parts) of the students tested had difficulty with this question. Three-dimensional visualization of much more complicated structures, such as the internal structures of solids and molecules, is essential for understanding many sections of chemistry and physics. Insufficient competence in this ability will hence seriously handicap meaningful learning and understanding of these sections.

Questions 9 and 10 test some important aspects concerning the understanding and application of inverse-proportion relationships and inverse-proportion reasoning. Question 9 tests some fundamental aspects of inverse-proportion relationships. It tests, for example, whether students recognize that the relationship between the time (t) needed to do some task and the number of men (N) employed to do that task is inversely proportional and also that the equation for this relationship is $t = k/N$. Though performance in parts (a) and (b) of this question was good, about a quarter of the students tested did not recognize (part c of the question) that the equation relating t and N is $t = k/N$. Inability to write this equation and use it for a calculation may be the main reason for students' difficulties with the last question in the question paper (question 10). About a half of the students tested could not answer this simple and familiar question which involves the calculation of the time needed by four men to do some task if three men need 12 hours. Since direct and inverse proportion relationships and direct and inverse proportion reasoning are very important not only in science but also in our daily lives, it is important that students are repeatedly trained in them until they become competent. Most students difficulties with the solution of question 10 seem to be associated with their use of verbal reasoning, instead of the equation $t = k/N$, to do the calculation.

6. Conclusion

This study which mainly tested competence in some important cognitive skills showed that students' competence was poor throughout the three years of their B.Sc. course. This limitation would have handicapped effective learning and problem solving. The percentages of students who answered correctly (average performance in all the 10 questions used for testing) were 41 % for first year students, 42 % for second year students and 49 % for third year students. Some examples of students' poor performance (Table 1) were:

- About 85 % of all the students tested could not deduce that for the equation $p^{1/2}V = kT^2$, when T is kept constant, $p^{1/2}V$ and not pV, will be constant;
- About 60 % had difficulty in processing the information given in the simple statement ' the mass of an object C (symbol m_C) is less than the mass of A (m_A) by 8 g' into an equation;
- About a half of all the students tested had difficulty in calculating the time needed by four men to do some task if three men needed 12 hours to do that task;
- About 30 % could not combine $d = m/V$ and $pV = kT^2$ so as to obtain the equation that relates d to p an T;
- About 25 % could not visualize from a drawing of a cube that the angle between any two faces of the cube will always be 90°.

The results also showed that there wasn't a marked improvement in students' competence in cognitive skills as they progressed from year to year in their B.Sc. course. This is despite the use (generally intuitively and unconsciously) of many types of skills and strategies in their courses to solve problems, and also despite some training in them in their courses. The training given however was only in a few classes in chemistry. Students' poor performance indicates that this training was not adequate. The lack of a marked improvement in students' competence in cognitive skills and strategies should not be surprising because many research studies have shown that skills and strategies learnt and used in one context are not easily transferred to another context[20]. For such transfer, many conditions have to be satisfied. For example, it needs explicit identification of the skills and strategies and repeated training in them in a variety of contexts until they are well learnt and become automatic mental operations and habits of the mind[21,22].

Training of students in important cognitive skills and strategies should be an important objective of all academic courses because such training will enable students to learn and solve problems more efficiently, not only in their academic courses but also throughout their lives. In addition, such training would help to increase their intelligence and promote self-confidence.

Training of students in cognitive skills and strategies needs time but time spent is worthwhile because it will be more than compensated, in the long-term, by the progressively increasing saving in time during subsequent learning and problem solving, which will then be much more efficient.

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