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High School Physical Sciences Teachers' Competence in Some Basic Cognitive Skills

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ABSTRACT

The successful implementation of the national high school Physical Sciences curriculum in South Africa, which places strong emphasis on critical thinking and reasoning abilities of students, would need teachers who are competent in cognitive skills and strategies. The main objectives of this study were to test South African high school Physical Sciences teachers' competence in the cognitive skills and strategies needed for studying Physical Sciences effectively and also to identify possible reasons for their difficulties and suggest methods for overcoming them. The study method used was the analysis of teachers' answers to questions that were carefully designed to test competence in explanation skills, mathematical skills, graphical skills, three-dimensional visualization skills, information-processing skills and reasoning skills. Seventy-three teachers from about 50 Dinaledi schools in the North West and Kwazulu-Natal provinces were tested. Teachers' competence was found to be poor in most of the skills tested. About 40 % (average performance in all 14 test questions) of them had difficulty in answering the questions. Teachers' lack of competence in cognitive skills and strategies would be an important limiting factor in the successful implementation of the Physical Sciences curriculum. An urgent need therefore exists for training teachers to increase their competence in the cognitive skills and strategies that are needed for studying science effectively.

KEYWORDS

Cognitive skills, thinking skills, questions testing skills, problem solving, teacher training, high school physical science.

1. Introduction

Cognitive skills and strategies (also called thinking skills and strategies and intellectual skills and strategies) are the basic 'tools' for all types of thinking. Competence in them is hence essential for all mental activities, for example the organization and storage of knowledge in memory and its recall and use for problem solving.[1–4] Many types of intellectual skills and strategies have been identified and they have been classified in many ways and at different levels of detail. Comprehensive classifications of them are given in books by Marzano *et al.*[1] and Jones *et al.*[2] Simpler classifications have been given by other researchers.[5,6]

Cognitive skills (thinking skills) are the basic 'building blocks' of thinking. Examples of them are reading skills, writing skills, mathematical skills, focusing skills, information-processing skills, organization skills, remembering skills, reasoning skills, analysis skills, synthesis skills and three-dimensional visualization skills. Some of these skills are used frequently in our daily lives (e.g. reading and writing) while others are specific to the subject studied (e.g. three-dimensional visualization skills for learning some topics in science). The skills also vary in complexity. *Cognitive strategies* are overall plans of action for managing, guiding and executing mental tasks such as knowledge organization, decision making and problem solving. They are broader than intellectual skills and the execution of a strategy generally needs competence in many cognitive skills.

An important student learning outcome in the present high school Physical Sciences curriculum is[7]:'The learner is able to use process skills, critical thinking, scientific reasoning and strategies to investigate and solve problems in a variety of scientific, technological, environmental and everyday contexts'. Though this emphasizes intellectual abilities, the syllabus and work schedules given to teachers are stated mainly in terms of acquisition of content knowledge. The actual conduct of the course, and also how students are assessed and evaluated at examinations, also places much greater emphasis on the acquisition of content knowledge than on training students in intellectual abilities.

The main purpose of the present research study was to find out the level of competence of high school Physical Sciences teachers in some basic intellectual skills and strategies that are essential for effective problem solving. The study was restricted to just a few aspects of problem solving and does not consider learning aspects such as the organization and remembering of knowledge. This type of study has not been done before on teachers in South Africa but some studies have been done on first year university students.[8–10] The questions used in this study tested both skills and strategies. This article discusses teachers' performance in the questions that tested intellectual skills. Their performance in the questions that tested competence in intellectual strategies was reported in an earlier article[11], which also gives details concerning the question papers and their administration.

Seventy-three teachers from about 50 Dinaledi schools in the North West and KwaZulu-Natal provinces were tested. Dinaledi schools are special schools selected by the National Department of Education in South Africa where the teaching of mathematics, science and technology is particularly emphasized and supported.

Teachers were tested at the start of four-day workshops organized by the Department of Education. Two question papers were used for testing North West Province teachers in

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July and September 2009, while only one of the papers was used for testing KwaZulu-Natal Province teachers in September 2009.

2. Objectives and Method of Study

The main objectives of this study were:

- to test the competence of high school Physical Sciences teachers in some basic cognitive skills that are important for problem solving in Physical Sciences;
- to identify the nature and possible reasons for teachers difficulties with these skills;
- to make suggestions for rectifying these difficulties.

The study method used was the analysis of teachers' answers to questions that were designed to test competence in intellectual skills. Since the objective of the study was to test competence in intellectual skills, two criteria must be satisfied by the questions. They are: a) any difficulty in answering a question must be due *only* to lack of competence in using some intellectual skill (it must not be due to difficulties associated with subject content knowledge); b) the solution to a question must not already be known to the persons tested (to prevent them from merely recalling the solution).

To help satisfy the first criterion the following was done. All science concepts and principles needed to answer a question were provided and the simplest possible questions were designed. Only three simple scientific concepts/principles are needed for answering the questions and these are density, speed and the law of conservation of mass. Some of the questions used were non-science questions and even non-scientists should be able to answer them. There are no disadvantages in using non-science questions because intellectual skills and strategies, since they are of general applicability, should be the same for answering both science and non-science questions. To satisfy the second criterion mentioned above, unfamiliar types of questions were designed. For example, to test whether one has the ability to deduce correctly the information organized in an equation, the unfamiliar equation $p^{½}V = kT^2$ was used (and not $pV = kT$, a familiar equation, for which one may remember that pV is a constant and therefore competence in deducing information from equations will not be tested). If a question does not satisfy these two criteria, conclusions drawn from the answers concerning competence in intellectual abilities will not be valid.

3. Test Questions

Fourteen questions were used for testing and these are given in Table 1. The cognitive skills tested are those that are particularly important for solving problems in Physical Sciences and are:

- Description/explanation skills;
- Mathematical skills;
- Graphical skills;
- Three-dimensional visualization skills;
- Information-processing skills;
- Reasoning skills.

Since only 14 questions were used for testing (due to time constraints), it was possible to test only a few aspects of the above skills.

4. Results and Discussion

Teachers' performance in the questions is shown in the last three columns of Table 1. These columns show (under heading: % correct) the percentages of teachers who correctly answered each question in the North West (NW) Province, KwaZulu-Natal (KZN) Province and in both the provinces (NW & KZN). Teachers' performance in the questions will be discussed below; the performance considered will be the overall performance of all the teachers from both provinces.

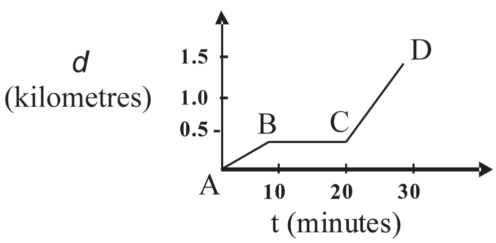
Question 1 tests ability to distinguish between descriptions and explanations. Descriptions are statements of facts, principles and laws that are obtained from observations or experiments while explanations attempt to understand and interpret these facts, principles, and laws in terms of the properties of the particles (molecules, atoms, ions, electrons, protons and neutrons) present in the system. Many difficulties of students, when learning chemistry, are due to their not distinguishing clearly between descriptions and explanations. This distinction is very important when learning science because descriptions and explanations have to be learnt in different ways. Explanations, unlike descriptions, are imaginary constructions of our mind and may have to be modified or changed. Also, many students' failures in some examination questions are due to their giving a descriptive answer when what was required was an explanatory answer. Of the statements given in question 1, only (b) is an explanation: it interprets gas pressure (which is an experimentally observed property) in terms of a property (translational motion) of the particles (molecules) present in the gas. The results in Table 1 show that most (about 85 %) of the teachers tested recognized this. But their performance in the other parts of the question was not so good. The worst performance was in part (d) for which 75 % of the teachers thought incorrectly that the statement 'copper conducts electricity because all metals conduct electricity' is an explanation. This statement is a logical statement but it is not an explanation because it does not interpret electrical conduction in terms of the properties of the particles (electrons) present in the system. This error was probably caused by the word 'because' in the sentence. Consider now parts (a) and (c) of the question where the statements given are quantitative laws. About 35 % (average performance) of teachers thought erroneously that these statements were explanations. They probably equated quantitative laws with explanations. Only two words were tested in this study because of time constraints. Other research studies have indicated that students have difficulties[15,16] with many other words too that are important for learning science (e.g. qualitative/quantitative, empirical/theoretical, variable/constant, fact/opinion, predict, hypothesis)

Mathematical skills are tested in questions 2–7. *Question 2* tests competence in some basic mathematical operations (addition, subtraction, multiplication, division), both with numbers and with physical quantities (which have numbers and units). The results in Table 1 show that about 30 % of teachers had difficulty with basic mathematical operations involving numbers in scientific notation (part (a) of the question whose solution is: $1.3 \times 10^{-3} - 4.0 \times 10^{-2} = 0.13 \times 10^{-2} - 4.0 \times 10^{-2} = -3.87 \times 10^{-2}$), and 25 % of them did not know the basic principle that physical quantities in different units must first be converted into the same unit before mathematical operations can be done with them (part (b) of the question whose solution is: 6.0×10^{-2} m / 12.0×10^{-3} km = 6.0×10^{-2} m / 12.0 m = $0.50 \times 10^{-2} = 5.0 \times 10^{-3}$). Performance in part (c) of the question was very good.

Questions 3 and 4 test respectively the ability to identify the information provided by the equations $p^{½}V = kT^2$ and $A = B^2/C$. Teachers' performance in *question 3* (*a*) was very poor. From the equation $p^{½}V = kT^2$ it is easy to see that when T is kept constant kT^2 will be constant and therefore that $p^{½}V$ (and not pV) will be constant. But more than 85 % of teachers thought incorrectly that pV will be constant. It was also surprising that 35 % thought incorrectly that k will change when T changes, even though k

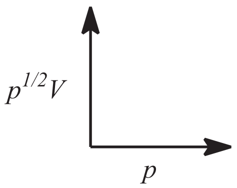
Table 1 The questions used for testing cognitive skills.

Question	% Correct NW	% Correct KZN	% Correct NW & KZN
Description/Explanation skills			
1. State whether the statements given below are descriptions or explanations. Explain			
a) The volume of a gas is inversely proportional to its pressure	57	–	57
b) A gas exerts pressure because the molecules present in the gas bombard the container walls	86	–	86
c) An ideal gas obeys the equation $pV = nRT$	75	–	75
d) Copper conducts electricity because all metals conduct electricity	25	–	25
e) The percentage of O_2 in air is 21 %	79	–	79
Mathematical skills			
2. Calculate the following:			
a) 1.3×10^{-3}–4.0×10^{-2}	68		68
b) $(6.0 \times 10^{-2}$ m$)/(12.0 \times 10^{-3}$ km$)$	75	–	75
c) 10 % of 125	97	–	97
3. For a non-ideal gas, the variable physical quantities V, p and T are related by the equation $p^{½}V = kT^2$, where k is a constant. For this gas			
a) At a constant T, will pV be a constant? Explain	18	06	13
b) If T increases, will k increase, decrease or remain unchanged?	78	48	65
4. A, B and C are variable quantities related by the equation $A = B^2/C$			
a) Is A directly proportional to B? Explain	46	–	46
b) Is A directly proportional to C? Explain	83	–	83
c) If the value of C is increased, will A increase, decrease or remain unchanged?	93	–	93
d) If the value of B is doubled, will A be doubled, quadrupled (i.e. increase 4 times), halved or remain unchanged?	57	–	57
5. The question below concerns density (d) which is defined by the equation $d = m/V$, where m = mass and V = volume. If the density of 1 g 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	07
6. Use the equation $t = k/N$ (where N = number of men employed to do some task, t = time needed to do the task k = a constant) to calculate the time needed by 4 men to do some task if 3 men needed 12 hours to do the same task	45	66	55
7. 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: $d = m/V$)	58	75	66
Graphical skills			
8. Use the graph given below, which shows the total distance (d) walked by a man plotted against time (t), to answer the following questions (Note: the defining equation for speed (s) is $s = d/t$)			

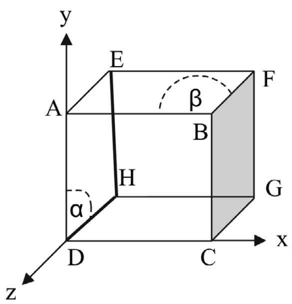


Question	NW	KZN	NW & KZN
a) Find the distance walked between 20 and 30 minutes	55	75	64
b) During the first 10 minutes (see line AB) does the man's speed increase, decrease or remain unchanged?	23	39	30
9. For a non ideal gas, the variable phusical quantities V, p, and T are related by the equation $p^{½}V = kT^2$ where k is a constant. For this gas			
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). Explain	03	12	07

Question	% Correct NW	% Correct KZN	% Correct NW & KZN
b) Show graphically how $p^{½}V$ will vary with p, at constant T	08	09	08



Question	% Correct NW	% Correct KZN	% Correct NW & KZN
Three dimensional visualization skills			
10. The questions concern the figure given, here the arrowed lines represent the x, y and z axes and the box is a cubic box			



Question	% Correct NW	% Correct KZN	% Correct NW & KZN
a) Is point F at a higher level, same level or lower level than point A	85	84	85
b) Which face of the cube is opposite to face HGCD?	88	93	90
c) Will the angle ADH (α) be 90°, less than 90° or greater than 90°?	80	87	93
d) Will the angle ABF (β) be 90°, less than 90° or greater than 90°	80	87	83
Information-processing skills			
11. Represent the information in the following statements as equations.			
a) The difference between masses (m) of two objects A and B is 5 g, object A having the higher mass	93	–	93
b) The price of N chocolates P_N is equal to the price of one chocolate (P_1) multilied by the number of chocolates	68	–	68
c) the rate of diffusion of a gas (R) is directly proportional to the square root of its molar mass (M)	71	–	71
d) The mass percentage (M_A%) of a substance in a mixture of A and B is equal to one hundred multiplied by the mass of A and divided by the total mass of A and B.	75	–	75
Reasoning skills			
12. Three men need 12 hours to tile the floor of a house. How many hours will be needed by four men, working at the same rate, to tile the floor of the house?	45	36	41
13. 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?	85	90	87
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	80	75	82
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) $t = kN^2$ (iv) $t = kN^{1/2}$ (v) $t = k \log N$	63	75	68
14. Consider the following two statements: All mammals are warm-blooded animals; Animal A is warm-blooded. Would it be correct to conclude from the above two statements that A is a mammal? Explain your answer.	39	–	39

was stated to be a constant in the problem. This may be due to these teachers either not understanding clearly the meaning of the word constant or to their rushing through the solution without reading the problem carefully. Though performance in question 4 was better, the results were still disappointing. More than 40 % of the teachers did not recognize, for example, that for the equation $A = B^2/C$ if the value of B is doubled the value of A will be quadrupled. Most of them thought that if B is doubled A too will be doubled.

Question 5 tests understanding of the defining equation for density. It may appear from the equation $d = m/V$ that d is directly proportional to m. This, however, is not generally true. This is true only if V is kept constant. In the problem considered, V is not constant and when m is doubled V too will be doubled. Hence m/V (i.e. density) will not change. The density of 2 g of the solid will therefore be the same as the density of 1g of the solid. Teachers' performance was very poor. The results from Table 1 show that more than 90 % of them did not correctly answer the question. Most of them thought that density will be doubled when mass is doubled.

Question 6 tests one of the most important uses of equations: their use for calculations. To calculate t when the number of men is four (i.e. $N = 4$), using the equation $t = k/N$, it is necessary to know the value of k. This is not given but can be calculated by substituting the given data ($N = 3$ men, $t = 12$ hours) in the equation $t = k/N$. Then $k = N \times t = 3$ men $\times$ 12 h = 36 men h. This value for k can then be used to do the required calculation ($t = k/N = 36$ men h/4 men = 9 hours). Though this calculation is not difficult, about 45 % of the teachers tested could not do it. About 15 % did not even attempt this calculation. The error of most teachers was due to their attempting to do the calculation by applying the equation just once. Step-by-step reasoning is needed to do the required calculation and the equation has to be applied twice.

Question 7 tests ability to combine two simple equations ($d = m/V$ and $pV = kT$). Two equations can be combined only if they have a common physical quantity. The common quantity in the two given equations is V, and V in the equation $d = m/V$ can be replaced by kT/p (because $V = kT/p$ from the equation $pV = kT$) to give $d = mp/kT$. Despite its simplicity, about 35 % of the teachers tested did not know how to combine the two equations and about 20 % did not even attempt to solve the problem. Since ability to replace an unknown quantity in an equation by a known quantity is crucially important in quantitative problem solving[17], lack of competence in this skill will seriously handicap the solution of quantitative problems.

Questions 3–7 test competence in the understanding and use of equations. The results show that teachers' competence is poor. About a half of them (average performance in questions 3–7) had difficulty in answering the questions. The understanding of equations and their use for storing and using knowledge is very important in the study of the quantitative aspects of all science courses. This is mainly because equations organize knowledge in a concise and unambiguous manner and hence are easier to remember, manipulate and use than verbal statements.

Graphical skills are tested in questions 8 and 9. *Question 8* tests understanding of a simple graph of distance travelled (d) *versus* time (t). Part (a) of the question merely needs the reading, from the graph, of the distance travelled between two times. Though the skills needed to solve this problem are fairly simple, about 35 % of teachers had difficulty. Some of them even tried to calculate the distance travelled using the equation $d = s\ t$, even though the question stated that the distance travelled should be obtained from the given graph. Teachers' performance in the second part of the question was worse. 70 % of them thought incorrectly that speed increases with time because distance traveled increases with time. This is despite the equation relating speed and distance travelled ($s = d/t$) being given in the question.

Question 9 tests ability to correlate an equation ($p^{1/2}V = kT^2$) with the general equation for a linear graph ($y = mx + c$) so as to identify the types of plots that will give linear graphs. Performance of teachers was very poor with more than 90 % of them being unable to answer the question.

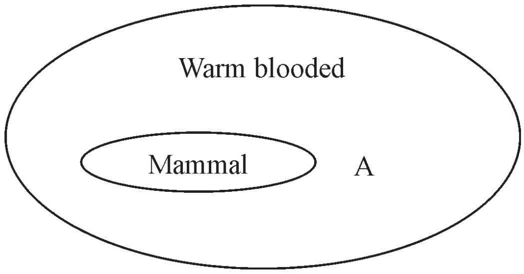
Three-dimensional visualization skills are tested in *question 10* which tests ability to visualize three-dimensionally the drawing of a cube. The overall performance of teachers was good. But about 15 % of them had difficulty despite the fact that the cube is a simple structure. More complicated structures (e.g. pyramid, tetrahedron, octahedron) need to be visualized three-dimensionally for understanding the internal structures of many molecules and solids, and this is a much more difficult task.

Information-processing skills[18] are involved in *question 11* which tests ability to process quantitative information given in verbal statements into equations. About a quarter (average performance in all four parts of the question) of the teachers tested could not transform information in statements into equations. This ability is important because calculations (and some types of deductions) are best done using equations and not by verbal reasoning which is generally cumbersome, error-prone and difficult, particularly when many items of information are involved. The difficulty with verbal reasoning is mainly associated with the need for processing lengthy information in our working memory (short-term memory) which is limited in capacity and duration in most people.[18,19]

Reasoning skills are tested in questions 12–14. *Question 12,* which is a type of problem often encountered in our daily lives, tests ability to identify an inverse proportion relationship and then use it to perform a calculation. This problem can be solved in two ways: (a) by using verbal reasoning (inverse proportion reasoning); (b) by writing first the equation that relates the time t and the number of men (N) (the equation is $t = k/N$ where k is a constant) and then using the equation to do the calculation. Method (b) is better because it forces us to clarify the problem and understand it: it requires mental effort to identify the variables and the type of relationship that exists between them. Though this is a simple and familiar problem, about 60 % of teachers could not do the required calculation. Most of the erring teachers merely manipulated the data given without first identifying the principle that has to be used to do the calculation.

Question 13 tests understanding, both qualitative and quantitative, of the inverse-proportion relationship between the time (t) needed to do some task and the number of men (N) needed to do the task. Part (a) of the question tests qualitative understanding. From our daily-life experience it should be clear that if the number of men employed to do some task is increased the time needed to do the task should decrease. It was surprising, therefore, that some teachers (13 %) did not recognize this 'common sense' conclusion. Teachers' answers to parts (b) and (c) also indicated that about 25 % of them did not fully understand the concepts associated with an inverse proportion relationship. Since direct and inverse proportion reasoning are basic cognitive skills needed not only for the effective learning of science but also for success in our daily lives, it is important to ensure that teachers and students become competent in them.

Question 14 is a simple question in symbolic logic. From the two statements 'All mammals are warm-blooded animals' and 'Animal A is warm-blooded' it would not be correct to conclude that animal A is a mammal. About 60 % of the teachers tested could not solve this problem. Their difficulty was mainly due to their attempting to use *abstract* reasoning to solve it. Instead of using abstract reasoning, if the information given in the two statements is first coordinated in a *visual* manner, for example as a 'Venn diagram' as shown below, the solution will be simplified. This diagram shows clearly that A can be warm blooded without it being a mammal. An important strategy that should always be used is to represent, whenever possible, information in verbal statements (which is *abstract* information) into *visual* information (diagrams or pictures). This would simplify learning and problem solving.



5. Conclusion

This study, whose main objectives were to test the competence of high school Physical Sciences teachers in some important cognitive skills and to identify possible reasons for their difficulties and make suggestions for rectifying them, showed that the competence of many teachers was poor. Six types of skills were tested and teachers' performance in them is shown in the table below. The type of skill is stated in the first column and the other column (under heading '% incorrect') shows the percentages (these are the average percentages for all the questions used for testing a particular type of skill – see Table 1) of teachers who were unable to answer the questions involving that skill.

Intellectual skill	% Incorrect
Description /explanation skills	36
Mathematical skills	50
Graphical skills	72
Three-dimensional visualization skills	15
Information-processing skills	23
Reasoning skills	47

The results in the table show that teachers' competence was poor for most of the skills tested, which are basic skills essential for the effective learning of high school Physical Sciences. The average value of the six percentages given in the table is about 40 which indicate that about 40 % of the teachers had difficulty, on the average, with the questions that were used to test their competence in intellectual skills. The performance of teachers was not much better (only about 10 % better) than the performance of final year B.Sc. students at our University in a similar test on cognitive skills.[20]

Teachers' lack of competence in intellectual skills and strategies would seriously handicap the successful implementation of the new high school curriculum which places strong emphasis on the development of the intellectual abilities of students. It would not be reasonable to expect teachers who are not very competent in cognitive skills and strategies to have a positive influence on the development of students' cognitive abilities. Furthermore, this lack of competence will foster negative attitudes and decrease self-confidence which will also impact negatively on the teaching and training of students. There is therefore a need for ensuring that teachers become more competent in cognitive skills and strategies.

Five suggestions for increasing teachers competence in cognitive skills and strategies are[11]:

- integration of cognitive skills and strategies with content knowledge during preservice training;
- conducting workshops in cognitive skills and strategies;
- provision of written material on cognitive skills and strategies;
- integration of cognitive skills and strategies with subject content knowledge;
- inclusion of questions on skills and strategies in examination papers.

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