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AUTHOR	Niaz, Mansoor
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ABSTRACT

Achievement in science depends among other factors on hypothetico-deductive reasoning ability; that is, on the developmental level of the students. Recent research indicates that developmental level of the students should be studied along with individual difference variables such as Pascual-Leone's M-capacity (information processing) and Witkin's Cognitive Style (disembedding ability). The purpose of this study was to investigate reasoning strategies of students in solving chemistry problems as a function of developmental level, functional M-capacity, and disembedding ability. A sample of freshman students (n=109) were administered tests of formal operational reasoning, functional M-capacity, disembedding ability, and chemistry problems (limiting reagent, mole, and gas laws). Results show that students who scored higher on cognitive predictor variables not only have a better chance of solving chemistry problems but also demonstrated greater understanding and used reasoning strategies indicative of explicit problem solving procedures based on the hypothetico-deductive method, manipulation of essential information and sensitivity to misleading information. It was also observed that students who score higher on cognitive predictor variables tend to anticipate important aspects of the problem situation by constructing general figurative and operative models leading to a greater understanding. Students scoring low on cognitive predictor variables tended to circumvent cognitively more demanding strategies and adopt others that helped them to overcome the constraints of formal reasoning, information processing, and disembedding ability. (Contains an annotated bibliography of 50 references.) (Author)

REASONING STRATEGIES OF STUDENTS IN SOLVING CHEMISTRY PROBLEMS AS A FUNCTION OF DEVELOPMENTAL LEVEL, FUNCTIONAL M-CAPACITY AND DISEMBEDDING ABILITY

MANSOOR NIAZ

CHEMISTRY DEPARTMENT, UNIVERSIDAD DE ORIENTE

APARTADO POSTAL 90, CUMANA, ESTADO SUCRE, VENEZUELA

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ABSTRACT

Achievement in science depends among other factors on hypothetico-deductive reasoning ability, that is, developmental level of the students. Recent research indicates that developmental level of the students be studied along with individual difference variables, such as Pascual-Leone's M-capacity (information processing) and Witkin's Cognitive Style (disembedding ability). The purpose of this study is to investigate reasoning strategies of students in solving chemistry problems as a function of developmental level, functional M-capacity, and disembedding ability. A sample of 109 freshman students were administered tests of formal operational reasoning, functional M-capacity, disembedding ability, and chemistry problems (limiting reagent, mole, gas laws). Results obtained show that students who scored higher on cognitive predictor variables, not only have a better chance of solving chemistry problems, but also demonstrated greater understanding and used reasoning strategies indicative of explicit problem solving procedures based on the hypothetico-deductive method, manipulation of essential information and sensitivity to misleading information. It was also observed that students who score higher on cognitive predictor variables tend to <u>anticipate</u> important aspects of the problem situation by constructing general figurative and operative models, leading to a greater understanding. Students scoring low on cognitive predictor variables tended to circumvent cognitively more demanding strategies and adopt others that helped them to overcome the

constraints of formal reasoning, information processing, and disembedding ability.

INTRODUCTION

In recent years various studies have shown that achievement in science depends on cognitive variables, such as developmental level, M-capacity, and disembedding ability of the students (Bender & Milakofsky, 1982; Bitner, 1991; Haidar and Abraham, 1991; Johnstone & Al-Naeme, 1991; Johnstone & El-Banna, 1986; Lawson, 1983; Mitchell & Lawson, 1988; Niaz, 1987a, 1987b, 1987c; Niaz & Lawson, 1985; Niaz & Robinson, 1992; Opdenacker, et al., 1990; Piburn, 1990; Roth, 1990; Staver & Jacks, 1988). Developmental level, that is, general hypothetico-deductive reasoning ability (cf. procedural knowledge, Anderson, 1980) is an important predictor variable as most science concepts are based on hypothetico-deductive systems of scientific explanation (for a review see Lawson, 1985). M-capacity (Pascual-Leone, 1970, 1987) represents the ability of the students to manipulate simultaneously a large number of facts before comprehending the problem to be solved. Empirical evidence (Niaz, 1988) shows that even small changes in the amount of information required for processing can lead to working memory overload due to: a) mobilization of functional M-capacity instead of the maximum structural M-capacity; and b) a situation in which the M-demand (amount of information processing required) of the task is greater than the M-capacity of the subjects. Disembedding ability/cognitive style (Witkin, et al., 1977; Pascual-Leone, 1989) represents the ability of the students to disembed information (cognitive restructuring) in a variety of complex and potentially misleading instructional contexts (Collings, 1985; Lawson, 1976; Linn, 1978; Niaz, 1989a, 1989b; Strawitz, 1984). According to Witkin and Goodenough (1981), Cognitive Style, "... is a pervasive dimension of individual functioning, showing itself in the perceptual, intellectual, personality, and social domains, and connected in its formation with the development of the organism as a whole. Second, it involves individual differences in process rather than content variables; that is to say, it refers to individual differences in the 'how' rather than the 'what' of behavior. Third, people's standing on the dimension is stable over time" (p. 57). For a recent review of the subject see McKenna (1990).

The importance of general hypothetico-deductive reasoning (i.e., procedural knowledge) as compared to domain-specific declarative knowledge has been the subject of considerable debate in the science education literature (for a recent review see Staver, 1990). Most science educators would perhaps agree with Kuhn, Amsel, O'Loughlin (1988) that, "The lack of generality of formal operational strategies across a range of content, however, has left science educators wondering whether it is reasonable to suppose that they reflect global developmental stages in scientific thinking ..." (p. 232). Nevertheless, it is important to point out that in his later years Piaget himself recognized that content played a significant role in formal reasoning (Vuyk, 1981).

Similarly, Kitchener (1986) has emphasized that in order to study the epistemic subject, Piaget specifically ignores the psychological subject and issues such as, "... cognitive styles, studies of variables that detract from correct reasoning, attention, and memory limitations" (p. 28). From this perspective it is essential that developmental level of the students be studied along with individual difference variables, such as Pascual-Leone's M-capacity and Witkin's Cognitive Style (disembedding ability). More recently, based on empirical evidence, Niaz (1990, 1991) has argued that Pascual-Leone's Theory of Constructive Operators provides explanatory constructs for understanding the developmental level of the students by postulating the antecedent variables of M-capacity, Field Factor (Cognitive Style), and the Mobility-Fixity Dimension. This article is based primarily on the, "... dialectical-constructivist idea that quantitative limitations and/or increments in mental processing capacity are in dynamic interaction with other organismic factors, the efficient causes of qualitative stages" (Pascual-Leone, 1987, p. 535). Furthermore, a fundamental assumption of this article is that the postulation of information processing load (M-capacity) and perceptual field factor (disembedding ability), leads to a 'progressive problemshift' (Lakatos, 1970) between Piaget's Epistemic Subject and Pascual-Leone's Metasubject (cf. Niaz, 1992 for details).

Although the importance of general hypothetico-deductive reasoning has been recognized for science achievement, very little work has been done to establish a relationship between reasoning strategies students actually use and their ability to reason hypothetico-deductively. Similarly, little work has been done to investigate the relationship between the reasoning strategies students actually use and their M-capacity and Cognitive Style. Gabel, Sherwood, and Enochs (1984), for example, found that students who were successful in solving chemistry problems (moles, stoichiometry, gas laws, and molarity) and those with high proportional reasoning ability tended to use algorithmic reasoning strategies more frequently than nonsuccessful and low proportional reasoning students. Atwater and Alick (1990) found that choice of a reasoning strategy is not significantly related to the developmental level (formal operational reasoning) of the students in specific types of stoichiometric (moles) problems. The authors, however, concluded that a higher level of cognitive development and reasoning may be crucial factors in solving more sophisticated types of problems in stoichiometry. At this stage, it is essential to point out that the degree to which general hypothetico-deductive reasoning and other individual difference cognitive variables, "... predict achievement depends to a great extent upon what apect of achievement one is interested in" (Mitchell & Lawson, 1988, p. 24).

PURPOSE

The purpose of the present study is to investigate the reasoning strategies of students in solving chemistry problems as a function of developmental level, functional M-capacity, and disembedding ability.

METHOD

One hundred and nine freshman students (Ss) enrolled in three sections of Chemistry I for science majors at the Universidad de Oriente, Venezuela (Mean age = 18.2 years; SD = 1.3) were pretested at the start of the semester to determine the following cognitive predictor variables:

(a) Developmental Level: A modified version of the Lawson (1978) Classroom Test of Formal Reasoning was used to assess developmental level. The test includes 15 items requiring the students to isolate and control variables and use proportional, probabilistic, combinatorial, and conservation reasoning. Split-half reliability of the modified test with the present sample was 0.74.

(b) Functional M-capacity: The Figural Intersection Test, FIT (Pascual-Leone & Burtis, 1974) was used to determine Functional M-capacity, M_f. The FIT is a group administered paper-and-pencil test, requiring no time limit in its original version and provides a measure of the Structural M-capacity (M_s) of the Ss. Each item of the test consists of two sets of figures, one 'presentation set' on the upper part of the page and one 'intersecting set' on the lower. In the presentation set a number of single geometric figures are arranged discretely. In the intersecting set the same figures are presented in an overlapping way, such that there is one area of common intersection. The figures in the presentation and intersecting sets correspond with respect to shape but not necessarily size or orientation. The subject's task is to find this area of intersection and mark it with a dot. The number of figures in the presentation and intersecting sets vary across items from two to eight. The number of figures in the presentation set designates the class of the item so that an item with four discrete figures falls into the category of class-4 items. To be solved correctly a class-8 item theoretically requires an M-capacity of 7. In this study it was hypothesized that by introducing a time limit (12 minutes) a measure of the Functional M-capacity (M_f), which is usually lower than M_s, could be obtained. See Niaz (1988) for the 12-minute time limit. The FIT version used in this study consisted of 31 items distributed in the following classes: two items of class 2 (that is, 2 figures), five items of class 3, five items of class 4, five items of class 5, four items of class 6, six items of class 7, and four items of class 8. A subject responding correctly in all items receives the following scores: for class 2 items, 2/2 = 1 point; for class 3 items, 5/5 = 1 point; for class 4 items, 5/5 = 1 point; for class 5 items, 5/5 = 1 point; for class 6 items, 4/4 = 1 point; for class 7 items, 6/6 = 1 point; and for class 8 items, 4/4 = 1 point. Total score in the FIT = 7 points and $M_f = 7$. A split-half reliability coefficient (odd versus even items at each level of complexity) of 0.78 was computed for the present sample.

(c) Disembedding Ability: This variable was assessed with the Group Embedded Figures Test, GEFT (Witkin, Oltman, Raskin, & Karp, 1971). According to standardized procedure, two minutes were allowed for the first section of the test, and five minutes were allowed for each of the second and third sections. A split-half reliability coefficient of 0.79 was obtained for the present sample.

The three sections of Chemistry I, on which this study is based, were taught by different instructors, who had a Course Coordinator. Most of the Ss had seen at least two courses of chemistry and mathematics in high school before coming to the University. A major difficulty for Ss on entering University is that most high school courses are oriented towards solving problems through algorithms. Ss were assigned to the three sections randomly and there were approximately the same number of students using a particular strategy in each section. The Course Coordinator ensured that the three instructors maintained the cognitive complexity of the course at about the same level. All sections received instruction in the traditional expository method in the different topics of the course and in the same sequence. All Ss were tested on a monthly exam which consisted of the following items:

Item 1

Barium oxide contains 10.46% of oxygen. How many grams of this compound can be obtained from 2.541 grams of barium and 0.444 grams of oxygen. Calculate the grams of barium and oxygen that reacted completely.

Item 2

A vessel contains 10 moles of a substance A and 10 moles of a substance B. If the mass of A is greater than that of B, it can be concluded that:

a) Molecular mass of A is equal to that of B.

b) Molecular mass of A is greater than that of B.

c) Molecular mass of A is less than that of B.

d) This problem cannot be solved with the informatin provided.

Item 3

A certain amount of gas occupies a volume (V_1) at a pressure of (P_1). If the temperature is maintained constant and the gas expands three times its initial volume (V_1), the final pressure of the gas would be:

a) same as the initial	b) nine times the initial
c) three times the initial	d) one-third of the initial
e) none of the previous	

Item 4

A certain amount of gas occupies a volume (V_1) at a pressure of 0.60 atm. If the temperature is maintained constant and the pressure is decreased to 0.20 atm, the new volume (V_2) of the gas would be:

a) $V_2 = V_1/6$	b) $V_2 = 0.33\ V_1$
c) $V_2 = V_1/3$	d) $V_2 = 3\ V_1$
e) none of the previous	

Ss were asked and encouraged to justify and explain their answers in all four items, which formed part of their regular course evaluation. Item 1 was adapted from Niaz (1988, 1989c). Items 3 and 4 were adapted from Niaz (1989c).

RESULTS AND DISCUSSION

Item 1

Reasoning strategies used by Ss in solving Item 1 were classified into the following categories:

Strategy a

- g of Ba = 100 - 10.46 = 89.54 (General Figurative Model)
- according to the Law of Definite Proportions: (General Figurative Model)
  g of Ba/g of O_2 = 89.54/10.46 = 8.56
- according to the given values: (Specific Figurative Model)
  g of Ba/g of O_2 = 2.541/0.444 = 5.72
- as 5.72 < 8.56 ; O_2 is in excess (General Operative Model)
- 89.54 g of Ba = 10.46 g of O_2 (Specific Operative Model)
  2.541 g of Ba = X = 0.2968 g of O_2
- g of Barium oxide = g of Ba and O_2 that reacted = 2.541 + 0.2968 = 2.838 g (Specific Operative Model)

Strategy b

- g of Ba = 100 - 10.46 = 89.54
- 10.46 g of O_2 = 89.54 g of Ba
  0.444 g of O_2 = X = 3.80 g of Ba
- 89.54 g of Ba = 10.46 g of O_2
  2.541 g of Ba = X = 0.2968 g of O_2 ; O_2 is in excess
- g of Barium oxide = g of Ba and O_2 that reacted
  = 2.541 + 0.2968 = 2.838 g

Strategy c

- g of Ba = 100 - 10.46 = 89.54 g
- 89.54 g of Ba are present in = 100 g of Barium oxide

  2.541 g of Ba are present in = X = 2.838 g of Barium oxide
- 100 g of Barium oxide have = 10.46 g of O_2

  2.838 g of Barium oxide have = X = 0.2968 g of O_2 ;

  O_2 is in excess

Strategy d

- g of Ba = 100 - 10.46 = 89.54 g
- 89.54 g of Ba = 10.46 g of O_2

  2.541 g of Ba = X = 0.2968 g of O_2
- 10.46 g of O_2 = 89.54 g of Ba

  0.444 g of O_2 = X = 3.80 g of Ba
- g of Barium oxide = g of Ba and O_2 that reacted

  = 3.80 + 0.2968 = 4.09 g

Strategy e

- first three steps are the same as in Strategy a
- 5.72 < 8.56 ; Ba is in excess

Strategy f

- 0.444 g of O_2 = 2.541 g of Ba

  10.46 g of O_2 = X = 59.86 g of Ba
- g of Barium oxide = 59.86 g of Ba + 10.46 g of O_2 = 70.32 g

Strategy g

- g of Barium oxide = 2.541 g of Ba + 0.444 g of O_2 = 2.985 g
- 100 g of Barium oxide have = 10.46 g of O_2

  2.985 g of Barium oxide have = X = 0.312 g of O_2
- 100 g of Barium oxide have = 89.54 g of Ba

  2.985 g of Barium oxide have = X = 2.67 g of Ba

It is instructive to examine these strategies within the epistemological framework of Pascual-Leone's 'dimensional analysis' (cf. Niaz, 1988, 1989c; Niaz & Robinson, 1992; Pascual-Leone, 1978; Pascual-Leone & Sparkman, 1980), which considers the essential informational dimensions in the subject's examination of the problem and anticipation of its solution. This examination of the problem and the <u>anticipation</u> of its solution is based on the construction of two types of models: figurative and operative. A General Figurative Model (GFM) represents the idealized objects or scientific general facts that inform the problem in question, in the sense that the problem is a particular case or concretization of the idealized objects or principles. Formulation of the GFM is a step towards the <u>anticipation</u> of the solution and helps in greater understanding of the problem. A General Operative Model represents the application to the Specific Figurative Model of 'operative transformations', that is, operations needed to obtain the solution. An analysis of Strategy a indicates that the first two steps would constitute the General Figurative Model, the third step would constitute the Specific Figurative Model, the fourth step would constitute the General Operative Model, and the last two steps would constitute the Specific Operative Model. A comparison of Strategy a with the other two correct strategies b and c, shows the essential difference, viz., Ss using Strategies b and c although solve the problem correctly, they do not anticipate that O_2 is in excess, as they do not construct a figurative model. More specifically, Step 2 (GFM) and Step 3 (SFM) of Strategy a is missing in both Strategies b and c. These results show an important qualitative difference between the ability to construct general figurative and operative models (Strategy a), which leads to a better understanding of the problem, and the ability to merely manipulate the data (Specific Operative Model), which may (Strategies b and c) or may not (Strategies d, f, and g) lead to the resolution of the problem.

Further analysis of the strategies shows that Ss using Strategies a, b, and c solved the problem correctly by using an approach that approximates hypothetico-deductive reasoning. Nevertheless, it is important to point out that only Strategy a uses hypothetico-deductive reasoning explicitly. Table I shows that

Insert Table I about here

Ss using Strategy a have a better mean score in all predictor variables as compared to Ss who used other strategies. The difference between the mean score in all predictor variables of Ss using Strategies a and b is, however, statistically not significant. Mean score in Developmental Level of the following groups of Ss is statistically (t test) significant: a and c ($p = 0.05$); a and d ($p = 0.001$); a and e ($p = 0.001$); a and f ($p = 0.001$); & a and g ($p = 0.001$). Mean score in Functional M-capacity of the following groups of Ss is statistically significant: a and c ($p = 0.05$); a and e ($p = 0.05$); a and f ($p = 0.05$); & a and g ($p = 0.05$). Mean score in disembedding ability of the following groups of Ss is statistically significant: a and c ($p = 0.001$); a and d ($p = 0.001$); a and e ($p = 0.05$); a and f ($p = 0.01$); & a and g ($p = 0.001$).

Comparison of Strategies a, b, and c shows that these Ss use hypothetico-deductive reasoning by going through the following sequence (cf. Lawson, 1982; Lawson, Abraham, & Renner, 1989):

a) Hypothesis: (IF ...)	According to the Law of Definite Proportions, 89.54 g of Ba react with 10.46 g of O_2.
b) Prediction: (THEN ...)	According to given values, 2.541 g of Ba will react with 0.2968 g of O_2.
c) Conclusin: (THEREFORE ...)	O_2 is in excess.

This hypothetico-deductive sequence, 'If ..... then ..... therefore .....' is presumably the hallmark of formal operational reasoning. In previous studies (Niaz, 1988, 1989c), based on Ss having the same social and cognitive background, Item 1 was estimated to have an M-demand of six, that is it could be solved by a series of six steps as outlined in Strategy a. The series of steps used by the Ss in other strategies were obtained in a similar fashion. Thus, it can be concluded that Ss using Strategies b and c construed the

M-demand of Item 1 to be 4 and 3, respectively. The essential difference between Strategies a and b is the decrease in the number of steps (M-demand) required to solve the problem, from 6 (Strategy a) to 4 (Strategy b). The difference between Strategies a and c is even more significant as the M-demand decreases from 6 (Strategy a) to 3 (Strategy c). As pointed out earlier Ss using Strategy c are working under constraint (Functional M-capacity) due to a limited information processing ability. These results indicate that although Ss using Strategies a, b, and c do use hypothetico-deductive approach to a certain extent, they do not process all the required information in a similar way. Ss using Strategies b and c, decrease the M-demand of the problem in order to cope with the information processing load and avoid working memory overload (cf. Niaz, 1988). Similar conclusions were reached by Scardamalia (1976) in Ss performance on control of variables problems, by emphasizing that, "... the major source of difficulty in the task is not a logical difficulty --- not a problem of applying the appropriate algorithm --- but is a problem of the burden placed on attentional capacity (i.e., M-capacity) of non-salient stimulus features" (p. 26). These results are important as they indicate that Ss try to circumvent certain strategies and adopt others which help them to reach the correct solution. A comparison of Strategies a and c is particularly illustrative of this problem solving approach, as it decreases the M-demand of the problem by almost 50%. It could, of course, be argued that although a problem can be solved by various strategies, we should encourage the Ss to use the one (e.g., Strategy a) that leads to a greater understanding. At this stage it is important to point out that alternative interpretations of the data are also possible, and M-demand of a problem can vary as a function of the social and cognitive background of the students.

Students using Strategy d require an explanation. These Ss use the hypothetico-deductive approach to a fair extent, but fail to take into account (disembed) a critical piece of information, viz., 3.80 g of Ba (see step 3) means that they would be using more than what is available. This inability to recognize that the reaction of 3.80 g of Ba is not possible is an indicator of the fact that disembedding ability is perhaps an essential pre-requisite of successful problem solving. In this context it is interesting to note that Ss using Strategy c have the lowest score in disembedding ability and still solve the problem correctly. This apparently anamolous finding suggests another interpretation: field-dependent (low disembedding) Ss perhaps need strategies appropriate to their Cognitive Style. Finally, Ss using Strategy e seem to be using a memorized algorithm, rather than the hypothetico-deductive method.

Item 2

Reasoning strategies used by Ss in solving Item 2 were classified into the following categories:

Strategy a

All Ss who selected alternative a. Most of these Ss reasoned: 'Both A and B have the same number of moles'.

Strategy b1

All Ss who selected alternative b and reasoned:

- According to the given information, moles of A = moles of B and mole = g/M.M., where M.M. = Molecular mass
- $g_A/(M.M.)_A = g_B/(M.M.)_B$
- Given that $g_A > g_B$; $(M.M.)_A > (M.M.)_B$

Strategy b2

All Ss who selected alternative b reasoned:

- Mole = g/M.M.
- Let us suppose that $g_A = 50$, and $g_B = 10$
- $(M.M.)_A = g_A/10 = 50/10 = 5$ g/mole
- $(M.M.)_B = g_B/10 = 10/10 = 1$ g/mole

Strategy b3

All Ss who selected alternative b and used a sort of intuitive reasoning in the following terms: 'Molecular mass of A is greater than that of B, as its mass is greater'.

Strategy c

All Ss who selected alternative c.

Strategy d

All Ss who selected alternative d and reasoned: 'Problem cannot be solved because masses of A and B are not given/ need to know the molecular mass of A and B'.

Insert Table II about here

Table II shows that Ss using Strategies b1 and b2 solved the problem correctly. It is important to point out that only Strategy b1 uses hypothetico-deductive reasoning explicitly. Students using Strategy b1 have a better mean score in all predictor variables, as compared to Ss who used other strategies. The difference between the mean score of Ss using Strategies b1 and b2 is, however, statistically significant only for Disembedding Ability. Mean score in Developmental Level of the following groups of Ss is statistically (t test) significant: b1 and b3 ($p = 0.001$); b1 and c ($p = 0.01$); b1 and d ($p = 0.01$); b1 and a ($p = 0.001$). Mean score in Functional M-capacity of the following groups of Ss is statistically significant: b1 and b3 ($p = 0.01$); b1 and d ($p = 0.05$); b1 and a ($p = 0.01$). Mean score in Disembedding Ability of the following groups of Ss is statistically significant at the $p = 0.001$ level: b1 and b3; b1 and c; b1 and d; b1 and a.

An analysis of Strategy b1 shows that Ss use hypothetico-deductive reasoning by going through the following sequence:

a) Hypothesis: According to the given information, moles of A = moles of B.
b) Prediction: $g_A/(M.M.)_A = g_B/(M.M.)_B$
c) Conclusion: Given that $g_A > g_B$; $(M.M.)_A > (M.M.)_B$

Strategy b2, on the other hand, shows what Neimark (1979) has referred to as the effect of task content, that is, familiar material (supposing that $g_A = 50$ and $g_B = 10$) should be more conducive to formal operations than abstract or symbolic material. According to Lawson (1985) the development of formal reasoning should precisely facilitate, "... successful behavior to extend beyond simple, familiar situations to complex, novel problems" (p. 594).

Item 3

Reasoning strategies used by Ss in solving Item 3 were classified into the following categories:

Strategy a

All Ss who selected alternative a.

Three of the Ss gave the following justifications. Student 1: 'What increases is the volume of the gas. The gas itself exerts no pressure; on the contrary if a person exerts pressure on a solid it can be noted'. Student 2: 'It remains the same as no pressure is being applied to the gaseous mass'. Student 3: 'At constant temperature, the pressure must also remain constant'.

Strategy b

All Ss who selected alternative b.

One of the Ss gave the following justification: 'As the volume increases, pressure should increase because the collisions between the molecules are more continuous, and consequently the pressure increases'.

Strategy c

All Ss who selected alternative c.

Some of the Ss gave the following justification:

$V_1/V_2 = P_1/P_2 \implies P_2 = P_1 V_2/V_1$; If V_1 = 1 liter,

V_2 = 3 liter; $P_2 = 3 P_1$

Strategy d1

All Ss who selected alternative d and reasoned:

- According to Boyle's Law at constant temperature: $P_1 V_1 = P_2 V_2$.
- As the gas expands three times its initial volume (V_1), final volume, $V_2 = 3 V_1$.
- $P_1 V_1 = P_2 (3 V_1)$; therefore $P_2 = 1/3 P_1$.

Strategy d2

All Ss who selected alternative d and reasoned:

- According to Boyle's Law at constant temperature: $P_1 V_1 = P_2 V_2$.
- Let us suppose that: $V_1 = 1$ liter, therefore $V_2 = 3$ liters, and $P_1 = 1$ atm.
- $P_2 = P_1 V_1/V_2 = 1/3$ atm.

Strategy d3

All Ss who selected alternative d but did not give an adequate justification.

Strategy e

All Ss who selected alternative e.

Insert Table III about here

Table III shows that Ss using Strategies d1 and d2 solved the problem correctly. It can, however, be observed that only Strategy d1 uses hypothetico-deductive reasoning explicitly. Ss using Strategy d1 have a better mean score in all predictor variables, as compared to Ss who used other strategies. The difference between the mean score of Ss using Strategies d1 and d2 is, however, statistically significant ($p = 0.05$) only for Developmental Level and Functional M-capacity. Mean score in Developmental Level of the following groups of Ss is significant: d1 and d3 ($p = 0.01$); d1 and e ($p = 0.01$); d1 and a ($p = 0.01$); d1 and b ($p = 0.01$); d1 and c ($p = 0.05$). Mean score in Functional M-capacity of the following groups of Ss is significant: d1 and d3 ($p = 0.01$); d1 and a ($p = 0.05$); d1 and b ($p = 0.05$); d1 and c ($p = 0.01$). In Disembedding Ability mean score of none of the groups differed significantly from that of group d1. An analysis of Strategy d1 shows that Ss use hypothetico-deductive reasoning by going through the following sequence:

a) Hypothesis: According to Boyle's Law at constant temperature: $P_1 V_1 = P_2 V_2$.

b) Prediction: As the gas expands three times its initial volume (V_1), final volume, $V_2 = 3 V_1$.

c) Conclusion: $P_1 V_1 = P_2 (3 V_1)$, therefore $P_2 = 1/3 P_1$

Strategy d2, on the other hand, once again (similar to Item 2) shows what Neimark (1979) has referred to as the effect of task content, that is, familiar material (supposing, $V_1 = 1$ liter, $V_2 = 3$ liters, and $P_1 = 1$ atm) should be more conducive to formal operations than abstract or symbolic material. Strategies a and b represent some of the alternative conceptions Ss hold about gases.

Item 4

Item 4 was included in the study for the following reasons: a) As Item 4 virtually reduces to what Ss using Strategy d2 in Item 3 actually did, it would be interesting to compare performance on Items 3 and 4; b) A previous study (Niaz, 1989c) had shown that Developmental Level of the Ss explained a significant (6.6%, F = 4.26, p = 0.043) amount of variance in performance on Item 3, and only 0.4% of the variance on Item 4. It is plausible to suggest that this difference could be attributed to the presence of the following logical step in Item 3: as the gas expands three times its initial volume (V_1), final volume, $V_2 = 3\ V_1$. This change in the logical difficulty of the problem could show an interesting relationship between Ss strategies and cognitive predictor variables. Table IV shows that 69 (63%) Ss responded correctly (selected and justified alternative d adequately) in Item 4, whereas 40 (37%) Ss (including d1 and d2) had responded correctly in Item 3, which shows a considerable gain in performance. In contrast to Item 3, mean score on all predictor variables of Ss using the correct strategy d in Item 4, do not differ significantly from those of Ss using other strategies. What is even more interesting is the fact that Ss using the correct Strategy d in Item 4 do not have the highest mean score on two of the cognitive predictor variables, viz., Functional M-capacity and Disembedding

Insert Table IV about here

Ability. These results indicate that problems like Item 4 do not evaluate Ss achievement related to cognitive abilities, such as hypothetico-deductive reasoning, information processing (Functional M-capacity), and Disembedding Ability, and shows quite clearly what Lawson has cautioned as to: What aspect of achievement one is interested in? (cf. Lawson, 1983; Mitchell & Lawson, 1988).

CONCLUSIONS AND EDUCATIONAL IMPLICATIONS

This study has found that students who score higher on cognitive predictor variables (Developmental Level, Functional M-capacity, and Disembedding Ability), not only have a better chance of solving chemistry problems, they use reasoning strategies that are indicative of explicit problem solving procedures based on the hypothetico-deductive method, manipulation of essential information, and sensitivity to misleading information. It was also observed that students who score higher on cognitive predictor variables tend to <u>anticipate</u> important aspects of the problem situation by constructing general figurative and operative models, leading to a greater understanding. Students scoring low on cognitive predictor variables tended to circumvent cognitively more demanding strategies and adopt others that helped them to overcome the constraints. Examples of some of these strategies are given below and it would be helpful for science teachers to take them into consideration:

a) Manipulation of M-demand of the problem in order to decrease the information processing load.

b) Instead of using abstract or symbolic material, students tended to use concrete examples, which facilitates formal operational reasoning. It was observed that if the logical structure of a problem is manipulated so that the problem situation refers to concrete changes (cf. Items 3 and 4), performance increases considerably.

c) Students with low disembedding ability tended to ignore relevant information. It was observed that some field-dependent (low disembedding) students were able to solve a problem by manipulating the logical structure and M-demand (cf. Item 1, Strategy c) simultaneously. This finding suggests that perhaps some students may need strategies appropriate to their Cognitive Style.

d) Manipulation of logical structure and M-demand of a problem may improve performance, but it may also 'trivialize the domain' to an extent (cf. Item 4) that science teachers may wonder: what aspect of achievement are we interested in? It is important that teachers be aware of what exactly are they evaluating. The degree to which a reasoning strategy requires understanding is always relative to another strategy that may reflect a lesser cognitive demand. For example, although Strategies a, b, and c in Item 1, lead to the resolution of the problem, they vary in their cognitive demand. As teachers we should encourage the students to use the strategy that leads to a greater understanding.

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TABLE I

Reasoning Strategies of Students in Item 1 as a Function of Developmental Level, Functional M-capacity, and Disembedding Ability (N = 109)

		Mean Score in		
Reasoning Strategy	N	Developmental Level	Functional M-capacity	Disembedding Ability
a[*]	14	8.56 (3.03)[#]	6.10 (0.49)	12.82 (3.91)
b[*]	14	6.52 (2.88)	5.54 (0.93)	9.85 (3.92)
c[*]	9	5.22 (2.68)	5.14 (1.25)	5.88 (2.93)
d	32	4.49 (2.49)	5.57 (1.14)	7.59 (4.12)
e	15	3.25 (2.56)	4.92 (1.73)	8.36 (4.82)
f	12	2.59 (1.48)	4.91 (1.31)	7.33 (3.01)
g	13	2.71 (1.64)	4.70 (1.27)	6.85 (3.76)

[*] Strategies that lead to correct response

[#] Standard deviation

TABLE II

Reasoning Strategies of Students in Item 2 as a Function of Developmental Level, Functional M-capacity, and Disembedding Ability (N = 109)

		Mean Score in		
Reasoning Strategy	N	Developmental Level	Functional M-capacity	Disembedding Ability
a	7	2.44 (1.18)[#]	4.50 (1.52)	5.00 (3.70)
b1[*]	15	7.15 (3.58)	6.07 (0.58)	12.31 (3.25)
b2[*]	23	5.26 (3.03)	5.50 (1.14)	7.64 (4.09)
b3	36	3.74 (2.78)	5.06 (1.32)	7.53 (4.46)
c	9	3.23 (2.39)	5.38 (1.59)	6.75 (3.85)
d	19	3.74 (2.96)	5.00 (1.65)	7.63 (4.23)

[*] Strategies that lead to correct response

[#] Standard deviation

TABLE III

Reasoning Strategies of Students in Item 3 as a Function of Developmental Level, Functional M-capacity, and Disembedding Ability (N = 109)

		Mean Score in		
Reasoning Strategy	N	Developmental Level	Functional M-capacity	Disembedding Ability
a	6	3.00 (2.32)[#]	5.00 (1.55)	7.00 (5.86)
b	4	2.65 (1.04)	5.00 (1.15)	8.00 (4.08)
c	24	4.44 (3.09)	4.90 (1.61)	7.96 (4.45)
d1[*]	23	6.67 (2.74)	6.00 (0.55)	9.60 (4.11)
d2[*]	17	4.24 (3.53)	5.31 (1.35)	7.94 (5.21)
d3	28	4.03 (3.18)	5.14 (1.41)	7.34 (4.43)
e	7	3.07 (1.28)	5.38 (1.69)	8.00 (3.78)

[*] Strategies that lead to correct response

[#] Standard deviation

TABLE IV

Reasoning Strategies of Students in Item 4 as a Function of Developmental Level, Functional M-capacity, and Disembedding Ability (N = 109)

		Mean Score in		
Reasoning Strategy	N	Developmental Level	Functional M-capacity	Disembedding Ability
b	15	3.55	5.42	7.67
		(2.38)[#]	(1.38)	(3.53)
c	9	4.26	5.75	9.44
		(3.19)	(0.71)	(4.53)
d[*]	69	4.75	5.40	8.23
		(3.41)	(1.26)	(4.51)
e	16	3.91	5.06	7.64
		(2.55)	(1.43)	(3.79)

[*] Strategy that leads to correct response

[#] Standard deviation