Molecular-Equilibrium Problems: Manipulation of Logical Structure and of M-Demand, and Their Effect on Student Performance

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ABSTRACT: Molecular-equilibrium (chemical-equilibrium) problems are among the most important, and at the same time most complex and difficult general chemistry problems. In this work, we examine the effect on student performance of the manipulation of the logical structure as well as of the M-demand of these problems. In addition, we study the relationship between student performance on the problems and a number of cognitive variables, viz., developmental level, working memory capacity, functional M-capacity and disembedding ability of students. In addition, we test the validity of the Johnstone–El-Banna model. Nine problems of varying number of operative schemata, as well as of varying number of M-demand, were used. The number of schemata varied from a minimum of two, to a maximum of four, while within each logical schema we had specific mental demand (M-demand), varying from four to six. As basic molecular-equilibrium schemata in these problems, we considered the following: (1) the process of establishment of chemical equilibrium; (2) the condition of chemical equilibrium; (3) the case of gaseous systems, with use of partial and total pressures as well as of K_p; and (4) the disturbance of equilibrium and the establishment of a new equilibrium. The correlation between student performance in the schemata and the steps of the problem solutions is low when the number of schemata is low, but high when this number is high. Of the cognitive factors studied, developmental level plays the most important role, especially as the logical structure of the problem increases. The other three cognitive variables also have an effect, with working memory capacity leading. The findings are mainly attributed to the fact that the problems were rather algorithmic exercises for the students, because of familiarity and training. © 1998 John Wiley & Sons, Inc. *Sci Ed* **82:**437–454, 1998.

INTRODUCTION

Recent research in science education shows the importance of cognitive variables, such as developmental level, information processing (working memory/M-capacity), and disembedding ability (Adey & Shayer, 1994; Bitner, 1991; Haidar & Abraham, 1991; Johnstone, 1984; Johnstone & Al-

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Naeme, 1991; Johnstone & El-Banna, 1986, 1989; Johnstone, Sleet, & Vianna, 1994; Johnstone & Su, 1994; Lawson, 1983; Mitchell & Lawson, 1988; Niaz, 1987, 1988a, 1988b, 1989a, 1989b, 1991a, 1996; Niaz & Lawson, 1985; Niaz & Robinson, 1992, 1993; Opdenacker et al., 1990; Piburn, 1990; Robinson & Niaz, 1991; Shayer & Adey, 1981; Staver & Jacks, 1988; Tsaparlis, 1994, 1995, 1997; Vaquero, Rojas, & Niaz, 1996). Developmental level (Inhelder & Piaget, 1958), that is, general hypotheticodeductive reasoning ability, is an important predictor variable because most science concepts are based on hypotheticodeductive systems of scientific explanation (for review, see Lawson, 1985). Working memory (Baddeley, 1986, 1990) and M-capacity (Pascual-Leone, 1970, 1987) intuitively capture the notion of some kind of hypothesized limited capacity mental resource that can be applied to learning and problem solving, and the two appear to be used interchangeably (for critical review, see Niaz & Logie, 1993). Disembedding ability/cognitive style (Pascual-Leone, 1989; Witkin, 1978; Witkin et al., 1974) represents the ability of 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).

RATIONALE

The importance of hypotheticodeductive reasoning as compared with domain-specific knowledge has been the subject of considerable debate in the science education literature (Burbules & Linn, 1991; Kuhn, Amsel, & O'Loughlin, 1988; Millar & Driver; 1987; Niaz, 1994a). Linn (1990) summarized the present state of research as follows: ". . . researchers from the cognitive science tradition have pushed the pendulum too far in the direction of domain-specific reasoning and that, in fact, domain-general reasoning is an important and frequently overlooked area of investigation" (p. 16). Furthermore, it is important to note that, in his later years, Piaget himself recognized the role of domain-specific knowledge in the acquisition of formal operational reasoning (Vuyk, 1981). According to Kitchener (1993), in order to understand Piaget, science educators must differentiate between Piaget's epistemic and psychological subjects. Niaz (1991b) has explained that, "The epistemic subject as compared to the psychological subject is an idealized abstraction, viz., that set of underlying epistemic structures common to everyone at the same level of development" (p. 569). From an epistemological perspective, Kitchener (1986) has emphasized that, 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 limitation" (p. 28). From this perspective it is essential that the developmental level of students be studied along with individual difference variables, such as Pascual-Leone's M-capacity, Baddeley's working memory, and Witkin's cognitive style. More recently, Niaz (1990, 1991a, 1994b, 1994c) has argued that Pascual-Leone's theory of constructive operators provides explanatory constructs for understanding the developmental level of students by postulating antecedent variables of M-capacity, cognitive style, and the mobility-fixity dimension. Furthermore, a fundamental assumption of this article is that the postulation of antecedent variables leads to a "progressive problemshift" (Lakatos, 1970) between Piaget's epistemic subject and Pascual-Leone's metasubject (Niaz, 1992).

Empirical evidence (Niaz, 1988a) shows that even small changes in the amount of information processing required (M-demand) can lead to working memory overload due to: (a) mobilization of functional M-capacity instead of the maximum M-capacity; and (b) a situation in which the M-demand of the task is greater than the M-capacity of the students. If the manipulation of the M-demand of a problem changes its cognitive complexity, thus affecting student performance significantly, it is plausible to suggest that the manipulation of the other two cognitive variables (logical structure and perceptual field effect) could also lead to significant changes in student performance. Lawton (1993) and Niaz (1988a) have shown that the manipulation of the perceptual field effect (disembedding/cognitive style) of proportional reasoning tasks changes student performance significantly. Niaz and Robinson (1992) have studied the manipulation of the logical structure of chemistry problems, which represents, ". . . the degree to which it requires formal operational reasoning, that is use of proportions, making quantitative correlations, generation of all possible combinations, controlling variables, and hypotheticodeductive reasoning" (p. 212). Results obtained show that even a small increase in the logical structure of a problem can affect student performance significantly more, as compared with a similar change in the M-demand of the problem. Frazer and Sleet (1984) have reported that students solving multiple-choice chemistry problems are often unsuccessful at problems requiring more complicated logic even though they could solve several less complicated subproblems. Similar observations using free-response questions were reported by Lazonby, Morris, and Waddington (1985). Given this background, it would be of interest to study the systematic manipulation of the logical structure and M-demand of chemistry problems.

Finally, the importance of information processing in science education has been formulated by Johnstone and Kellet (1980) in a working hypothesis, which was later developed into a prediction model in science education, the Johnstone–El-Banna model (Johnstone, 1984; Johnstone & El-Banna, 1986, 1989); this model states that a subject will not be successful in solving a problem, unless the problem has an M-demand that is less than or equal to the subject's working memory capacity. The condition (M-demand $\leq$ working memory capacity) is a necessary but not sufficient condition for problem-solving success. This sufficiency and some of the factors affecting it have been examined by Tsaparlis (1994, 1995, 1997).

PURPOSE—MOLECULAR EQUILIBRIUM PROBLEMS

The main objectives of this study are to: (a) systematically manipulate the logical structure and M-demand of molecular-equilibrium problems; (b) study the degree to which developmental level, working memory capacity, functional M-capacity, and disembedding ability can explain changes in student performance; and (c) to check the validity of the Johnstone–El-Banna model with our sample.

Molecular-equilibrium (chemical-equilibrium) problems are among the most important, and at the time most complex and difficult general chemistry problems. It is not then surprising that many researchers have dealt with them from a number of perspectives.

Camacho and Good (1989) studied the problem-solving behaviors of experts and novices engaged in solving chemical-equilibrium problems, and reported that unsuccessful subjects had many knowledge gaps and misconceptions about chemical equilibrium. Wilson (1994) examined the network representation of knowledge about chemical equilibrium, and found that the degree of hierarchical organization of conceptual knowledge (as demonstrated in concept maps constructed by the students) varied, and that the differences reflect achievement and relative experience in chemical equilibrium. Similar findings have previously been reported by Gussarsky and Gorodetsky (1988). On the other hand, a conclusion that applies to the students in general is that by Gabel, Sherwood, and Enochs (1984), whose subjects used algorithmic methods without understanding the concepts upon which the problems were based. Quite recently, Niaz (1995a) has compared student performance on conceptual and computational problems of chemical equilibrium and reported that students who perform better on problems requiring conceptual understanding also perform significantly better on problems requiring manipulation of data, that is, computational problems; he further suggested that solving computational problems before conceptual problems would be more conducive to learning. Finally, Tsaparlis and Kousathana (1995) have reported students' common misconceptions and errors in solving molecular equilibrium problems.

Although there is consensus among educators that the emphasis should be moved away from learning to use complex algorithms, into activities that require higher-order cognitive skills (Zoller & Tsaparlis, 1997), the use of algorithms is still at the heart of teaching and learning practice throughout the world. As such, it calls for the thorough investigation of the factors affecting it, as well as of the factors that differentiate it from novel problem solving. In addition, at this stage it is plausible to suggest that students' ability to solve computational/algorithmic problems (based on well-rehearsed procedures) is an essential prerequisite for a "progressive transition" leading to a resolution of novel problems that require conceptual understanding (Blanco & Niaz, 1997; Niaz, 1995b). The progressive nature of students' understanding is similar to what Lakatos (1970) has referred to as "progressive problemshifts" in the history of science, and the importance of such transitions has been recognized in the science education literature (Chinn & Brewer, 1993; Linn & Songer, 1991; Niaz, 1993).

RESEARCH METHODOLOGY

The research program was carried out in the year 1994–1995, with 154 upper-secondary students in their final third grade (age 17–18) from four mixed-ability, public upper secondary (senior high) schools in the greater Athens (Greece) area. Nine problems were administered to all participating students, at a rate of one problem per week.

Logical Schemata and M-Demand in Molecular-Equilibrium Problems

The logical structure of a problem is specified by the number of *operative schemata* entering the problem. According to Piaget, a *schema* is an internal structure or representation, while the ways we manipulate schemata are called *operations*. In Piaget's theory, schemata are continually growing and developing rather than remaining fixed. Describing thinking at various stages thus becomes a problem of trying to define the schema (or mental structure) and the operations (or internal actions) that a problem solver is using.

After having analyzed a large number of molecular equilibrium problems, we first distinguished *chemical* from *mathematical schemata*. Mathematical schemata are of two kinds, namely algebraic and calculational. We have chosen not to pay special attention to mathematical schemata in this work. On the basis of our analysis, as well as of previous work on this topic (Hackling & Garnett, 1985; Niaz, 1995a), we have arrived at the following schemata of molecular equilibrium:

Schema 1: The process of establishment of the chemical equilibrium.
Schema 2: The condition of chemical equilibrium.
Schema 3: The case of gaseous systems, with use of partial and total pressures as well as of K_p.
Schema 4: The disturbance of the equilibrium and the establishment of a new equilibrium.

Various general chemical schemata also enter these problems, such as the ideal gas equation, Dalton's law of partial pressures, and the density of a mixture. In addition, a general schema that enters most chemical-equilibrium problems is stoichiometry; however, because stoichiometry is an integral part of Schema 1, we have not considered it as a separate schema, but as constituting *one step* in the determination of the M-demand of a problem. A *step* must be interpreted as corresponding to an *operation* within a schema.

One important difference in this work, as far as the determination of the M-demand is concerned, is that we have not considered as M-demand the number of all steps for the solution, but rather the number of steps in the schema with the maximum number of steps. This situation is analogous to the rate-determining step of a chemical reaction, and is in agreement with Case's concept of M-demand (Case, 1978).

The determination of the M-demand of chemistry problems is based on a dynamic interaction between the general and figurative models constructed by the students and the logical structure of the problem (Niaz, 1989c, pp. 153–157). Furthermore, M-demand reflects, to a greater extent, the problem-solving procedures of the students rather than of the teachers. The actual process that a student follows affects the M-demand for that problem and for that student (cf. chunking, in Pascual-Leone, Goodman, Ammon, & Subelman, 1978).

In this work, a preliminary marking of the papers was made with the aim to help us identify the solution strategies and the steps followed by the students in each problem. In addition, a committee of ten experienced secondary school teacher-chemists reviewed the strategies and the steps followed by the students for each problem and agreed on the schemata and steps for each problem. The Appendix has one example of the problem, together with the decomposition of its solution into operative schemata and steps.

As stated previously, nine problems of varying number of operative schemata as well as of varying number of M-demand were used. The number of schemata varied from a minimum of two, to a maximum of four, while within each logical schema we had a specific M-demand, varying from four to six. The structure of the nine problems was as follows (the first number stands for the number of schemata, the second number stands for the M-demand): (2,4), (2,5), (2,6), (3,4), (3,5), (3,6), (4,4), (4,5), (4,6).

Teaching and Testing Methodology

An integral part of this project was the device and testing of a method for teaching problem solving in chemistry. According to this method, students were taught first the schemata that enter the problems (in our case, molecular-equilibrium problems). Afterwards, when solving example problems, students were called to try to identify the schemata that enter each particular problem, and then to separate and write down on a diagram the data according to the relevant schema. The detailed solution of the separate schemata, with the entering steps, followed.

Before the actual testing of the nine problems started, students were given a test in which all the schemata and steps entering the problems were tested in simple form. This test was checked and returned to the students. In this way, we wanted to secure as well as possible that the students were familiar with the separate schemata and steps; consequently, their failure in the actual tests could not be attributed to lack of knowledge and ability to apply the partial schemata and steps entering the problems (Tsaparlis, 1994, 1995, 1997).

Developmental level of students was assessed by means of Lawson's pencil–paper test of formal reasoning (Lawson, 1978), in its multiple-choice revised form (Lawson, 1993). From the 13-item multiple-choice test, items 7, 8, and 13 were deleted from the analysis because they were not parallel to items on similar tests (Westbrook & Rogers, 1994). One point was given for each item for which a correct choice was made for both the basic question and the explanation. Students with scores of 0–3 were classified as concrete operational; with scores of between 4 and 6 as transitional; and with scores from 7 to 10 points as formal operational. A split-half reliability coefficient of 0.91 was obtained for the present sample.

Working memory capacity of the students was assessed by means of the digit span backward (DSB) test, which is part of the Wechsler Adult Intelligence Scale (Wechsler, 1955). Students listened to sequences of digits and had to hold them before writing them in reverse order. There were three sequences of digits with two digits each, three sequences with three digits each, and so on until three sequences of eight digits each. To avoid the possibility of cheating (writing the digits in reverse order from right to left, and in particular simultaneously with listening), students had to write the digits by filling in printed grids, with one digit in each square; in addition, there was not a progressive increase in the complexity of sequences, but some alteration was made, as follows: 222–334–344–556–566–778–788. The value for working memory capacity was taken to be the maximum number of digits successfully written for at least two of the three corresponding sequences. Half-integer values were assigned in some cases. Students with a working memory capacity of 5.5 or higher were classified as high processors; with 4.5 or 5 as intermediate processors;

and with 4 or lower as low processors. The split-half reliability coefficient was 0.88 for the present sample.

Functional M-capacity was assessed by means of the timed figural intersection test (FIT) (Niaz, 1988b; Pascual-Leone & Burtis, 1974), in a modified way. Students were shown the nonoverlapping figures on a screen (by means of a 35-mm slide projector) and had to spot the intersection of the overlapping figures printed on paper. The test contained 31 items. (The five two-figure items were excluded as very simple, but taken into account in the marking of the test.) Each item was shown for a short period according to the number of overlapping figures as follows: 11 seconds were allowed for the three-figure items; 11 + 7 = 18 seconds for the four-figure items; 18 + 8 = 26 seconds for the five-figure items; 26 + 9 = 35 seconds for the six-figure items; 35 + 10 = 45 seconds for the seven-figure items; 45 + 11 = 56 seconds for the eight-figure items; and 56 + 12 = 68 seconds for the one (8 + 1)-figure item. Thus, the duration of the test was 17 minutes and 18 seconds, which is longer by 44% than the 12-minute limit suggested by Niaz (1988b), because of the delay introduced by having students look at both the screen and their papers. In that way, all students dealt with all the test items. The evaluation of the M-capacity was made using the procedure suggested by Johnson (1982) (see also Al-Naeme, 1988). Students with an M-value of 6.0 or higher were classified as high processors; with an M-value higher than 4.6 and lower than 6.0 as intermediate processors; and with an M-value equal or lower than 4.6 as low processors. A split-half reliability coefficient of 0.93 was found.

Disembedding ability (the degree of field dependence–independence) was assessed by use of the timed (20 minutes) test, which was devised and calibrated by El-Banna (1987) from Witkin's original test materials (the group embedded figures test, GEFT) (Witkin, 1978; Witkin et al., 1971, 1974). In this test students have to locate a "hidden" figure, which is embedded inside a complicated figure. Eighteen such items are given. Students with 13 or more successes were classified as field-independent; with 7–12 successes as field-intermediate; and with 6 or less successes as field-dependent. The split-half reliability coefficient was 0.78 for the present sample.

Marking Scheme

In the marking of the papers, all schemata were taken as equivalent among themselves, and all steps were considered equivalent among themselves. Thus, for a problem with four schemata, each schema was allocated one quarter of the total mark for the schemata. On the other hand, if there was a total of 18 steps in the problem, each step was allocated 1/18 of the total mark for the steps. All marks have been expressed as percentages. The total mark for the problem resulted from the mean of the two marks for the schemata and the steps; that is, schemata and steps had an equal contribution to the final mark.

To check the reliability of the above marking scheme, we have used a second marking scheme in which each schema and each step were allocated a number of points, in concordance with their difficulty. From the preliminary marking of the papers mentioned earlier, success rates per schema and step were established. Following that, points were given to each schema and step, according to the corresponding success rate as follows: 0–33% correct answers: three points given to correct answers; 34–67% correct answers: two points given to correct answers; 68–100% correct answers: one point given to correct answers. The total mark for the problem resulted from the mean of the two marks for the schemata and the steps; that is, schemata and steps again had an equal contribution to the final mark.

Note that, in a number of cases, the two marking schemes resulted in identical results; that is, the weighting factors were the unity. The correlation coefficients between the two marking schemes were higher than 0.98 in all cases. It is not surprising then that the two marking schemes led to the same findings. For this reason, we present the results from the equivalent marking scheme only.

Finally, ten papers of varying performance were selected and marked separately by four experienced teacher-chemists. The correlations between the markings of the ten papers by the four teachers for the schemata, the steps, and the total problem varied between 0.91 and 0.99 with only one correlation coefficient (0.83) being outside this range.

The reliability of the test was judged on the basis of two coefficients. Coefficient alpha (Cronbach's alpha) was 0.77 for the schemata, 0.94 for the steps, and 0.91 for the whole problems. Split-half reliability coefficients was 0.84 for the schemata, 0.94 for the steps, and 0.93 for the whole problems.

Statistical Analysis of the Data

Because, in most cases, the distributions were asymmetric and deviated from the normal curve, as judged by the skewness and kurtosis coefficients, we used both nonparametric and parametric methods in our statistical analysis. For the multiple comparison of means, we used nonparametric (Kruskal–Wallis) one-way ANOVA, as well as one-way parametric ANOVA. Similarly, for the study of correlations we used both the Spearman rho and the Pearson r correlation coefficients. Statistically significant differences were at $p = 0.01$, or in some cases at $p = 0.05$. In almost all cases, the results of the nonparametric and parametric analyses coincide. For this reason, we present only parametric results. Results of multiple regression analyses of the data are also reported.

RESULTS AND DISCUSSION

Table 1 gives the mean percentage performance in the sets of problems with the same number of schemata, as well as in the sets of problems with the same M-demand. We note first that the overall performance was relatively high; this is due to the fact that our subjects were highly motivated for this course, because it was very crucial for their university entrance examinations. As expected, increasing the schemata or the M-demand resulted in drops of performance, which were statistically significant in all cases ($p < 0.01$). We note also that there was a larger drop in performance when one increased the logical structure by adding schemata than when one increased the M-demand. This finding is accordance with that of Niaz and Robinson (1992).

Table 2 shows the mean percentage performance of students in the sets of problems with the same number of schemata or the same M-demand, in relation to developmental level. In all cases, formal students performed better than transitional ones, and the latter performed better than concrete students. All these differences were statistically significant at the $p = 0.01$ level, except the differences between formal and transitional students for two and three schemata, which were at the 0.05 level. Detailed comparisons in the separate problems are made later.

TABLE 1
Mean Percentage Performance of All Students ($N = 154$)[a]

	Mean	SD
Problems with two schemata	92.0	10.1
Problems with three schemata	83.4	16.0
Problems with four schemata	71.0	26.0
Problems with M-demand = 4	88.7	13.2
Problems with M-demand = 5	84.3	18.8
Problems with M-demand = 6	73.4	20.0

[a] Includes the sets of problems with: (a) the same number of schemata [e.g., problems (3,4), (3,5), and (3,6)]; and (b) the same M-demand [e.g., problems (2,5), (3,5), and (4,5)].

TABLE 2
Mean Percentage Performance in Sets of Problems with Same Number of Schemata or Same M-demand in Relation to Developmental Level of Students[a]

	Concrete (N = 45)	Transitional (N = 38)	Formal (N = 71)
Number of schemata			
2	85.3 (10.9)	91.8 (9.1)	96.5 (7.1)
3	72.6 (17.7)	83.2 (15.6)	90.4 (10.3)
4	49.0 (19.5)	68.6 (23.3)	86.1 (19.2)
M-demand			
4	79.1 (13.4)	87.8 (12.1)	95.3 (9.3)
5	71.4 (19.2)	83.4 (17.5)	93.1 (13.5)
6	56.6 (16.3)	72.4 (18.2)	84.8 (14.8)

[a] Standard deviation in parentheses.

Again, increasing the schemata or the M-demand resulted in drops of performance, which were statistically significant in most cases ($p < 0.01$): not significant was only the difference between M = 4 and M = 5 for the transitional as well as for the formal students, whereas just under the $p = 0.01$ value was the difference between three and four schemata for the formal students. It is further observed that concrete students suffered larger drops in performance with the increase of schemata than with the increase of M-demand. The findings are similar when we take into account the corresponding data (not shown here) for working memory capacity, functional M-capacity, or disembedding ability; that is, the low working memory, the low functional M-capacity, and the field-dependent students strongly demonstrated the aforementioned difference.

Correlation between Performance in the Schemata and the Steps

Table 3 shows the Pearson correlation coefficients r for the correlation between the performance of the students in the schemata and the steps for the various problems. We note that there were substantial increases in correlation each time a schema was added; no similar increases were observed when the number of steps (M-demand) was increased.

Performance in the Schemata and the Steps and Effect of Cognitive Factors

Table 4 shows the mean percentage mark in the schemata and the steps for the nine molecular-equilibrium problems for concrete, transitional, and formal thinkers in the Piagetian sense. Table 5

TABLE 3
Correlations between Performance in the Schemata and Steps[a]

	Problem							
	(2,5)	(2,6)	(3,4)	(3,5)	(3,6)	(4,4)	(4,5)	(4,6)
Pearson r	0.30 (0.0002)	0.32 (0.0001)	0.62 (0.0000)	0.66 (0.0000)	0.62 (0.0000)	0.94 (0.0000)	0.93 (0.0000)	0.91 (0.0000)

[a] Significance levels given in parentheses.

TABLE 4
Mean Percentage Performance of Students in Various Molecular-Equilibrium Problems in Relation to Students' Developmental Level[a]

	Problem								
	(2,4)	(2,5)	(2,6)	(3,4)	(3,5)	(3,6)	(4,4)	(4,5)	(4,6)
C	100.0	98.9	98.9	95.6	88.9	80.7	59.4	59.4	48.0
	94.8	71.4	49.8	73.1	61.5	36.5	50.2	52.0	27.0
T	100.0	100.0	96.0	95.6	93.0	91.2	77.0	77.6	65.1
	98.0	81.6	74.0	86.1	79.3	54.7	67.4	71.6	54.0
F	100.0	99.3	99.3	99.5	96.7	93.9	90.5	91.9	84.5
	98.6	92.1	89.5	95.1	90.5	67.2	87.3	89.9	74.4

C: concrete level; T: transitional level; F: formal level.
[a] For each variable, performance on schemata appears above, and performance on steps below.

shows the corresponding statistically significant differences of means. The difference between the different groups was more pronounced when performance was evaluated in terms of steps (M-demand, information processing required) rather than schemata (logical structure). Indeed, when the number of schemata was small (two), there was no effect of developmental level in the performance in the schemata.

The observed trends were similar, but with some exceptions, in relation to the other three cognitive factors; that is, working-memory capacity, disembedding ability, and functional M-capacity (data are not shown). In the performance in the steps, disembedding ability and functional M-capacity both showed similar trends, affecting mainly the low ability (field-dependent and low M processors) in all problems. Developmental level had a strong effect from problem (2,6) upward, whereas working-memory capacity distinguished among all categories of processors from problem (3,6) upward.

TABLE 5
Multiple Comparisons of Means in Schemata and Steps of Various Molecular-Equilibrium Problems in Relation to Students' Developmental Level[a]

	Problem								
	(2,4)	(2,5)	(2,6)	(3,4)	(3,5)	(3,6)	(4,4)	(4,5)	(4,6)
Schemata					C-F[b]	C-T C-F	C-T C-F T-F	C-T C-F T-F	C-T C-F T-F
Steps	C-F[b]	C-T[b] C-F	C-T C-F T-F	C-T C-F T-F[b]	C-T C-F T-F[b]	C-T C-F T-F[b]	C-T C-F T-F	C-T C-F T-F	C-T C-F T-F

C: concrete level; T: transitional level; F: formal level.
[a] Only statistically significant differences are shown, on the basis of the least-significance-difference (LSD) criterion.
[b] $p < 0.05$; in all other cases $p < 0.01$.

TABLE 6
Correlation Coefficients between Performance on Molecular-Equilibrium Problems and Cognitive Variables (N = 154)

	Problems								
Variables	(2,4)	(2,5)	(2,6)	(3,4)	(3,5)	(3,6)	(4,4)	(4,5)	(4,6)
Developmental	—	0.05	0.05	0.18	0.24[a]	0.30[b]	0.55[b]	0.55[b]	0.59[b]
level	0.19	0.40[b]	0.59[b]	0.47[b]	0.48[b]	0.47[b]	0.57[b]	0.57[b]	0.62[b]
Working	—	−0.02	0.01	0.20	0.14	0.17	0.48[b]	0.47[b]	0.47[b]
memory	0.14	0.40[b]	0.41[b]	0.42[b]	0.43**	0.44[b]	0.47[b]	0.50[b]	0.50[b]
Functional	—	0.08	−0.02	0.15	0.19	0.26[a]	0.35[b]	0.36[b]	0.36[b]
M-capacity	0.27[a]	0.31[b]	0.35[b]	0.35[b]	0.39[b]	0.42[b]	0.37[b]	0.40[b]	0.40[b]
Disembedding	—	−0.11	−0.17	0.08	0.07	0.23[a]	0.26[a]	0.28[a]	0.30[a]
ability	0.16	0.22	0.26[a]	0.27[a]	0.29[a]	0.32[b]	0.25[a]	0.29[a]	0.33[b]

Note: For each variable, coefficients with schemata appear above, and those with steps below.
[a] $p < 0.005$; [b] $p < 0.0001$.

Correlation between Performance in the Problems and the Various Cognitive Factors

Correlation coefficients shown in Table 6 are quite revealing. Correlations between developmental level and problems with two schemata are almost zero, but increase to about 0.2–0.3 for problems with three schemata and to about 0.5–0.6 for problems with four schemata. This shows that students perceived the difficulty of the problems at three levels of increasing complexity (logical structure); that is, problems with two, three, and four schemata, respectively. On the other hand, if performance is evaluated in terms of M-demand (steps), developmental level correlates significantly with all problems [except problem (2,4)] at about the same level.

Correlations between working memory and problems with two schemata are almost zero, increase to about 0.15–0.2 for problems with three schemata, and to about 0.47 for problems with four schemata. This shows, once again, that students perceived the difficulty of the problems at three levels of logical structure (schemata). On the other hand, if performance is evaluated in terms of M-demand (steps), working memory correlates significantly with all problems [except problem (2,4)] at about the same level. Similar results were obtained with functional M-capacity, the predictor variable that represents information processing in Pascual-Leone's theory of constructive operators.

In problems with four schemata, the correlations with schemata assume equal importance as that with the steps. The highest correlations are with developmental level, in accordance with previous findings (Niaz & Robinson, 1992). In all cases, the lowest correlations are with disembedding ability, whereas the correlations with functional M-capacity are intermediate between those with working-memory capacity and disembedding ability, a result that is reasonable if we take into account the fact that the figural intersection test correlates with both the digit span backward test and Witkin's group embedded figures test.

Multiple Regression Analysis

Table 7 summarizes the results of multiple regression analysis of the performance of the students in the nine problems of this study, with the four cognitive factors (developmental level, working memory capacity, functional M-capacity, and disembedding ability) as independent variables. We

TABLE 7
Percentage Variance Explained from Multiple Regression Analyses with Developmental Level, Working Memory Capacity, Functional M-Capacity, and Disembedding Ability as Independent Variables ($N = 154$)

	Problem								
	(2,4)	(2,5)	(2,6)	(3,4)	(3,5)	(3,6)	(4,4)	(4,5)	(4,6)
Schemata									
% Variance	—	1.7	2.1	2.4	4.3	9.5	33.4	32.6	36.4
F		1.68	1.82	1.92	2.72	5.03[a]	20.2[a]	19.5[a]	22.9[a]
Steps									
% Variance	6.1	18.8	33.9	23.9	25.5	26.4	34.1	35.9	40.7
F	3.48	9.82[a]	20.65[a]	13.0[a]	14.1[a]	14.7[a]	20.8[a]	22.5[a]	27.2[a]
Total									
% Variance	6.1	16.0	29.0	17.9	17.6	22.6	35.5	35.9	40.1
F	3.49	8.26[a]	16.6[a]	9.31[a]	9.14[a]	12.2[a]	22.0[a]	22.4[a]	26.6[a]

Note: Adjusted for degrees of freedom coefficients of multiple determination were used.
[a] $p < 0.0001$.

see that the percentage of the variance explained increases as both the logical structure and the M-demand of the problems increase.

Because the independent variables are not truly independent, since there is considerable overlap (correlation coefficients from 0.40 to 0.63) among them, it is not reliable to proceed to a decomposition of the total variance explained into components. On the other hand, if we carry out simple regression analyses, we find that developmental level is the main predictor variable in most cases, in accordance with the findings of Niaz and Robinson (1992, 1993). For instance, for problem (4,6) (the whole problem), developmental level alone can explain 38.0% of the variance, and working memory can explain 23.3%, functional M-capacity 14.0%, and disembedding ability 9.8%. (We recall that the four cognitive variables together explain 40.1% of the variance.) The dominant part played by developmental level can be accounted for by taking into account that these problems were of an algorithmic nature for the subjects of this study, because of their extended practice (the "training effect"), in accordance with the research finding of Niaz and Robinson (1992). On the other hand, working memory also maintains some importance, because there is always a need for information processing in solving the problems; however, training on task could lead to "chunking," which reduces the M-demand of a task and thus improves student performance (Pascual-Leone et al., 1978).

In view of the aforementioned findings and their explanation, we can handle this multicolinearity problem by combining developmental level and working memory capacity ($r = 0.55$), to arrive at a regression equation that is sufficient to provide a predictive measure of performance (Cronbach, 1990, pp. 437–440). For problem (4,6), for instance, this model can explain 37.1%, 41.3%, and 40.7% of the variance for the schemata, the steps, and the whole problem, respectively. Therefore, adding functional M-capacity and disembedding ability makes no difference.

Testing the Johnstone–El-Banna Model

Figure 1 shows student performance in the nine problems for various working memory capacities. The performances are expressed as percentages of entirely correct answers to the problems so that we can check the validity of the Johnstone–El-Banna model. Although the

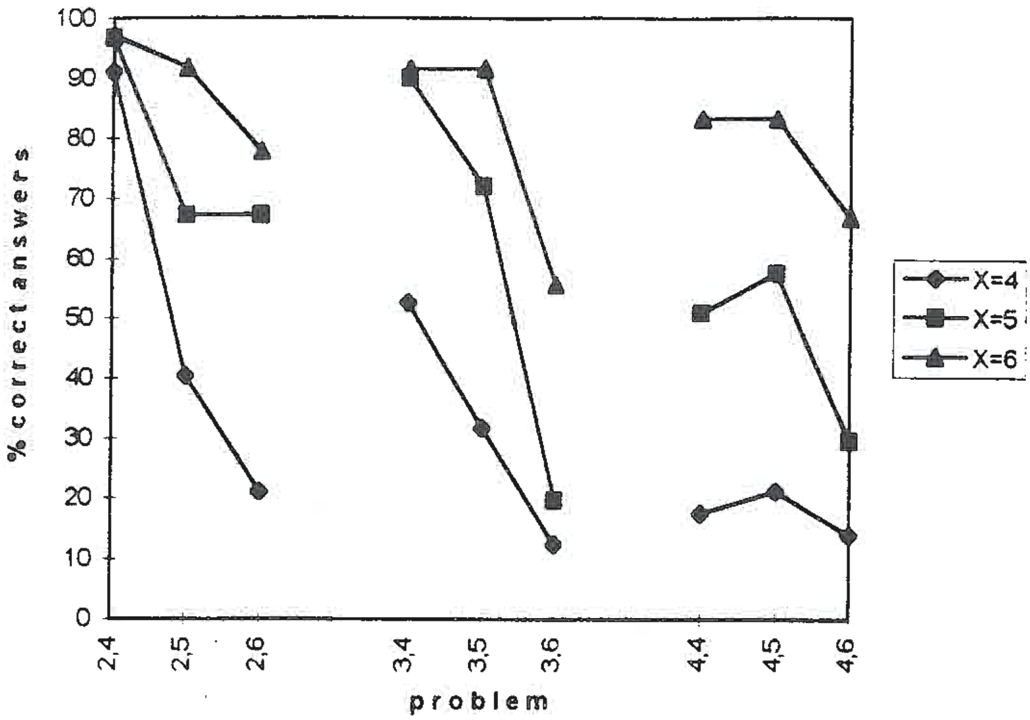

Figure 1. Percentage correct answers in the various problems for three levels of working memory capacity X.

model does not apply strictly, we can observe a trend that is in accordance with the model, especially for problems of low logical structure (with two schemata). Note, however, that a similar trend is observed when we examine the corresponding lines for various developmental levels, levels of disembedding ability, and M-capacities of students.

The failure of strictly observing the Johnstone–El-Banna model can be accounted for if we consider that a number of necessary conditions for its successful application were not fulfilled (Tsaparlis, 1994, 1995, 1997). In particular, in our case:

(a) We did not have a simple logical structure.
(b) We did not have novel problems, but rather algorithmic exercises, because of the familiarity and the training (both initially and in the course of the tests) of the students with such problems.

Note, however, that a number of other necessary conditions were satisfied, namely: (i) the partial steps, required for the solution (see Appendix), were available and accessible in the students' long-term memory, due to initial training and testing of the students; (ii) for the same reason, the partial steps were very likely equivalent among themselves as far as their accessibility was concerned; and (iii) no "noise" was present in the problems.

CONCLUSIONS AND EDUCATIONAL IMPLICATIONS

Results obtained in this study show that students in the formal operational stage of development, who have a working memory of 6, a functional M-capacity of 6, and a field-independent cognitive style, perform considerably better than other groups of students.

Compared with previous research, this study makes an important contribution toward an understanding of the role of cognitive variables in problem solving. For example, a previous study

(Niaz & Robinson, 1992) showed that manipulation (increase) of the logical structure of chemistry problems could lead to a situation in which developmental level was the only cognitive variable that significantly explained variance in performance.

A novel feature of this study is that performance was evaluated in terms of both the logical structure (schemata) and the M-demand (steps). Furthermore, the correlations between each of the cognitive variables and the two modes of evaluating performance were reported. Interestingly, developmental level correlated significantly with performance (based on schemata) only when the logical structure of the problems increased considerably [problem (3,5) and upward]. In contrast, developmental level correlated with performance (based on steps) on all problems [except problem (2,4)], thus showing the importance of general hypotheticodeductive reasoning. In addition, developmental level was the most important predictor variable explaining a significant part of the variance, as found from multiple regression analyses. This predictive power increased considerably as the logical structure of the problems increased.

Working memory and functional M-capacity, the two variables representing information processing, correlated significantly with all problems [except problem (2,4)] at about the same level, with a range of 0.3–0.5. However, it may be that the latter had less power to explain variance. This finding is even more important and may be accounted for if we recognize that working memory and functional M-capacity pertain to two different theoretical frameworks (Baddeley's and Pascual-Leone's theories of information processing). Recent literature has reported differences in the degree to which the two theories explain academic performance (Niaz & Logie, 1993; Vaquero, Rojas, & Niaz, 1996).

It is important to note that all four cognitive variables (developmental level, working memory, functional M-capacity, and disembedding ability) are quite consistent in correlating with performance only when the logical structure is fairly complex and even when the M-demand is relatively low.

It was found that the Johnstone–El-Banna predictive model of problem solving was not observed strictly with the present data: first, because we did not have a simple logical structure here (Tsaparlis, 1994, 1995, 1997); and, second, the problems were algorithmic exercises for the students of our sample. Related with the algorithmic nature of the problems was the finding that developmental level is the most important cognitive factor, which explains a considerable amount of the total variance.

An important educational implication is that even problems with low M-demand (information processing required) can be difficult for some students and, combined with increasing logical complexity, can become a stumbling block for many students.

Results obtained in this study provide the following suggestions for future research:

1. Study of the relationship between the logical structure of chemical-equilibrium problems and students' alternative conceptions (Garnett, Garnett, & Hackling, 1995; Quilez-Pardo, & Solaz-Portoles, 1995).
2. Design of teaching strategies that can facilitate conceptual understanding (beyond the algorithmic strategies) based on the manipulation of the logical structure, M-demand, and field factor (disembedding) of chemical-equilibrium problems (Niaz, 1997b).
3. Construction (based on points 1 and 2) of students' and teachers' understanding of chemical equilibrium based on a historical development of the subject (Matthews, 1994; Niaz, 1995c).
4. Exploration of those parts of the logical structure/alternative conceptions of chemical-equilibrium problems that resist change more strongly and hence constitute the "hard core" (Lakatos, 1970, p. 153) of students' understanding. "Auxiliary hypotheses" used by students to defend their "core beliefs" can provide clues and guidance for the construction of new teaching strategies.

These suggestions for future research require primarily qualitative methods, which may facilitate the integration of qualitative and quantitative methodologies. The importance of such an integration in science-education research has been recognized in the literature (Niaz, 1997a; Tobin, 1993; Yeany, 1992). Tobin (1993), for example, emphasizes such integration in the following terms: "The theoretical underpinnings of quantitative data were often at odds with those of qualitative data. However, this did not have to be the case. Over time I learned to build a coherence between data types used in my research, such that qualitative and quantitative data could contribute in complementary ways to the solutions of problems."

APPENDIX

An Example of a Problem with Analysis of Schemata and M-Demand

In a vessel of fixed volume $V = 4.5$ L, 198 g of $COCl_2$ plus 44.8 L of CO (in STP) are introduced. The mixture is heated to 1000°C and allowed to reach the equilibrium $COCl_2$ (g) $\rightleftharpoons$ CO (g) + Cl_2 (g). You have to calculate the equilibrium constant K_c, taking into account that, at equilibrium, the total pressure of the gas mixture is 82 atm, at 1000 K.

Three schemata enter here: (1) the process of establishment of the chemical equilibrium; (2) the ideal-gas equation; and (3) the condition of chemical equilibrium (K_c).

(1) *Establishment of equilibrium*

Calculation of moles of $COCl_2$: a mol (Step 1)

Calculation of moles of CO : b mol (Step 2)

	$COCl_2$ (g)	$\rightleftharpoons$	CO (g)	+	Cl_2 (g)	
Initially:	a mol		b mol			(Step 3)
React (−) or produced (+):	$-x$ mol		$+x$ mol		$+x$ mol	(Step 4)
At equilibrium (moles):	$(a - x)$ mol		$(b + x)$ mol		x mol	
At equilibrium (concentrations):	$(a - x)/V$ mol/L		$(b + x)/V$ mol/L		x/V mol/L	(Step 5)

(2) *Ideal-gas equation*:

$p_{total}V = n_{total}R\,T$ (Step 1)

$n_{total} = p_{total}V/(R\,T)$ (Step 2)

Calculation of n_{total} (Step 3)

Calculation of x (Step 4)

(3) *Condition of chemical equilibrium* (K_c)

$K_c = (CO)(Cl_2)/(COCl_2)$ (Step 1)

$K_c = [(b + x)/V](x/V)/[(a - x)/V)]$ (Step 2)

Calculation of K_c (Step 3)

Estimation of M-demand. Schema (1) of the establishment of equilibrium involves the largest number of steps (five), therefore, we postulate an M-demand of 5 for this problem.

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