A Model of Problem Solving: Its Operation, Validity, and Usefulness in the Case of Organic-Synthesis Problems

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ABSTRACT: The Johnstone–El-Banna model of problem solving is based on working-memory theory as well as on Pascual-Leone's *M*-space theory. The operation and validity of the model depends on a number of necessary conditions, such as a simple logical structure, availability and accessibility of the partial steps, absence of "noise," and lack of familiarity with the problem type. If these, and some other conditions, are not fulfilled, the model may not operate; that is, solvers may be successful, even if the information-processing demand (*Z*-demand) is greater than their information-processing capacity and, vice versa. Sixteen organic chemical-synthesis problems, with a simple logical structure and varying *Z*-demand from 2 to 8, were used in this work. We studied two samples of students (age 17–18), one without (N = 128) and the other with (N = 191) some previous training (at least in part) in organic-synthesis problems. Although the predicted pattern was observed in both samples, it was found that the model was more useful in the case of the students without previous training. Finally, the model predicts better with the field-independent and the field-intermediate students, but less so with the field-dependent ones.
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INTRODUCTION

> Problem solving is a process by which the learner discovers a combination of previously learned rules that he/she can apply to achieve a solution to a new situation (that is, the problem). (Holroyd, 1985)

The problem-solving process requires that the solver must be able to use what has been termed as higher order cognitive skills (HOCS) (Zoller, 1993; Zoller & Tsaparlis, 1997). At the outset, a distinction must be made between problems and exercises, with the latter requiring for their solution only the application of well-known and practiced procedures (*algorithms*). The skills that are necessary for the solution of exercises are, as a rule, *lower order cognitive skills* (LOCS). However, the degree to which a problem is a novel problem or an exercise depends on student background and the teaching (Niaz, 1995a); thus, a problem that requires HOCS for some students may require LOCS for others in a different context.

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A more thorough classification of problem types has been made by Johnstone (1993) and is reproduced here in Table 1. Types 1 and 2 are the "normal" problems usually encountered in academic situations. Only type 1 is of the algorithmic nature (exercise). Type 2 can become algorithmic with experience or teaching. Types 3 and 4 are more complex, with type 4 requiring very different reasoning from that used in types 1 and 2. Types 5–8 have open outcomes and/or goals, and are very demanding. Type 8 is the nearest to real-life, everyday problems.

Problem-solving research has entered a new phase with the consideration of the importance of information processing. Working-memory theory "can account for performance on tasks that involve both processing and storage, and both of these cognitive functions are likely to be required for most forms of scientific problem-solving" (Niaz & Logie, 1993, p. 519). Each learner has a certain working-memory capacity (X) (Baddeley, 1986, 1990; Johnstone & El-Banna, 1986), whereas each problem has a demand (Z). One definition of demand is, "the maximum number of thought steps and processes which have to be activated by the least able, but ultimately successful solver, in the light of what he has been taught" (Johnstone & El-Banna, 1989). The Johnstone–El-Banna model (Al-Naeme, 1988; Johnstone, 1984; Johnstone & El-Banna, 1986, 1989; Johnstone, Hogg, & Ziane, 1993; Johnstone & Kellet, 1980) is a predictive model, which states that a student is likely to be:

- successful in solving a problem if the problem has a Z-demand that is less than or equal to the subject's X capacity ($Z \leq X$), but may fail for lack of information or recall; and

TABLE 1
Classification of Problems (Johnstone, 1993)

Type	Data	Methods	Outcomes/Goals	Skills Bonus
1	Given	Familiar	Given	Recall of algorithms.
2	Given	Unfamiliar	Given	Looking for parallels to known methods.
3	Incomplete	Familiar	Given	Analysis of problem to decide what further data are required.
4	Incomplete	Unfamiliar	Given	Weighing up possible methods and then deciding on data required.
5	Given	Familiar	Open	Decision making about appropriate goals. Exploration of knowledge networks.
6	Given	Unfamiliar	Open	Decisions about goals and choices of appropriate methods. Exploration of knowledge and technique networks.
7	Incomplete	Familiar	Open	Once goals have been specified by the student, these data are seen to be incomplete.
8	Incomplete	Unfamiliar	Open	Suggestion of goals and methods to get there; consequent need for additional data. All of the above skills.

- unsuccessful in solving a problem if $Z > X$, unless the student has strategies that enable him/her to reduce the value of Z to become less than X.

That is, as the problem increases in complexity (in terms of what has to be held and what processing has to be performed), there must be a decrease in performance; moreover, if the holding/thinking space has a final limit, the decrease in performance may be rapid after the limit has been reached (Pascual-Leone, 1969; Scandarmalia, 1977).

Related to the working-memory capacity, X, is the mental capacity, or M-capacity, which derives from Pascual-Leone's neo-Piagetian theory (Pascual-Leone, 1970, 1987). A mental power, or M-space (or M-capacity), is attributed to each subject, which is the maximum available M-capacity or structural M-capacity (M_s). However, the actually mobilized M capacity or functional M-capacity (M_f) may be less. (An analogous distinction can be made with working memory, linking it with the degree of field dependence/field independence: potential working memory vs. usable working memory [Johnstone & Al-Naeme, 1991].) Niaz has reported significant correlations between M-capacity and Z-demand in numerous studies (e.g., Niaz, 1987, 1988a, 1988b, 1989a, 1989b, 1989c, 1991, 1994, 1996; Niaz & Lawson, 1985). Even small changes in Z-demand can lead to working-memory overload; furthermore, the manipulation of the logical structure (i.e., the degree to which the problem requires formal operational reasoning) could also lead to significant changes in student performance (Niaz & Robinson 1992).

Both working memory and M-capacity refer to some kind of hypothesized limited-capacity mental resource that can be applied to learning and problem solving, and the two models appear to be used interchangeably (Niaz & Logie, 1993; Vaquero, Rojas, & Niaz, 1996).

BLOCKING MECHANISMS IN PROBLEM SOLVING, AND NECESSARY CONDITIONS FOR USING THE JOHNSTONE–EL-BANNA MODEL

In a number of cases, the solution of a problem may be blocked, despite the satisfaction of the condition $Z \leq X$. Using nonnumerical organic chemical-synthesis problems, Tsaparlis (1994, 1998) examined the following mechanisms that may block the solution: (1) the lack in the subject's repertoire of even a single step in the solution; (2) the nonequivalence of the partial steps of the solution; and (3) the blocking that occurs when subjects fail to solve a problem, even if they have the partial steps available. (It is known that knowledge of terms is a necessary, but not sufficient, prerequisite for successful problem solving [Sumfleth, 1988].) Two other hindering mechanisms are the presence of "noise" in the problem (Johnstone & Wham, 1982) and the logical structure of the problem (Niaz & Robinson, 1992). By "noise" one means information that is in the problem, but has no actual involvement in the solution. It was found (Tsaparlis 1994, 1998) that predominantly students with low working-memory capacity are most affected by the noise (see also Johnstone & Al-Naeme, 1991). Thus, the low working memory may be drastically reduced (as a fraction of the potential working memory) by the noise; on the other hand, in the case of high potential working memory, the same noise may block only a relatively small proportion of the total high working memory, leaving a lot of space for functioning.

The aforementioned findings led Tsaparlis (1994, 1995, 1998) to state the following necessary conditions that must be observed for the successful operation of the Johnstone–El-Banna model to problem solving in science education:

1. The partial steps must be *available* in long-term memory, and *accessible* from it.
2. The partial steps must be easily accessible. The organization and the connections in long-term memory are crucial for the accessibility of knowledge (Johnstone, 1991).
3. The logical structure of the problem must be simple; otherwise, developmental level (Inhelder & Piaget 1958), that is, general hypotheticodeductive reasoning ability, may play a more important role than working-memory capacity (Niaz & Robinson, 1992). The best situation is when only one operative schema exists in the problem. The organic-synthesis problems, which exclude numerical or algebraic calculations, are one example of such simple-structure problems.
4. No "noise" should be present in the problem statement. The presence of "noise" is more likely to lead to working-memory overload for field-dependent people than for field-independent people (Johnstone & Al-Naeme, 1991).
5. The degree of field dependence/field independence (disembedding ability) has an effect. Low and, to a lesser extent, intermediate working-capacity subjects who are field dependent may experience a working-memory overload because of a reduction in the available X space.
6. Devices to reduce Z to be less than X, such as familiarity with the problem or subdivision ("chunking") of the problem into familiar chunks, result in a reduction of the Z-demand of the problem. It has been found (Niaz, 1995a; Niaz & Robinson, 1992; Tsaparlis, Kousathana, & Niaz, 1998) that developmental level is the most significant psychometric factor related to performance in familiar problems. Therefore, the model must be valid more in the case of novel problems than in the case of exercises.

Failure to observe these conditions may lead to data that will not follow the model, or it will not follow it closely. In our opinion, it is this type of failure that led to the invalidation of the model by Opdenacker et al. (1990), in which highly competent medical students, who were likely to be field independent and who had many learning strategies, were involved. These students never overloaded, and this explains the lack of fit of their performance with the model.

In this work, we report data that not only demonstrate the validity of the model but also show the effect of deviations from the necessary conditions.

METHOD

Subjects

The subjects in this study were upper secondary students in their final school year, preparing to take entrance examinations for tertiary education (ages 17–18). They attended three urban public schools (N = 191) in the greater Athens region, of which two were "experimental," prestigious schools. In addition, there was another sample of students (N = 128) from two special, private urban schools ("*frontisteria*," *ipso infra*), one in the Athens region and the other in the town of Arta; note that the frontisteria students attended, at the same time, various urban upper secondary public schools.

Organic-Synthesis Test

In previous work (Tsaparlis, 1994, 1998), simple nonnumerical organic chemical synthesis problems of Z-demand = 2 were used. These problems not only exclude numerical or algebraic calculations, but also have a unique chemical logical structure. The number of logical schemata involved in a problem may be the main factor in determining the difficulty of the problem, overriding its *Z*-demand (Niaz & Robinson, 1992).

In this study, we used organic-synthesis problems (Ongley, 1959) of varying number of steps and, consequently, of varying *Z*-demand. To avoid student interaction, students seated adjacent in the class were assigned different problems. Thus, each student was assigned only one of two sets of problems. The Appendix contains one set of 16 problems, which consists of four problems with a *Z*-demand of 2, plus two problems for each of the *Z*-demands 3, 4, 5, 6, 7, and 8. The Kuder–Richardson coefficient of reliability for this test was found to be 0.74. Our results derive from 2 years of collection, namely 1991–1992 and 1992–1993.

The assignment of *Z*-demand for each problem was based on the judgment of two of the researchers, and followed directly from the minimum number of partial steps required to accomplish the synthesis; the assigned *Z*-demands were further confirmed by a *post factum* analysis of students' answers. This method is consistent with the four-stage procedure for the evaluation of the *Z*-demand known as "dimensional analysis" (Niaz, 1989d).

Psychometric Tests

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). This test involves both storage and processing and has been used as measure of working-memory capacity by Johnstone and his group in all their relevant work. 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 no 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.

Disembedding ability (the degree of field dependence/field independence) was assessed by use of a timed (20-minute) test, which was devised and calibrated by El-Banna (1987) from Witkin's original test materials (the Group Embedded Figures Test, or GEFT) (Witkin, 1978; Witkin, Oltman, Raskin, & Karp, 1971; Witkin, Dyk, Paterson, Goodenough, & Karp, 1974) using hidden figures. This test has been used by the Johnstone group as a measure of the degree of field dependence/independence in all their relevant work, while Niaz used the GEFT in his work. Students had to locate a hidden figure embedded inside a complicated figure. Eighteen such items were given. Subjects with ≥ 13 successes were classified as field independent, 7–12 successes as field intermediate; and ≤ 6 successes as field dependent. The split-half reliability coefficient was 0.68 for the present sample.

Checking the Necessary Conditions

Some necessary conditions for the successful application of the Johnstone–El-Banna model were stated previously. In what follows we verify the extent to which these conditions were fulfilled in this work.

Condition 1 (availability and accessibility of the partial steps). Prior to starting the tests, handouts were distributed to all students in which all single-step syntheses entering all problems were shown. Students were asked to study them. A test followed. Then students were advised on their errors or omissions and asked to go through the same material again.

Condition 2. Considering the large number of problems of varying number of steps that were used in this work, it was impossible to have equivalency of the partial steps. Therefore, we expected to have some deviations caused by the inability to satisfy this condition.

Condition 3. In principle, we had one logical structure in the organic-synthesis problems. However, one may see some "substructures"; for instance, the change of the number of carbon atoms in the compound may constitute a logical substructure, or may be another logical structure.

Condition 4. No noise was present in the problems. This follows from the fact that all problems were clearly stated, with no incidental, irrelevant, redundant, confusing, or peripheral information.

Condition 5. Although in the analysis we included all students, irrespective of their degree of field dependence/field independence, we examine later the effect of this disembedding ability.

Condition 6. Familiarity with the problems. Here, we have two complications. First, the familiarity gained through the practice of solving the problems; that is, even if students start as being unfamiliar, they will gain familiarity as the tests progress. To reduce this effect, we divided our data into two sets: one is the performance of the students on all 16 problems, and the other is the performance of the students on the first 7 problems of the tests, which spanned all the required Z-values. In the first two periods of testing, each student had to answer four problems each time with Z-demands 2, 4, 5, and 7 in the first period, and 2, 3, 6, and 8 in the second period. (We averaged the performance in the two $Z = 2$ problems, hence we were left with seven problems instead of eight.) In what follows we call these two sets of data "performance in all problems" and "performance in the first seven problems" respectively.

Each student was judged as successful, or not, on each Z-demand, based on performance on the corresponding problems (i.e., the four problems with $Z = 2$ and the two problems for each of $Z = 3-8$). The criterion was that the student was successful in at least half of the corresponding problems (i.e., two of the four or one of the two); otherwise, the student was judged as having failed. This performance has been used for the construction of the facility value (FV) versus Z-demand diagrams, and the corresponding marking scheme is termed "successful or failed."

In addition, each student was assigned an average mark for performance on the first seven problems as follows: two points were given for an entirely correct synthesis route; one mark for a correct overall route, but with some minor omissions or errors; and zero marks for wrong answers. However, the marks reported here are percentages.

The second complication was due to the fact that our students were in the final school year, and were actually preparing to take entrance examinations (including chemistry) at higher institutions. However, apart from the public no-fee school, almost all students received, at the same time, paid private lessons or attended paid private, special schools, or frontisteria. In these extra lessons, students may have been instructed in organic-synthesis problems prior to taking the tests. In one of the schools in our sample, students were asked to state if they had previous experience with organic-synthesis problems. In addition, we carried out the tests with a sample of students from frontisteria as well. We divided our subjects into: (1) all students, that is, the combination of (2) + (3); (2) public school students; (3) frontisteria students; and (4) public school students without practice, representing a subset of (2).

RESULTS AND DISCUSSION

Figure 1 shows the performance in terms of completely right or wrong; that is, the facility value (FV) of all students (N = 319) in problems of varying Z-demand, according to the measured working-memory capacity of the students. Figures 2 and 3 show the corresponding information for public school students (N = 191) and for frontisteria students (N = 128), respectively.

The operation of the Johnstone–El-Banna model is evident in all cases, but it is more pronounced in the case of frontisteria students. All figures clearly show that students with a measured working-memory capacity $X = 4$ did well on problems up to a Z-demand of 4, but declined rapidly for questions with a $Z \geq 5$ (a fall of FV from about 0.65 to about 0.20). Similarly, those with $X = 5$ did poorly for questions with $Z \geq 6$. A similar pattern appeared for those with $X = 6$ and $X = 7$. In the case of public schools (Fig. 2), there was a less dramatic fall for the $X = 7$ group, showing that their previous experience and their chunking skills may have been operating. On the other hand, frontisteria students with $X = 7$ approached the ideal prediction of 100% success up to $Z < X$, followed by a large drop (from FV = 1.0 to FV = 0.3) when $Z > X$.

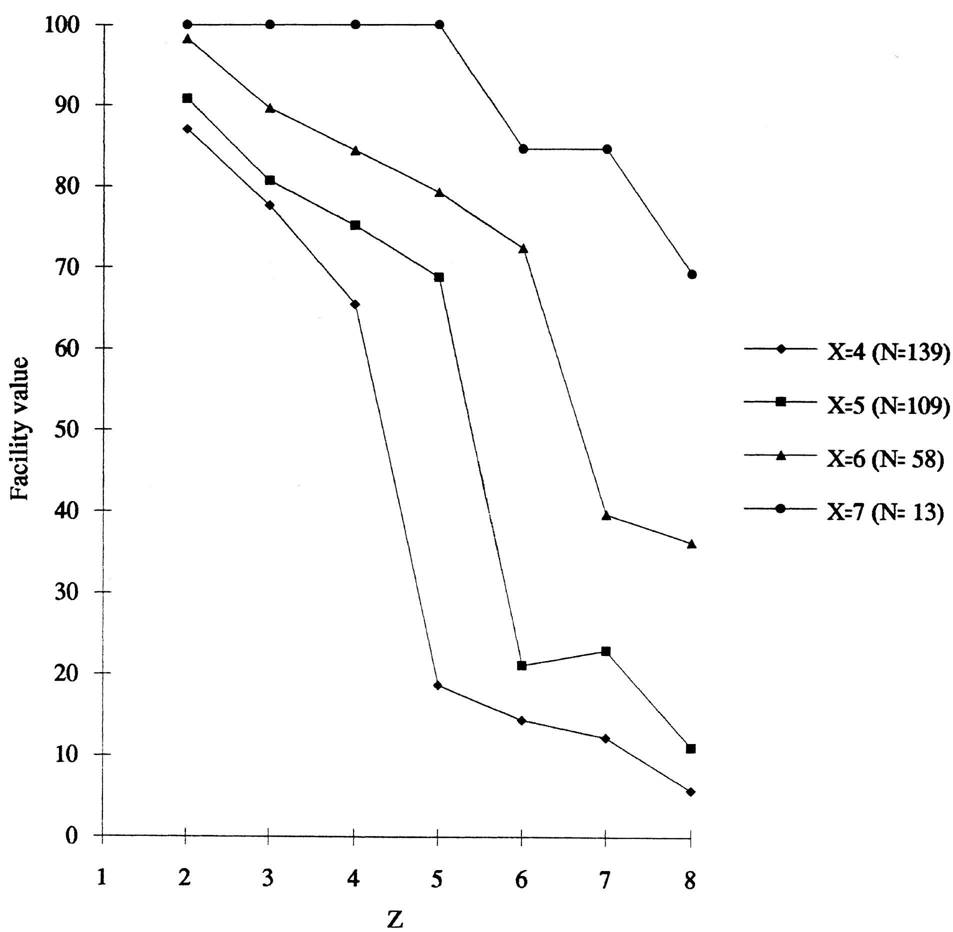

Figure 1. Whole sample (N = 319). Marking: successful or failed.

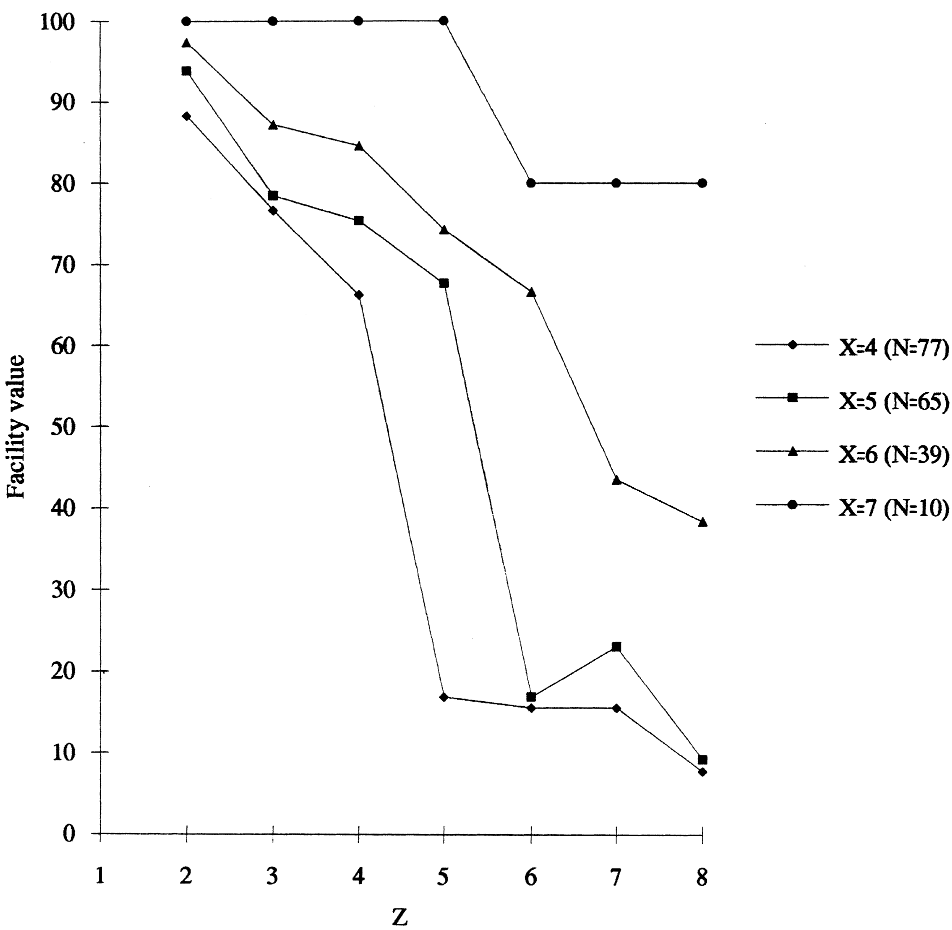

Figure 2. Public schools (N = 191). Marking: successful or failed.

The same pattern emerged when one considers the corresponding graphs for the student performance on the first seven problems. Figure 4 is the graph for frontisteria students.

An obvious question is why the fall in each case was not to FV = 0. Presumably, part of each sample used chunking devices to keep $Z < X$. However, it seems that the proportion of students who could use such devices was considerably higher for students with high information-processing capacity. In any case, most (>70%) students were not chunking, but rather falling at $Z = X + 1$.

The aforementioned observations are reinforced by statistics. Table 2 shows the statistical significance at $p = 0.01$ of all possible comparisons between X values with the various values of Z from $Z = 5$ to $Z = 8$ for frontisteria students held constant. (Because of their small number, students with $X = 7$ were excluded from this analysis.) For the problems with $Z = 5$, only the differences between $X = 4$ and $X = 5$, and between $X = 4$ and $X = 6$ were statistically significant; for problems with $Z = 6$, the differences between $X = 4$ and $X = 6$, and between $X = 5$ and $X = 6$ were statistically significant; for problems with $Z < 5$ and $Z > 6$ no significant differences are seen, with one exception between $X = 4$ and $X = 6$ for $Z = 8$ (A similar exception for $Z = 8$ was most likely between $X = 4$ and

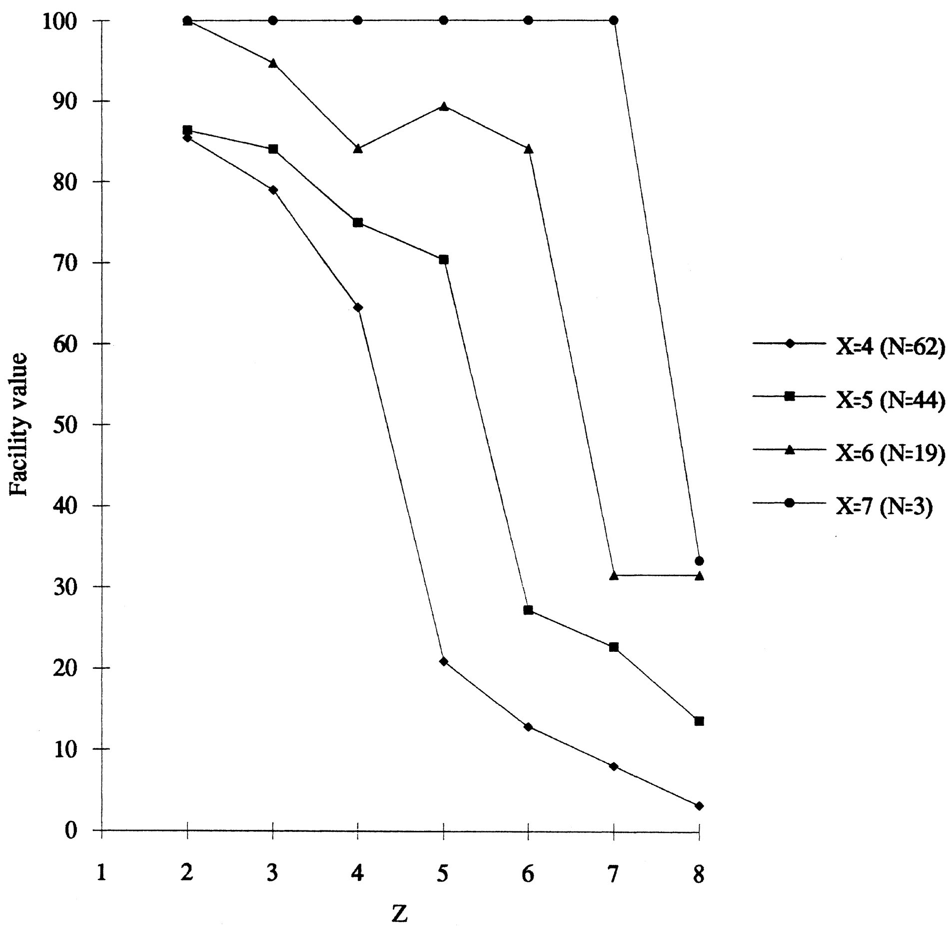

Figure 3. Frontisteria (N = 128). Marking: successful or failed.

$X = 7$; see Figs. 3 and 4.) The exceptions can be explained if we take into account the significant difference in chunking between high and low information processors.

In summary, we found that, as Z increased, there was a general *slow* fall in performance, but no difference was significant until Z *just* exceeded X. The fall was significant at the "break" point, but, after that, a gentle slow fall occurred again, in which no difference was significant. In each case, the significant fall took place when $Z = X + 1$. Finally, a number of students, notably higher for higher information-processing capacity, could use chunking devices, and this kept performance from eventually falling to zero.

The Training Effect

One of the most important necessary conditions for operation of the Johnstone–El-Banna model is the lack of familiarity with the problems. On the other hand, it has been assumed that a considerable number of public school students may have some familiarity with organic-synthesis problems, gained through frontisteria training.

We have already found that the data from frontisteria students conform better to the

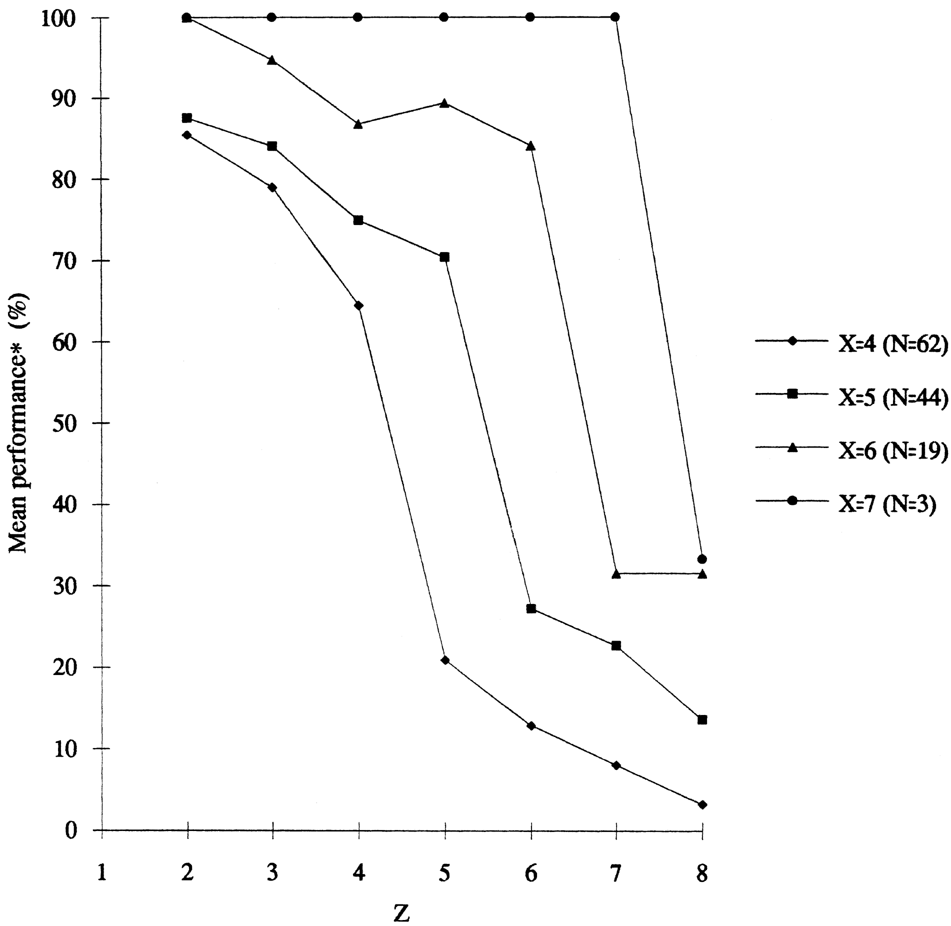

Figure 4. Frontisteria (N = 128). Asterisk: mean performance on the first seven problems.

model than the data from public school students. A further independent piece of evidence will now be invoked. Students from one particular school were asked to state whether they had or had not any previous experience with such problems. Thirty-six of the students stated that they had experience, whereas 62 students stated that they had no such experience. The graph of working-memory capacity versus *Z*-demand of the problems for the students with no previous experience is shown in Figure 5, and for those with previous experience in Figure 6. A number of features of the Johnstone–El-Banna pattern were maintained in the former case, whereas the model was obscured in the latter case. This finding, therefore, is not only an indication of the validity of the model, but also demonstrates the importance of the requirement for problems to be novel problems and not learned algorithms in order for the model to operate.

The Effect of Disembedding Ability

Disembedding ability/cognitive style (Pascual-Leone, 1989; Witkin et al., 1974) represents the ability of students to disembed information (cognitive restructuring) in a variety of complex and potentially misleading instructional contexts. As we found, although there

TABLE 2
Significance of Differences[a] at $p = 0.01$ in Performance for Frontisteria Students (N = 125),[b] Judged from Tukey's Honesty Significant Difference Tests According to One-Way ANOVA[c]

Problem with:		$X = 4$	$X = 5$	Mean Performance (%)
$Z = 5$	$X = 4$		#	21.0
	$X = 5$	#		70.5
	$X = 6$	#		89.5
$Z = 6$	$X = 4$			13.0
	$X = 5$			27.5
	$X = 6$	#	#	84.0
$Z = 7$	$X = 4$			8.0
	$X = 5$			22.5
	$X = 6$			31.5
$Z = 8$	$X = 4$			3.0
	$X = 5$			13.5
	$X = 6$	#		31.5
Total first seven problems	$X = 4$			37.0
	$X = 5$			46.8
	$X = 6$	#	#	67.7

[a]The symbol # marks significant differences.
[b]Three students with $X = 7$ were excluded.
[c]As expected, for problems with Z-demand equal to 2, 3, and 4 there are no significant differences (at $p = 0.01$). The corresponding mean performances are as follows. For $Z = 2$: 85.5 ($X = 4$), 88.5 ($X = 5$), 100.0 ($X = 6$); for $Z = 3$: 85.5, 84.0, 94.5; for $Z = 4$: 85.5, 75.0, 89.0.

were no statistically significant differences among degree of field independence and performance on problems with $Z = 2$, there were such differences in performance between field-independent and field-dependent students in all other problems ($p < 0.005$, except in the case of $Z = 5$, where $p < 0.01$). In addition, in only two cases (problems with $Z = 3$ and $Z = 8$) were there differences between field-independent and field-intermediate students as well. We can conclude that mainly field-dependent students show poorer performance in organic-synthesis problems when compared with field-intermediate or field-independent students. Figure 7 compares the average performance of all students in the first seven problems versus the working-memory capacity of students for various levels of disembedding ability. It is seen again that only the field-dependent students seemed to have been disadvantaged.

Figures 8–10 demonstrate the change in facility value versus Z-demand separately for field-dependent, field-intermediate, and field-independent students, respectively. It is obvious that the Johnstone–El-Banna model was in operation with the field-independent and the field-intermediate students, but to a lesser extent with the field-dependent ones. It is probably the case that field-dependent individuals lost a relatively high proportion of their potential working-memory space, and therefore their usable space was severely curtailed. This is much less pronounced in the case of those who were not field dependent.

Unfortunately, there were only five field-dependent subjects in the frontisteria sample, and all with $X = 4$, so we could not ascertain the effect of disembedding ability in such

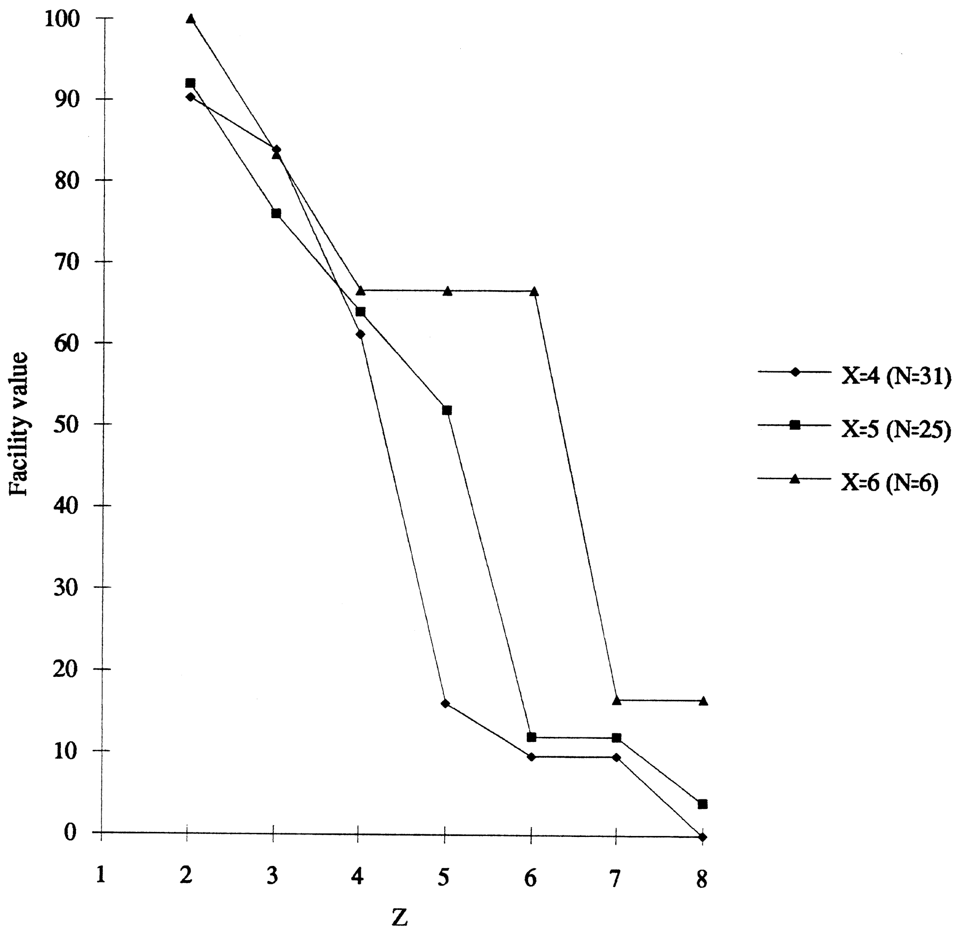

Figure 5. Public school students with no previous experience with organic-synthesis problems (N = 62). Marking: successful or failed.

cases (Fig. 11). In the case of field-intermediate (N = 66) and field-independent (N = 23) students, the graphs (Figs. 12 and 13) are in agreement with the model, but again the case of the field-independent students proved closer to the ideal situation. The small number of field-dependent students in the frontisteria sample is likely to have contributed to the fact that that sample showed the best fit with the model (Figs. 3 and 4 and Table 2).

Correlational Study

Table 3 shows the correlation coefficients between performance in the first seven problems and the two psychometric measures (working-memory capacity and disembedding ability). The correlation of performance in the problems with working memory was considerable, especially in the case of frontisteria students, showing the importance of information processing for the solution of novel problems. The correlation with disembedding ability assumes smaller but still statistically significant values; the smaller values must be the result of only the field-dependent students being severely affected, as was found earlier.

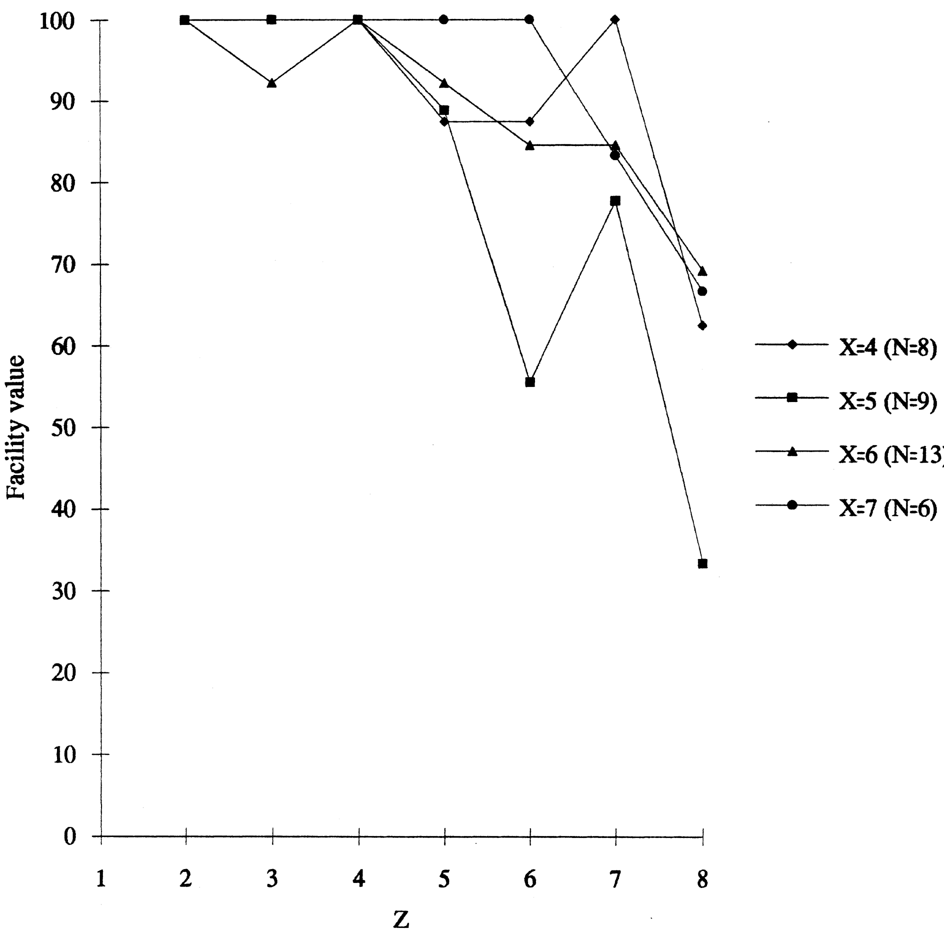

Figure 6. Public school students with previous experience in organic-synthesis problems (N = 36): Marking: successful or failed.

CONCLUSIONS AND EDUCATIONAL IMPLICATIONS

This study demonstrates convincingly that the Johnstone–El-Banna model of problem solving is valid, provided that a number of necessary conditions are fulfilled. In that case, there is a significant fall in performance when the *Z*-demand of problems exceeds the working-memory capacity of students. An important condition for the model to operate best is that the problems are novel problems, not learned algorithms. Working-memory capacity not only is the cognitive variable that forms the basis for the model, but it also correlates strongly with performance in novel problems that fulfill the necessary conditions.

Considerable, but much lower than that of working memory, is the correlation of disembedding ability when practice is absent or limited, as was the case with the frontisteria students. (Disembedding ability was not found to correlate strongly in the case of nonstringent fulfillment of the necessary conditions for the Johnstone–El-Banna model, in particular in the case of presence of practice; i.e., problems not novel.) Thus, it seems that the field factor assumes importance mainly in the case of novel problems. It was found that the model did not work well with field-dependent subjects, whereas it worked best

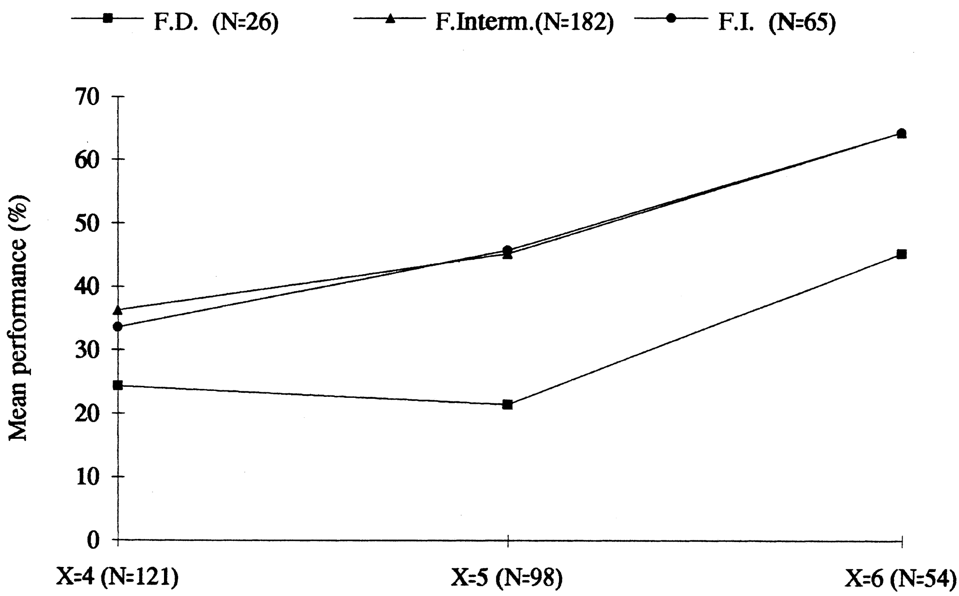

Figure 7. Mean performance of all students on the first seven problems versus the working-memory capacity of students at various levels of disembedding ability (N = 273).

with field-independent subjects. People who are not field dependent use most of their potential working memory space, whereas field-dependent people can lose a significant proportion of that space.

Although chunking devices can strongly interfere with the model, the use of such devices by the students is useful and desirable. It was found that students with high information-processing capacity were much more likely to be able to "chunk" than students with low information-processing capacity.

Taking these findings together, it can be predicted that students who have a high working memory capacity (at least of six), and at the same time are not field-dependent (and especially the field-independent ones), are capable of high levels of information processing, with an advantage in problem solving.

Results obtained in this study, together with those from other studies (Niaz, 1995a, 1995b; Tsaparlis, Kousathana, & Niaz, 1998), suggest that problem solving is a very complicated process, involving more than one cognitive variable, as well as affective ones, and have important implications for instruction in problem solving. Nonetheless, predictive–explanatory models, based on cognitive variables, can provide a rigorous and quantitative basis for the study of factors that affect the general problem-solving ability of students, as well as of the structure of the problems themselves. Guided by the findings of research, we are able to construct a series of problems in a science topic with the same reasoning pattern (same logical structure) and different *Z*-demand. We can then facilitate student success by first introducing problems of low *Z*-demand, and leaving problems of high *Z*-demand for later use in the course when the students have acquired experience and motivation.

Clearly the demand of problems must be carefully controlled for novices to build confidence with success. Only when strategies have been learned, should complexity be allowed to increase so that students can learn to keep the value of *Z* (not the actual, but their

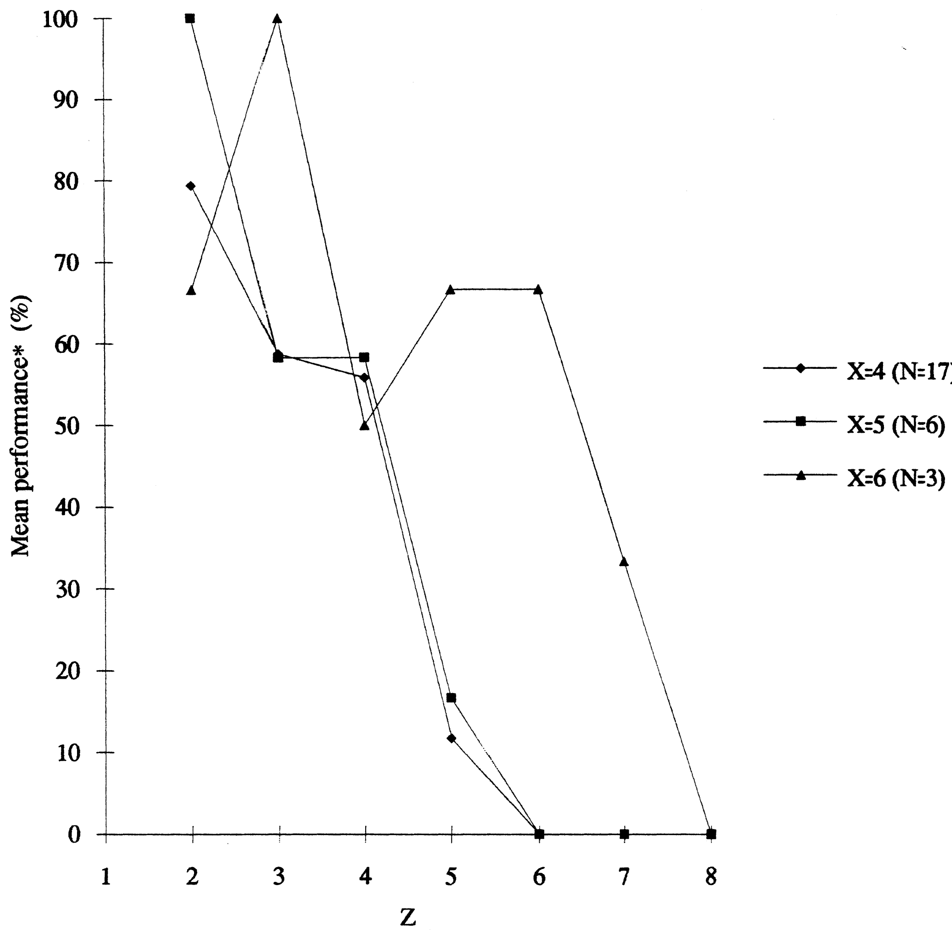

Figure 8. Whole sample. Field dependent (N = 26). Asterisk: mean performance on first seven problems.

TABLE 3

Correlation Coefficients[a] between (a) Performance (on First Seven Problems) and Working Memory Capacity, and (b) Performance and Disembedding Ability

	Public School Students (N = 163)	Frontisteria Students (N = 94)
Working memory capacity	0.46[b]	0.58[b]
	(0.43)[b]	(0.53)[b]
Disembedding ability	0.19[c]	0.31[c]
	(0.19)[c]	(0.29)[c]

[a]Pearson correlation coefficients appear above, and Spearman's rho appear below (in parentheses).

[b]$p < 0.001$.

[c]$p < 0.02$.

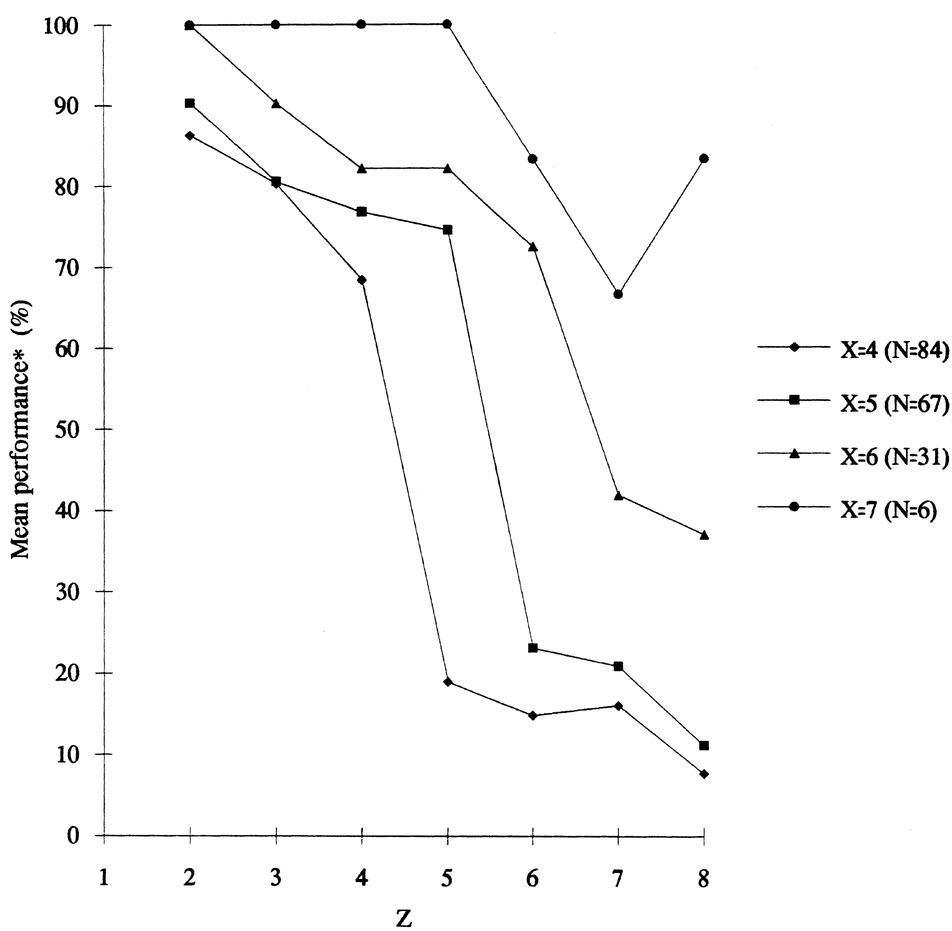

Figure 9. Whole sample. Field intermediate (N = 188). Asterisk: mean performance on first seven problems.

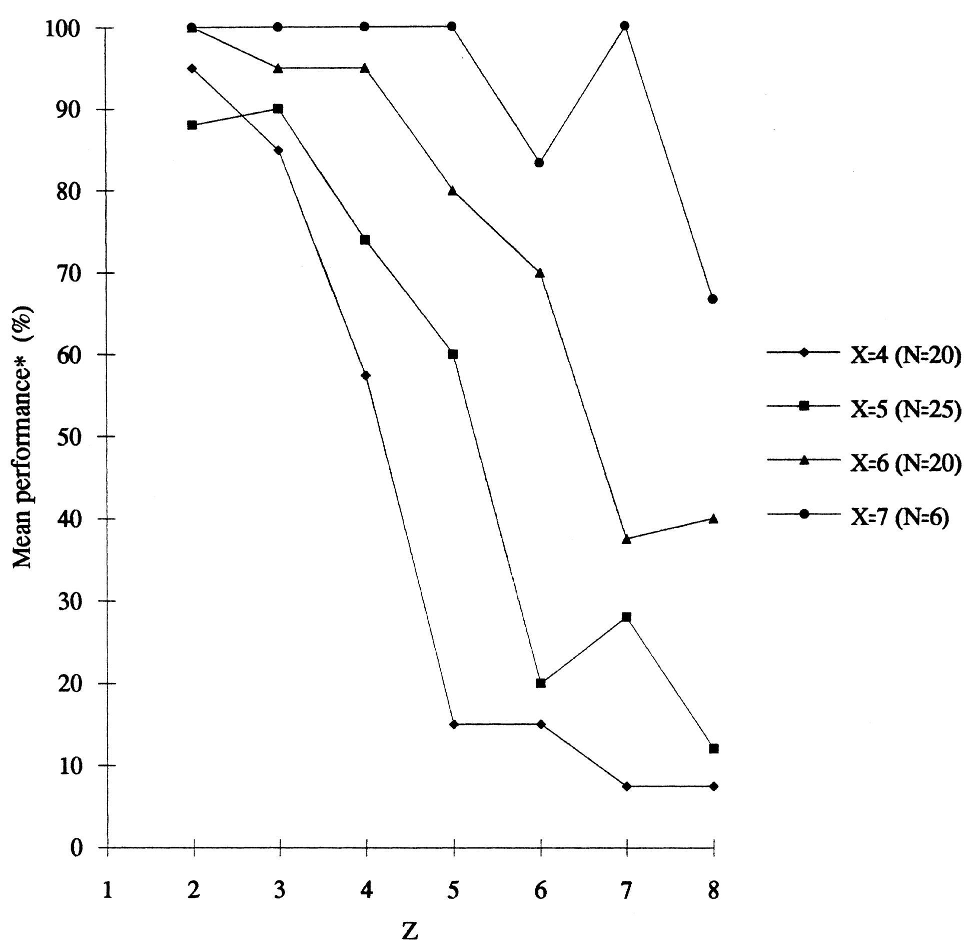

Figure 10. Whole sample. Field independent (N = 71). Asterisk: mean performance on first seven problems.

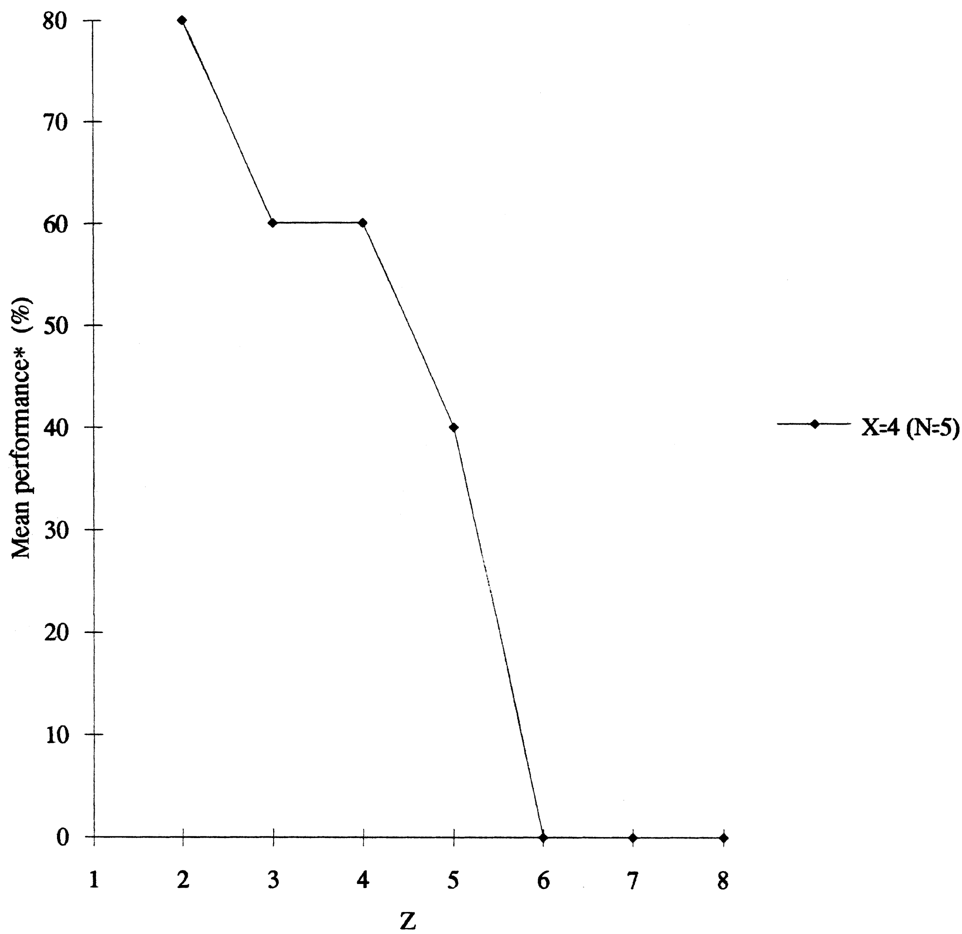

Figure 11. Frontisteria students. Field dependent (N = 5). Asterisk: mean performance on first seven problems.

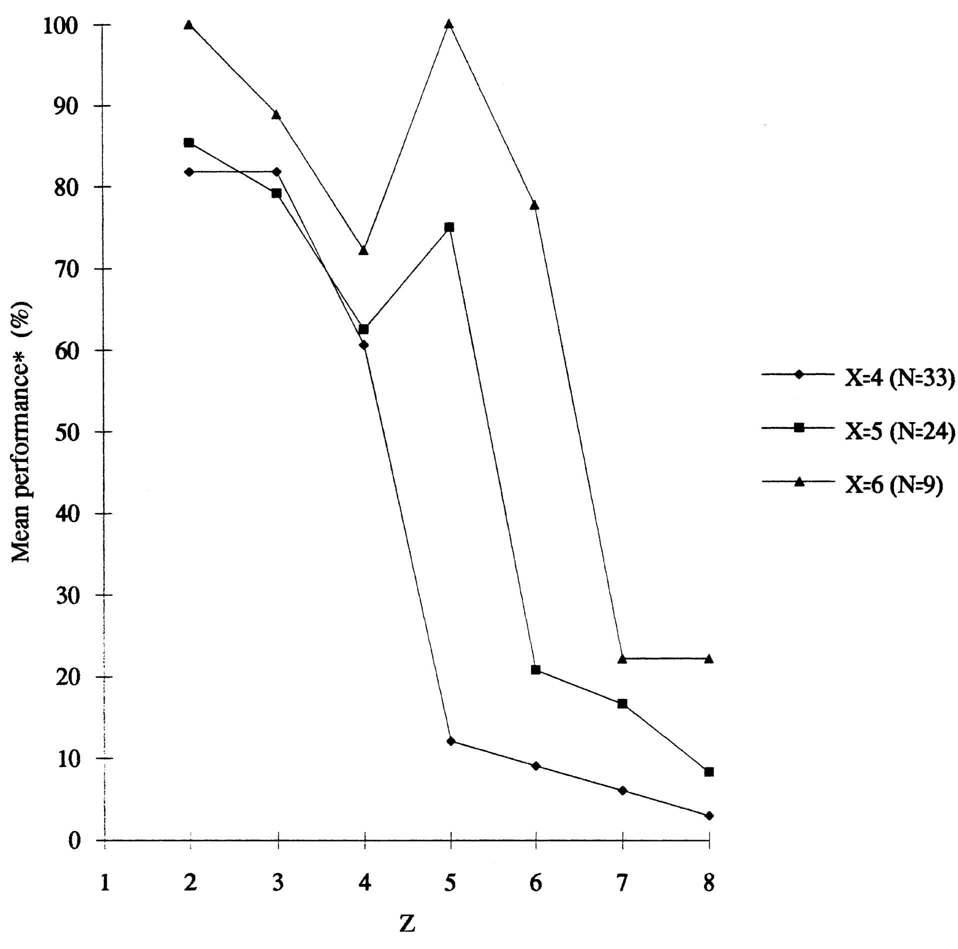

Figure 12. Frontisteria students. Field intermediate (N = 66). Asterisk: mean performance on first seven problems.

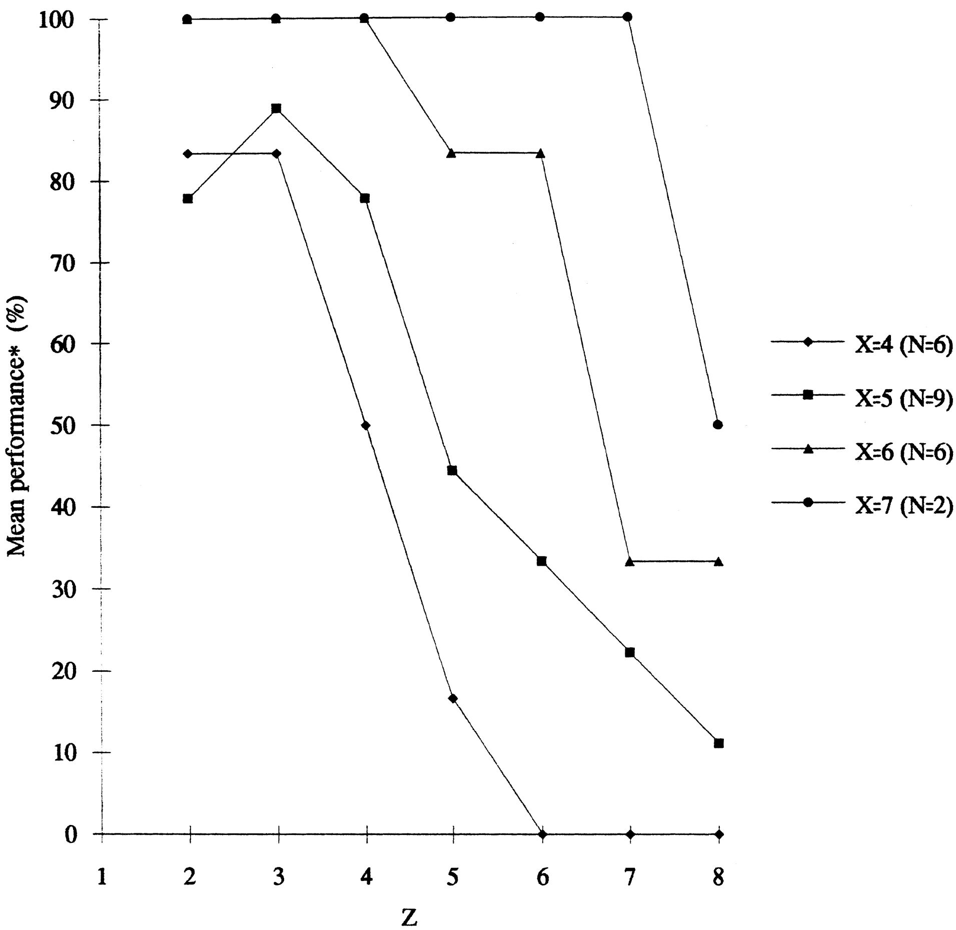

Figure 13. Frontisteria students. Field independent (N = 23). Asterisk: mean performance on first seven problems.

modified value of *Z* by "chunking") well within their capacity (*X*). In this way, confidence can be maintained while complexity increases, leading novices toward the expert state. To make this transition in students efficient and satisfying, teachers cannot leave strategies to chance, but must emphasize and consciously teach them throughout their teaching.

Finally, of paramount importance is the incorporation in teaching of methods that contribute to the acceleration of the development and the improvement of general cognitive abilities such as developmental level, information processing, and field independence. One example is that of CASE (cognitive acceleration through science education) (Adey & Shayer, 1994). In addition, the design of teaching strategies that can facilitate conceptual understanding (beyond the algorithmic strategies), plus the use of a variety of problems of variable logical structure and of demand for information processing, and in particular the extended use of novel problems, can provide a means for the development of various cognitive abilities, and for effecting the transition from lower to higher order cognitive skills (Zoller & Tsaparlis, 1997).

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APPENDIX

One (of the Two) Set of 16 Organic-Synthesis Problems

Students were asked to suggest in writing synthesis routes for the preparation of the following organic compounds, with starting material being the organic compound given in each case. All proposed reactions should be standard reactions, included in the school textbook, show good yield, and lead predominantly to the required compound. Thus, synthesis of a compound by means of the pyrolysis of a saturated hydrocarbon or that of an alkyl halide by the reaction of the corresponding halogen with the proper alkane were not accepted methods. Furthermore, reduction of an organic acid to the corresponding aldehyde is a difficult process, and should not be used.

First period of testing:

1. Acetaldehyde, CH_3CHO, from ethene, $CH_2{=}CH_2$.
2. 1,2,3-Trichlorobutane, $CH_3CHClCHClCH_2Cl$ from ethyne, $CH{\equiv}CH$.
3. 2-Cetoproprionic acid, $CH_3COCOOH$, from acetone, CH_3COCH_3.
4. 2-Methylbutanoic acid, $CH_3CH(CH_3)COOH$, from acetaldehyde, CH_3CHO.

Second period of testing:

1. Acetic acid, CH_3COOH, from methyliodide, CH_3I.
2. 2-Propanol, $CH_3CH(OH)CH_3$, from 1,1-dichloropropane, $CH_3CH_2CHCl_2$.
3. Pentanoic acid, $CH_3CH_2CH_2CH_2COOH$, from ethyne, $CH{\equiv}CH$.
4. Isopropylmethylether, $CH_3CH(CH_3)OCH_3$, from formaldehyde, HCHO.

Third period of testing:

1. 1-Chloropropane, $CH_3CH_2CH_2Cl$, from propene, $CH_3CH{=}CH_2$.
2. Acetone, CH_3COCH_3, from propanal, CH_3CH_2CHO.
3. Amide of acetic acid, CH_3CONH_2, from methanol, CH_3OH.
4. Propene, $CH_3CH{=}CH_2$, from dimethylether, CH_3OCH_3.

Fourth period of testing:

1. Formaldehyde, HCHO, from sodium acetate, CH_3COONa.
2. Propyne, $CH_3C{\equiv}CH$, from 2-propanol, $CH_3CH(OH)CH_3$.
3. Pentane, $CH_3CH_2CH_2CH_2CH_3$, from 1-propanol, $CH_3CH_2CH_2OH$.
4. 3-Hydroxyproprionic acid, $HOCH_2CH_2COOH$, from formaldehyde, HCHO.