DOCUMENT RESUME

ED 381 394 SE 056 247

AUTHOR Mason, Diana

TITLE Assessing Student Problem-Solving Success on Selected Topics in Introductory Chemistry.

PUB DATE Apr 95

NOTE 21p.; Paper presented at the Annual Meeting of the National Association for Research in Science Teaching (San Francisco, CA, April 22-25, 1995).

PUB TYPE Reports - Research/Technical (143) -- Speeches/Conference Papers (150)

EDRS PRICE MF01/PC01 Plus Postage.

DESCRIPTORS *Algorithms; *Chemistry; College Students; Higher Education; Instructional Improvement; *Introductory Courses; *Problem Solving; Science Education; *Scientific Concepts; Student Evaluation; Student Surveys; *Thinking Skills; Undergraduate Study

ABSTRACT

Incident identification graphs can be used to diagnose areas of difficulty in a subject's problem-solving schema at the episodic level. In this study, 22 subjects (2 experts and 20 novices) categorized into five problem-solving groups (expert, high algorithmic/high conceptual, low algorithmic/high conceptual, high algorithmic/low conceptual, and low algorithmic/low conceptual) were interviewed while solving problems on four topics generally found in introductory-level college chemistry (i.e. density, stoichiometry, bonding, and gas laws). Further analysis yielded that the conceptual-mode problem of the paired question was far more difficult and less often solved correctly for all groups of subjects (except high algorithm/high conceptual groups) than the corresponding algorithmic-mode problem although the algorithmic-mode problem took longer and required more transitions between episodes. Correct conceptual understanding, as reported by the problem solvers on transcribed think-aloud interviews, rested upon a known definition and an increased understanding of the language of chemistry. Suggestions are given to improve students' conceptual base in introductory chemistry. (Author/LZ)

Assessing Student Problem-Solving Success on Selected Topics in Introductory Chemistry

Diana Mason

The University of Texas at Austin

Department of Chemistry

A Contributed Paper for the 1995 Meeting of the National Association for Research in Science Teaching, San Francisco, CA.

Assessing Student Problem-Solving Success on Selected Topics in Introductory Chemistry

Abstract

Incident identification graphs can be used to diagnose areas of difficulty in a subject's problem-solving schema at the episodic level. In this study 22 subjects (two experts and twenty novices categorized into five problem-solving groups (expert, HA/HC, LA/HC, HA/LC, and LA/LC) were interviewed while solving problems on four topics generally found in introductory-level college chemistry (i.e., density, stoichiometry, bonding, and gas laws). Of these topics the one which presented all categories of problem-solvers the most difficulty was the paired algorithmic-conceptual question on stoichiometry. Consequently, this paired problem was investigated in greater depth. Further analysis yielded that the conceptual-mode problem of the paired question was far more difficult and less often solved correctly for all groups of subjects (except HA/HC) than the corresponding algorithmic-mode problem although the algorithmic-mode problem took longer and required more transitions between episodes. Correct conceptual understanding, as reported by the problem solvers on transcribed think-aloud interviews, rested upon a known definition and an increased understanding of the language of chemistry. At the episodic level of the problem-solving schema, the time needed to read a problem for the LC groups was almost twice the time needed for the expert and HA/HC groups. Suggestions are given to improve students' conceptual base in introductory chemistry.

Purpose

Obvious differences were seen in the problem-solving schema representative of different categories of problem solvers when algorithmic and conceptual problems typically found in introductory-level chemistry courses were solved (Mason & Crawley, 1994). This investigation sought to establish a comparison between a subject's problem-solving ability and the similarities and differences of their approach to solving stoichiometric problems common to many introductory-level chemistry courses. The central question is: what are the similarities and differences in the problem-solving schema used by different groups of problem solvers as they solve paired algorithmic and conceptual problems regarding stoichiometric relationships in chemical reactions?

Theoretical Base

The main focus of this study was to examine the similarities and differences in the ways different categories of problem solvers found solutions to problems from different topic areas (i.e., density, stoichiometry, bonding, and gas laws). In this study comparisons were made between different categories of problem solvers at the episodic level of their respective problem-solving schema as they solved paired problems. Novices were classified into groups reflective of their problem-solving ability (Mason & Crawley, 1994; Nakhleh, 1993); namely, high algorithmic/high conceptual (HA/HC), high algorithmic/low conceptual (HA/LC), low algorithmic/high conceptual (LA/HC), and low algorithmic/low conceptual (LA/LC). The episodes chosen to represent the problem-solving schema were that of read, define, set up, solve, and check. The selection of these specific episodes was based on previously published heuristics (Bodner & McMillen, 1986; Bunce, Gabel, & Samuel, 1991; Pólya, 1945; Powers, 1984; Schoenfeld, 1979, 1980; Tingle & Good, 1990; Woods, 1987, 1992).

The four topics investigated (i.e., density, stoichiometry, bonding, and gas laws) also were chosen because of their frequency of occurrence in research literature and in introductory chemistry courses. Modifications of the selected paired questions on density, stoichiometry, and gas laws used in this study were previously investigated by Nakhleh and Mitchell (1993) and Mason and Crawley (1994). Only the topic of stoichiometry is considered in this research paper because the data collected from all paired questions support that this topic is far more difficult for both experts and novices than any of the other three topics (i.e., density, bonding, and gas laws), and therefore warrants a more detailed investigation.

Novice problem solvers usually have difficulty in solving problems due to a lack of prior knowledge in a specific content area, not because they simply lack the ability to solve problems (Shuell, 1990a). Shuell (1990b, p. 532) reported that "learning is an active, constructive, cumulative, and goal-oriented process that involves problem solving." Neural connections made during a learning situation either strengthen or weaken previously established connections.

Therefore, it is imperative that new inputs appropriately target prior knowledge by strengthening correct associations and by deleting any misconceptions which may be held by a student.

Novice problem solvers in chemistry usually have greater success with solving problems of a algorithmic-mode than problems having a more conceptual base (Bunce, 1993; Nakhleh, 1993). Niaz and Robinson (1992) concluded that student training in computational problems did not guarantee successful understanding of conceptual problems. According to the study, Niaz and Robinson (1992) concluded that algorithmic and conceptual problems required different cognitive abilities.

Design and Procedures

Novices (n=20) were selected from a large-lecture university class (n=180) using stratified random sampling techniques (based on college enrollment) to solve paired algorithmic and conceptual problems by a think-aloud protocol along with two chemistry professors. Four different problem topics were investigated over the course of this one semester study. The topics selected included density, stoichiometry, bonding, and gas laws. Subjects were grouped into the various problem-solving categories based on the correctness of their responses to a selected problem (see Table 1). (A subject who succeeded at solving three or four problems correctly was classified as high algorithmic (HA) and high conceptual (HC) depending upon the mode of the problem, and accordingly, a subject was placed into the low algorithmic (LA) and low conceptual (LC) categories if only one or two problems of a particular mode were solved correctly.)

Table 1

Distribution of novices within problem-solving categories for the experimental sample, n=20

	HA	LA
HC	2	0
LC	13	5

Next, comparisons were made from the interpretation of the incident identification graphs completed for each subject at the time of the think-aloud interviews on all selected topics. The interpretation of data from these graphs led to the selection of the paired stoichiometric problem for extended study. The incident identification graphs used in this study on stoichiometry were similar to those reported as examples reflective of the problem-solving schema of the typical member of each problem-solving category (Mason & Crawley, 1994). Comparisons made were based on the time required to complete the problems and the number of transitions needed to solve the problems. Selected variables were graphed on an x-y axis for further comparisons between the topics and for identification of specific problem areas in the problem-solving schema associated with stoichiometry.

The paired stoichiometric problem used in this part of the investigation can be found below. This problem is a modification of a paired stoichiometric problem published by Nakhleh (1993). By dissecting the problem-solving schema of the 22 interviewed subjects, grouped according to their problem-solving category, the following research questions and hypotheses were tested.

How do experts and high-ability algorithmic/high-ability conceptual (HA/HC), low-ability algorithmic/high-ability conceptual (LA/LC), high-ability algorithmic/low-ability conceptual (HA/LC), and low-ability algorithmic/low-ability conceptual (LA/LC) novices solve paired algorithmic and conceptual problems on the selected topic of stoichiometry? (What are the similarities and differences between their approaches to solving paired algorithmic and conceptual problems?)

H_1 - There are differences among the problem-solving strategies of experts, HA/HC, LA/HC, HA/LC and LA/LC novices in the methods used to solve algorithmic-mode problems on the selected topic of stoichiometry in introductory chemistry.

H_2 - There are differences among the problem-solving strategies of experts, HA/HC, LA/HC, HA/LC and LA/LC novices in the methods used to solve conceptual-mode problems on the selected topic of stoichiometry in introductory chemistry.

Example Stoichiometric Problem Selected for Interviewing

A. Calculate the maximum weight of NH_3 that could be produced from 1.9 mol of hydrogen and excess nitrogen according to the following reaction:

$$N_2 + 3H_2 Æ 2NH_3$$

(A) 15 g
(B) 28 g
(C) 22 g
(D) 30 g
(E) 17 g

C. Any quantity of Cu in excess of one mole will always react with two moles of $AgNO_3$ to produce one mole of $Cu(NO_3)_2$ and two moles of Ag. Therefore we know that 1.5 moles of Cu will react with two moles of $AgNO_3$ to produce 215.74 grams of Ag. Which of the following concepts is the only concept NOT associated with all balanced equations?

(A) Chemical reactions involve the rearrangement of atoms about one another.
(B) In an ordinary chemical reaction mass is not created nor destroyed.
(C) Identical compounds are always composed of the same elements in the same proportion by mass.
(D) Moles of chemical compounds are always conserved in balanced equations.
(E) The number of moles of products formed is determined by the number of grams of the limiting reactant available.

Data

Tables 2-5 consist of data gathered for each of the four topics regarding the paired algorithmic and conceptual problems solved by subjects from each category of problem solvers. (In these tables "A" abbreviates algorithmic problem and "C" abbreviates conceptual problem, and "trans" is used to represent number of transitions between episodes of the problem-solving schema.) Table 2 presents the results for a typical algorithmic and conceptual problem for the topic of density solved by members of each subgroup available for study (i.e., expert, HA/HC, HA/LC, LA/LC), and also reports the means for all the novices as one group. (No data are reported for the members of the LA/HC group, because this research study produced no members classified as LA/HC.) Table 3 reports the same results for a typical algorithmic and conceptual stoichiometric problem; Tables 4 and 5 depict the results for the typical bonding and gas law problems, respectively. (Data from Table 3 are the focus of this paper, but Tables 2, 4, and 5 are included for purpose of comparison.) The data exhibited in Tables 2-5 were collected from the incident identification graphs (see Figures 1-8) of the interviewed subjects' problem-solving schema and serve to illustrate composite examples of a typical subject found in each category.

Table 2

Means of the Algorithmic and Conceptual Density Problems for each Category of Problem Solver

Subgroup	A time	C time	A trans	C trans	A rate	C rate
Expert	2:28	0:45	3	2	1.3	3.0
HA/HC	3:28	3:06	6	7	1.7	1.6
HA/LC	3:47	1:20	7	3	1.8	2.2
LA/LC	3:51	2:31	8	5	2.1	2.0
All Novices	3:46	1:48	7	4	1.9	2.2

Table 3

Means of the Algorithmic and Conceptual Stoichiometric Problems for each Category of Problem Solver

Subgroup	A time	C time	A trans	C trans	A rate	C rate
Expert	1:10	1:35	2	2	1.8	1.6
HA/HC	2:15	2:56	5	3	2.2	1.0
HA/LC	6:58	4:09	13	8	1.9	1.9
LA/LC	10:27	5:22	22	12	2.1	2.2
All Novices	7:22	4:20	14	8	1.9	1.8

Table 4

Means of the Algorithmic and Conceptual Bonding Problems for each Category of Problem Solver

Subgroup	A time	C time	A trans	C trans	A rate	C rate
Expert	0:50	0:15	2	1	2.4	4.5
HA/HC	1:35	1:30	2	3	1.3	2.0
HA/LC	3:14	1:04	5	3	1.5	2.8
LA/LC	3:16	1:48	7	5	2.1	2.8
All Novices	3:05	1:18	5	4	1.6	2.7

Table 5

Means of the Algorithmic and Conceptual Gas Law Problems for each Category of Problem Solver

Subgroup	A time	C time	A trans	C trans	A rate	C rate
Expert	1:35	0:40	6	1	3.4	1.5
HA/HC	3:26	1:40	9	4	2.6	2.4
HA/LC	4:42	2:44	9	4	1.9	1.5
LA/LC	6:01	3:16	14	7	2.3	2.1
All Novices	4:54	2:46	10	5	2.0	1.8

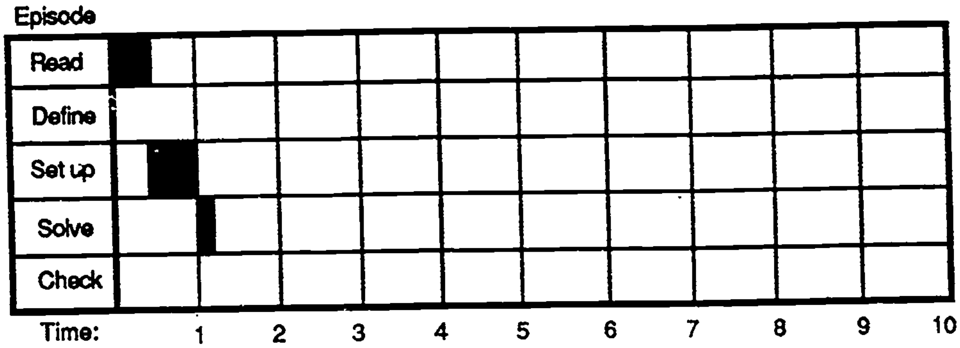

Figure 1. Algorithmic episodic graph of a typical expert for stoichiometry.

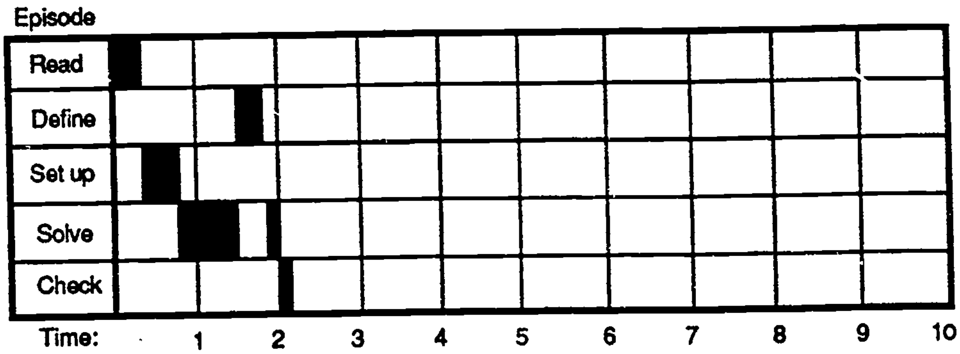

Figure 2. Algorithmic episodic graph of a HA/HC novice on stoichiometry.

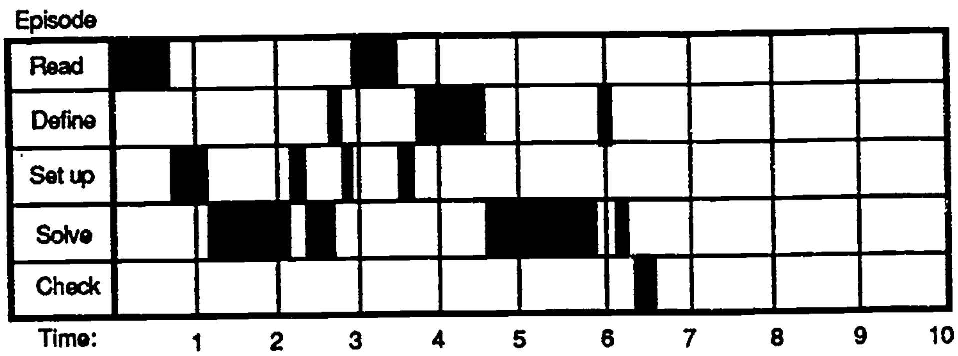

Figure 3. Algorithmic episodic graph of a typical HA/LC novice on stoichiometry.

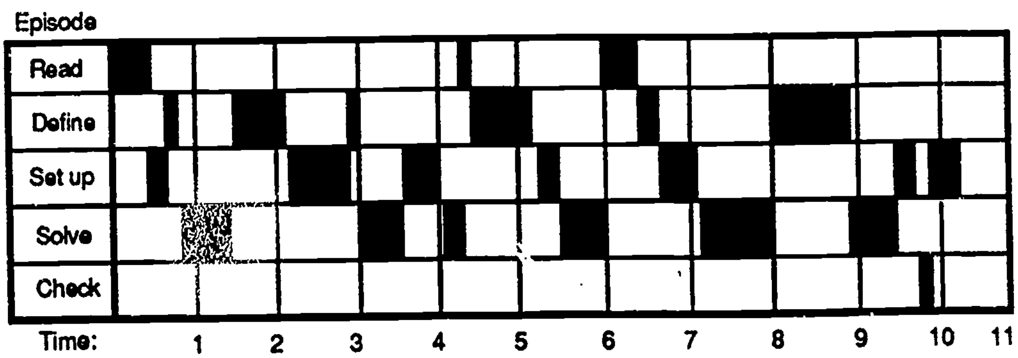

Figure 4. Algorithmic episodic graph of a typical LA/LC novice on stoichiometry.

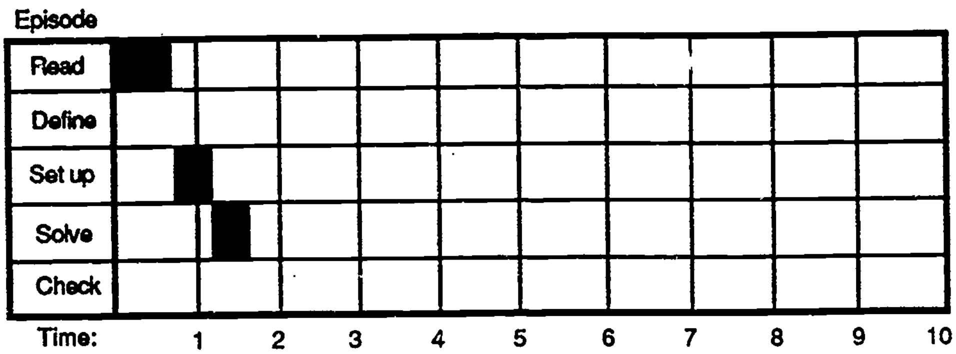

Figure 5. Conceptual episodic graph of a typical expert on stoichiometry.

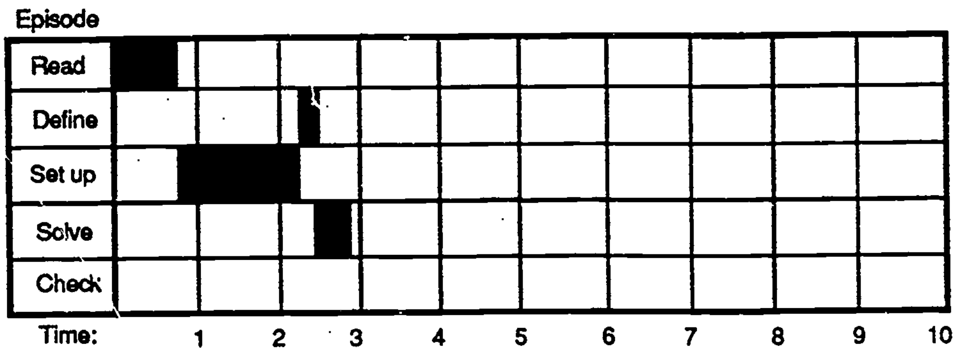

Figure 6. Conceptual episodic graph of a typical HA/HC novice on stoichiometry.

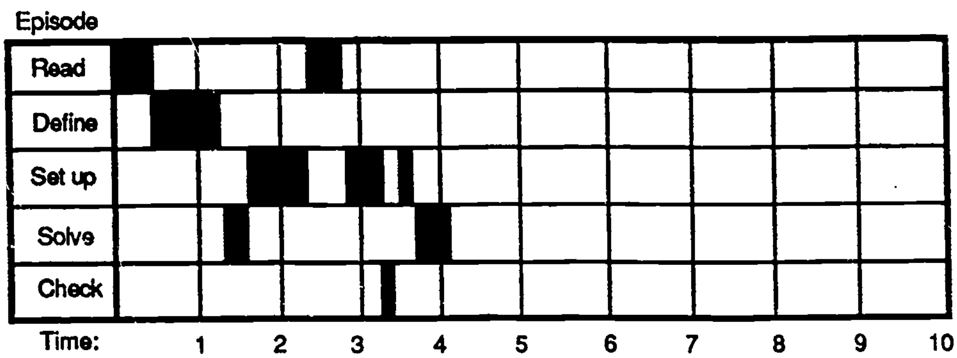

Figure 7. Conceptual episodic graph of a typical HA/LC novice on stoichiometry.

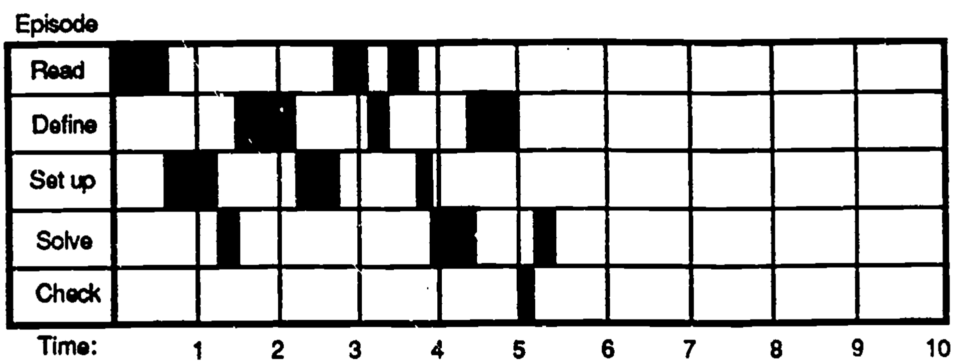

Figure 8. Conceptual episodic graph of a typical LA/LC novice on stoichiometry.

Figures 9 and 10 present data included in Tables 2-5, graphically. Figure 9 represents the total time needed to solve problems according to topic (i.e., density, stoichiometric, bonding, and gas laws) of the typical algorithmic problems for each group of problem solvers. Figure 10 represents the total time needed by every group of problem solvers to solve each of the typical conceptual problems. In Figure 9 all times for the solving of an algorithmic-mode problem gradually increased as the problem-solving ability decreased, except in the cases of the time needed to solve an algorithmic-mode stoichiometric problem for the LC groups. In these cases there appears to be a much longer amount of time needed to solve an algorithmic-mode stoichiometric problem for the two LC groups, than for the other groups (see Figure 9). In Figure 10 (except for the HA/HC conceptual density problem), there can be seen almost a linear relationship between problem-solving performance and the time required to solve a problem. (The anomaly seen in Figure 10 for the density problem of the typical HA/HC problem solver can be explained due to the fact that one of the two novices in that group experienced momentary confusion.)

As the problem-solving performance decreased for the conceptual-mode problems on the topics of stoichiometry, bonding, and gas laws, the amount of time needed for subjects to solve a problem increased. Particularly note the curves on Figures 9 and 10 (reflective of the data presented in Table 3) for problem-solving time for each group regarding the topic of stoichiometry. As problem-solving ability decreased, there were dramatic increases in times required to solve both the algorithmic and conceptual stoichiometry problems.

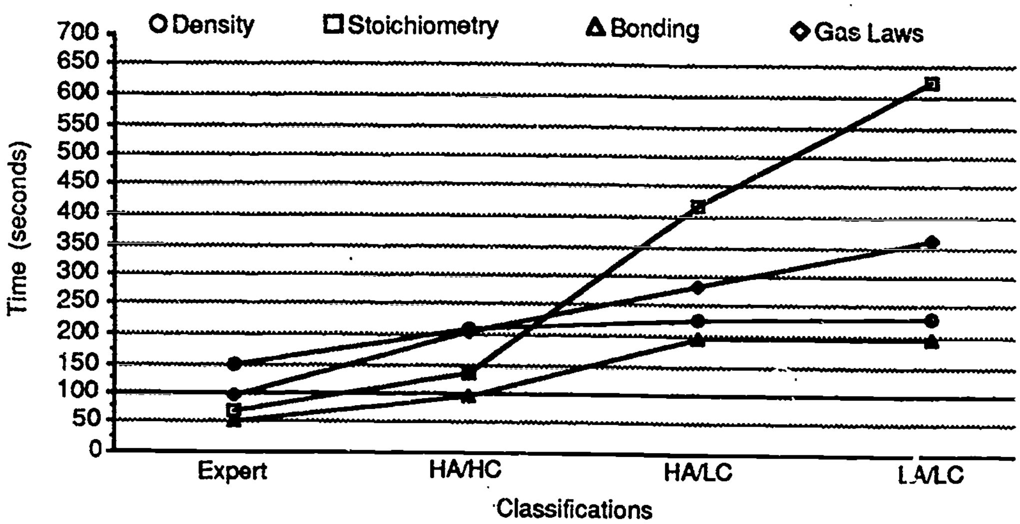

Figure 9. Time required for a typical problem-solving schema for an algorithmic problem of each problem-solving classification.

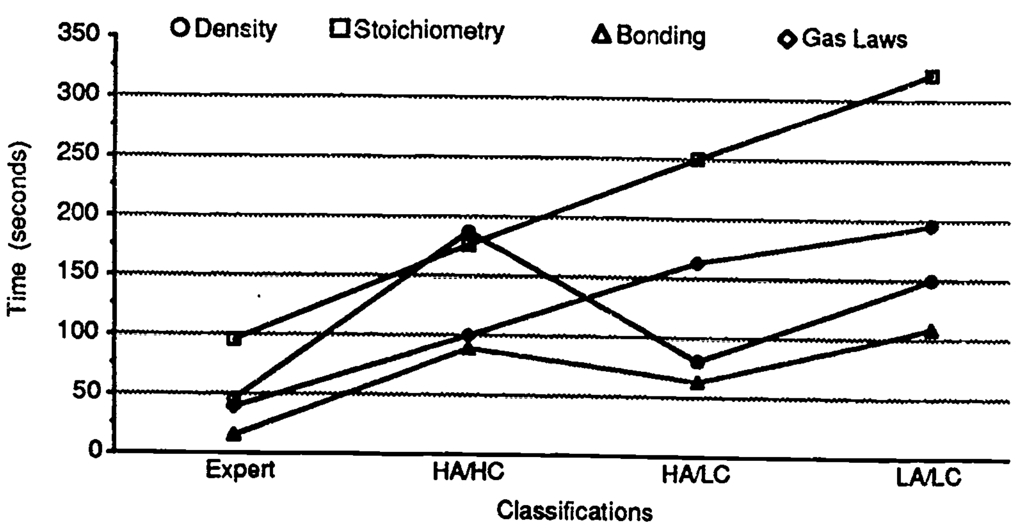

Figure 10. Time required for a typical problem-solving schema for a conceptual problem of each problem-solving classification.

Figures 11 and 12 present graphs representing the data for the number of transitions for the typical algorithmic and conceptual problems (by topic), respectively. Figure 11 depicts the appropriate algorithmic data, and Figure 12 depicts data representative of a conceptual problem according to the problem topic. The same divergence of the curves on the graphs are seen as the problem-solving performance of the novices decline. Also as the performance level of the groups of novices decreased, the number of transitions required to solve the paired problems generally increased. The number of transitions required to solve an algorithmic and conceptual-mode problems appears somewhat clustered for all groups on all topics, except in the case of the stoichiometric problem. For the HA/LC and LA/LC groups of problem solvers, the number of transitions necessary for solving a conceptual-mode stoichiometric problem greatly exceeded that needed by members of the HA/HC and expert categories. However, the same general trend was established: the longer the amount of time required to solve an algorithmic or conceptual-mode problem (regardless of topic), the greater the number of transitions made by members of all experimental groups.

Figures 13 and 14 graphically present the mean data for time and transitions for the novice groups only. Figure 13 depicts the average time required to solve each of the four pairs of algorithmic and conceptual problems, by topic of problem. In all cases the time required for a novice to solve an algorithmic-mode problem exceeded the time needed to solve the corresponding conceptual-mode problem. Figure 14 shows the average number of transitions made by the novices for algorithmic and conceptual-mode problems by topic. This graph is similar to the graph in Figure 13 in that in each case the number of transitions was always greater for the algorithmic problem than for the conceptual problem.

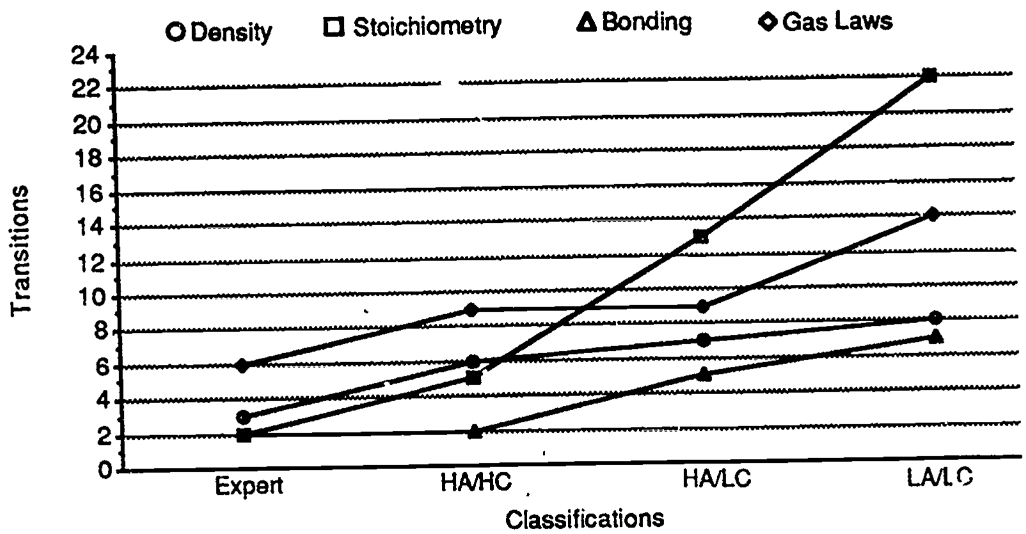

Figure 11. Number of transitions for a typical algorithmic problem of each classification of problem solver by type of problem.

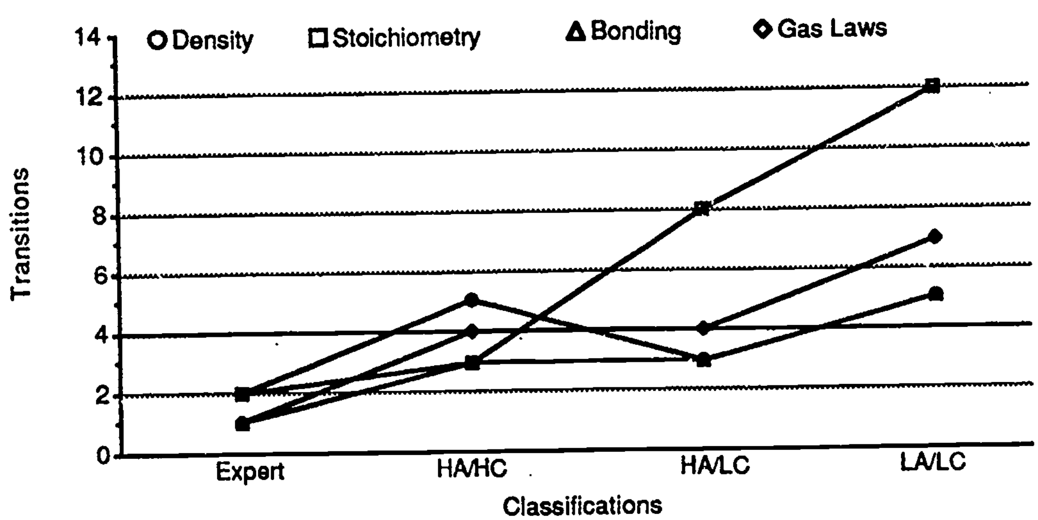

Figure 12. Number of transitions for a typical conceptual problem of each classification of problem solver by type of problem.

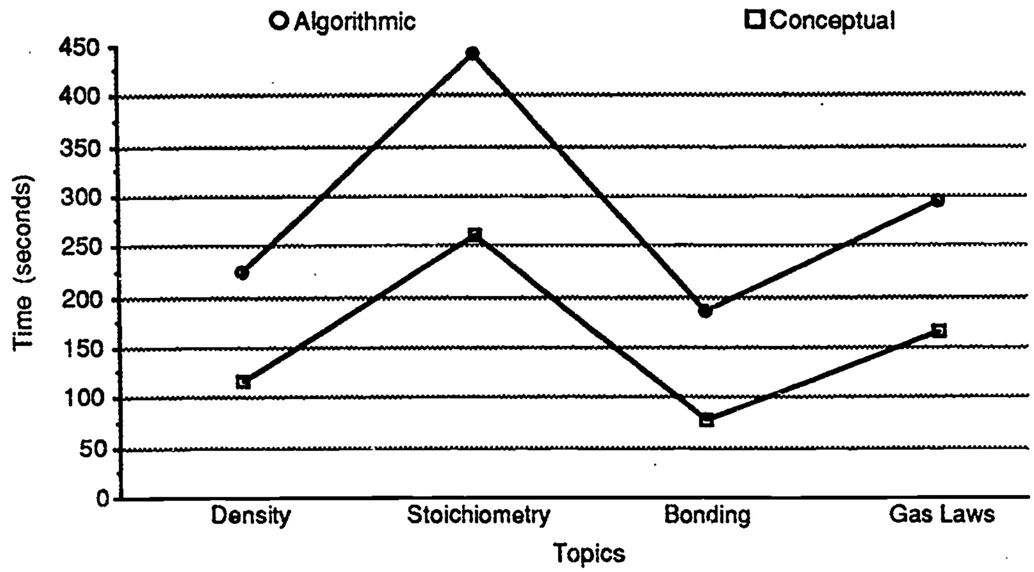

Figure 13. Time required to solve each type of paired problems.

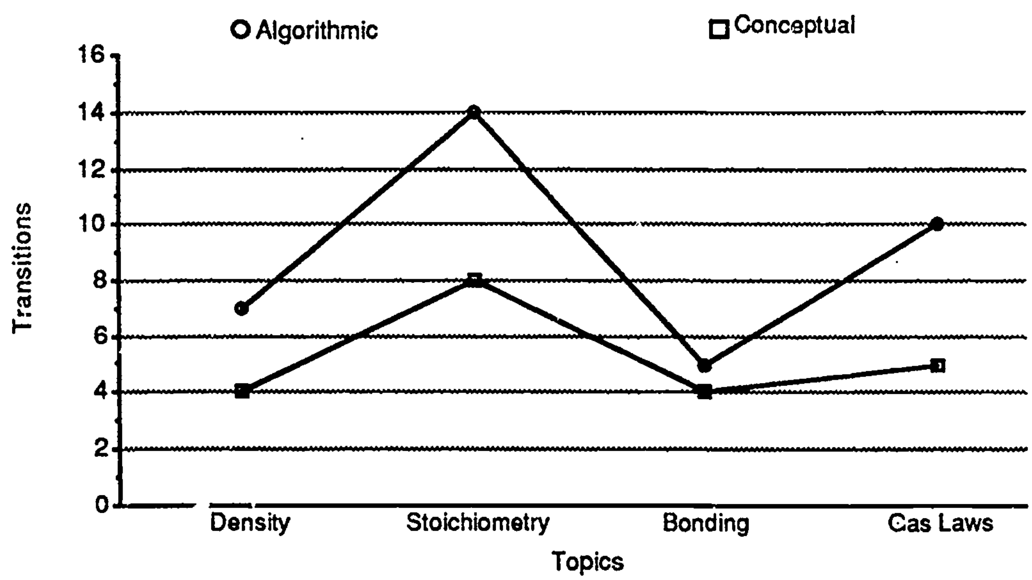

Figure 14. Number of transitions required to solve each type of paired problems.

Interpretations of the graphed data from Tables 2-5 deems necessary a more in depth analysis of the problem-solving ability of all subjects regarding procedures used to solve stoichiometric problems. Since both the algorithmic and conceptual-mode stoichiometric problems presented all groups increased difficulty, transcripts from the think-aloud interviews of each individual were reviewed. Correct solutions to the algorithmic-mode problem were obtained by nearly all interviewed subjects (i.e., all experts and both HA/HC novices solved the algorithmic-mode problem correctly, along with all but three of the remaining 17 LC novices). In light of the fact that only three interviewed subjects failed to obtain the correct solution to the algorithmic-mode problem, the remaining part of the investigation focuses on the conceptual understanding exhibited by individuals on the topic of stoichiometry.

Of the 22 interviewed subjects, 16 failed to concluded the correct solution to the conceptual-mode problem. Of the 16 subjects who obtained an incorrect solution to the conceptual-mode problem, one was an expert, ten fell into the HA/LC category, and all five LA/LC novices arrived at an incorrect solution to the given problem. The frequency of the incorrect choices is reported in Table 6.

Table 6

Frequency of incorrect responses to the conceptual-mode stoichiometric problem by problem-solving category

group	n	A	B	C	D*	E
Expert	2					1
HA/HC	2					
HA/LC	13	1		5		4
LA/LC	5		2	2		1

*correct solution

Responses from the think-aloud interviews given by subjects in the high conceptual categories (expert and HA/HC groups) who correctly solved the conceptual-mode stoichiometric problem, rarely stated anything after reading the problem outside of simply giving the answer to the problem as choice "D". When asked to justify why they had selected choice "D", the answers given by all three subjects were similar. They basically responded they knew that moles were not conserved in balanced chemical equations and therefore this must be the correct choice (or that choice "D" is the given statement that was not associated with all balanced equations). (See example problem on stoichiometry.) For the other 16 subjects who incorrectly solved the problem, all attempted to obtain the correct solution by a process of attempting to eliminate (sometimes haphazardly) four of the five possible choices. Figures 3, 4, 7, and 8 clearly depict that these subjects' ability to arrive at a solution to the problem in a logical, sequential manner is discouraging. An increased amount of time and numerous transitions between episodes are needed for these students to arrive at any solution. Both choices "C" and "E" contributed as competing distracters for the correct solution to the problem (see Table 6). Answer "C" is a restatement of the Law of Definite Proportions and choice "E" defines a limiting reactant.

When average reading times for LC novices are compared to the typical subjects in the HC groups, there is almost a two-fold increase. Where the typical expert and HA/HC novice spend only minimal time defining issues within the problem, the subjects from the LC novice groups exhibit seemingly erratic logic between the episodes of define and set up (see Figures 5-8). The average number of transitions required while the conceptual-mode problem was solved for the expert group is 2, the HA/HC group is 3, the HA/LC group is 8, and the LA/LC is 12 (see Table 3). Likewise, dramatic increases in the number of transitions between episodes (i.e., expert = 2, HA/HC = 5, HA/LC = 13, and LA/LC = 22) was seen in the incident identification graphs for the algorithmic-mode problem (see Table 3 and Figures 1-4), but these problems were eventually solved correctly by most individuals interviewed.

Results and Conclusions

These results led to the acceptance of research hypotheses, H_1 and H_2, of the research question. There were similarities and differences in the ways different groups of problem solvers solved both algorithmic and conceptual-mode stoichiometric problems typical of the ones found in introductory chemistry courses. Not only did LA/LC problem solvers take more time to solve both algorithmic and conceptual-mode problems, than did members of the other categories, but also they required more transitions between the episodes of the problem solving schema than did members of the other categories of problem solvers. Other results indicated that stoichiometric problems (both modes) were most difficult for the novices in the LC groups. Not only was more time required, but also more transitions were needed over those required to solve paired problems on the other three topics. An implication of this observation is that there must have been some confusion among the members of this category of novices as they solved the algorithmic and conceptual-mode stoichiometric problems. Gas law problems (whether algorithmic or conceptual) appeared to be the second most difficult problem-solving topic for the LC novices. This conclusion was based on the increased times required and the greater number of transitions needed to solve problems on this topic over that needed to solve problems on topics of density and bonding.

As observed from the graph of Figure 9, there is a large divergence in the times needed to solve an algorithmic-mode stoichiometric problem by members of the different problem-solving categories. This same separation is evident in the corresponding conceptual-mode graph (see Figure 10). This observation emphasizes that students with low-algorithmic and low-conceptual performance find problems on stoichiometry to be much more difficult than do members of the other groups. This result is revealed again by the graph for the number of transitions needed to solve algorithmic and conceptual-mode stoichiometric problems (see Figures 11 and 12). However, regardless of the problem topic, all groups tended to solve the conceptual-mode problem of the pair more quickly and with fewer transitions (see Figures 13 and 14) than the corresponding algorithmic-mode problem. This reaffirms that conceptual understanding is more dependent upon a known definition or relationship which can be more quickly accessed by the solver.

Regardless of problem topic, the time required for a novice to solve an algorithmic-mode problem exceeded the time needed to solve the corresponding conceptual-mode problem. As subjects' problem-solving ability decreased, the times and number of transitions needed for each group of problem-solvers to complete the problems gradually increased on topics of density, bonding, and gas laws regardless of whether the problem was of a computational or conceptual nature, but the divergence of the curves of the stoichiometric problems exhibited a much steeper slope. This finding is consistent for both the algorithmic and conceptual-mode problems. These results also reaffirm that conceptual understanding is more dependent upon the subjects' ability to access prior knowledge regarding chemical interactions and relationships than is their ability to compute answers to algorithmic-mode problems. In light of the fact that over 85% of the sample tested succeeded in answering the computational problem correctly, we can assume that lack of mathematical ability may only play a small role in overall student success in introductory chemistry. The major portion of the novices' difficulty in solving stoichiometric problems may lie in their lack of conceptual understanding. Consequently, more time and effort should be exerted by instructors to assure that introductory-level students have sufficient practice to succeed at solving these more difficult conceptual problems.

Implications

Another aspect of the selected conceptual problem which must be addressed is the inclusion in this problem on stoichiometry the many facts and numeral values which were not necessary in order to arrive at a satisfactory solution (i.e., all the introductory information in the first two statements). In the real world most problems present themselves with many variables which need to be identified as pertinent, or not, to obtaining a solution. Some variables may prove to be important and some may not, so problem solvers must learn to differentiate important facts that are needed from those which simply contribute to the general data base.

There are several techniques that can be used to aid our students in solving conceptual-mode problems relevant to the study of introductory chemistry: (1) present lecture information to students in a format representative of the two distinct problem-solving modes; (2) design examinations to reflect emphasis not only on computations, but also on basic chemical concepts; (3) include in examinations/problem sets "extra" information that allows the student to explore more than the traditional "plug n' chug" mentality; (4) train students in the use of the language of chemistry by encouraging in-class assignments that invite a collaborative effort between the instructor and the students and among the students themselves; and (5) find ways to introduce the more conceptual aspects of chemistry to younger/less experienced students.

References

Bodner, G. M., & McMillen, T. L. B. (1986). Cognitive restructuring as an early stage in problem solving. Journal of Research in Science Teaching, 23, 727-737.

Bunce, D. M. (1993). Introduction. Symposium: Lecture and Learning: Are they compatible? Journal of Chemical Education, 70, 179-180.

Bunce, D. M., Gabel, D. L., & Samuel, J. V. (1991). Enhancing chemistry problem-solving achievement using problem categorization. Journal of Research in Science Teaching, 28, 505-521.

Mason, D. S., & Crawley, F. E. (1994). Differences between algorithmic and conceptual problem solving by nonscience majors in introductory chemistry. Paper presented at the 67 Annual Conference of the National Association for Research in Science Teaching (NARST).

Nakhleh, M. B. (1993). Are our students conceptual thinkers or algorithmic problem solvers?: Identifying conceptual students in general chemistry. Journal of Chemical Education, 70, 52-55.

Nakhleh, M. B., & Mitchell, R. C. (1993). Concept learning versus problem solving: There is a difference. Journal of Chemical Education, 70, 190-192.

Niaz, M., & Robinson, W. R. (1992). From 'algorithmic mode' to 'conceptual Gestalt' in understanding the behavior of gases: An epistemological perspective. Research in Science & Technological Education, 10, 53-64.

Pólya, G. (1945). How to solve it: A new aspect of mathematical method (pp. xvi-xvii). New Jersey: Princeton University Press.

Powers, M. H. (1984). A computer assisted problem solving method for beginning chemistry students. Journal of Computers in Mathematics and Science Teaching, 4(1), 13-19.

Schoenfeld, A. H. (1979). Presenting a model of mathematical problem solving. Paper presented at the 63 Annual Meeting of the American Educational Research Association. (ERIC Document Reproduction Service No. ED 171 536)

Schoenfeld, A. H. (1980). Teaching problem-solving skills. American Mathematical Monthly, 87, 794-805.

Shuell, T. J. (1990a). Phases of meaningful learning. Review of Educational Research, 60, 531-547.

Shuell, T. J. (1990b). Teaching and learning as problem solving. Theory into Practice, 29, 102-108.

Tingle, J. B., & Good, R. (1990). Effects of cooperative grouping on stoichiometric problem solving in high school chemistry. Journal of Research in Science Teaching, 27, 671-683.

Woods, D. R. (1987). Use life skills programs to help develop courses. Journal of College Science Teaching, 16, 212-217.

Woods, D. R. (1992). Workshop on "Teaching Thinking". Presented at the 12th Biennial Conference on Chemical Education. University of California at Davis, Davis, CA, August 2-6.