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ABSTRACT

Two studies were conducted to determine the effects of gender, reasoning level, and inductive and deductive computer-simulated experiments (CSE) on problem-solving abilities in introductory general chemistry. In the pilot study, 254 subjects were randomly assigned to control (computer-assisted-instruction tutorials), inductive or deductive CSE treatments for the entire semester. On the comprehensive final examination consisting of 78% problem-solving items, formal reasoners outperformed transitional reasoners who, in turn, outperformed concrete reasoners, ANOVA, $p<.0001$, and males outscored females, $p=.0452$. On gain in reasoning ability among the concrete reasoners, those in the inductive group tended to outgain those in the other two groups. For the main study using 187 subjects and no control group, the CSE's were revised to make the structure more explicit. No significant differences were found among the types of reasoners on three cognitive levels of the final examination. In a reversal of the expected gender differences, males tended to score higher on lower cognitive items, whereas females tended to score higher on higher cognitive items with no gender differences on middle cognitive items. A subsequent analysis revealed that this reversal was due to significant gender-reasoning level interactions for both middle- and higher-cognitive problem-solving measures. A discussion of the relationships among problem-solving abilities, cognitive styles, and the use of guided discovery within an interactive CSE instructional environment is provided. (Author/ZWH)

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CHEMISTRY PROBLEM-SOLVING ABILITIES: GENDER, REASONING LEVEL AND COMPUTER-SIMULATED EXPERIMENTS

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Abstract

Two studies were conducted to determine the effects of gender, reasoning level, and inductive and deductive computer-simulated experiments, CSE, on problem-solving abilities in introductory general chemistry. In the *pilot study*, 254 subjects were randomly assigned to control (CAI tutorials), inductive or deductive CSE treatments for the entire semester. On the comprehensive final examination, 78 % problem-solving items, formal reasoners outperformed transitional reasoners who, in turn, outperformed concrete reasoners, ANOVA, $p < .0001$, and males outscored females, $p = .0452$. On gain in reasoning ability among the concrete reasoners, those in the inductive group tended to outgain those in the other two groups. For the *main study*, 187 subjects and no control group, the CSE's were revised to make the structure more explicit. No significant differences were found among the types of reasoners on three cognitive levels of the final examination. In a reversal of the expected gender differences, males tended to score higher on lower cognitive items, whereas females tended to score higher on higher cognitive items with no gender differences on middle cognitive items. A subsequent analysis revealed that this reversal was due to significant gender-reasoning level interactions for both middle- and higher-cognitive problem-solving measures. We discuss the relationships among problem-solving abilities, cognitive styles, and the use of guided discovery within an interactive CSE instructional environment.

Introduction

The problem-solving abilities of college students in introductory general chemistry develop as they acquire knowledge and skills from both the lecture and laboratory portions of the course. Traditionally, problem-solving ability in lecture is associated with two types of skills: algebraic skills applied to topics such as stoichiometry (Herron & Greenbowe, 1986; Niaz, 1989), and spatial skills applied to atomic and molecular structures (Carter, LaRussa, & Bodner, 1987; Gabel & Sherwood, 1980). Conversely, the laboratory portion of the course places emphasis on the development of skills such as laboratory technique and science process skills (Toh & Woolnough, 1993). Lecture demonstrations have been used to link lecture and laboratory problem-solving skills together in one lesson, however, valuable lecture time is consumed and active problem-solving skills may not be developed (Causey, 1987).

Computer-simulated experiments, CSE's, can be used as a replacement for laboratory experiments when the objective is to provide decision-making practice or to teach scientific principles (Cavin, Cavin, & Lagowski, 1978; Rivers & Vockell, 1987). Furthermore, CSE's may be more efficient than traditional laboratory experiments in teaching scientific processes or thinking (Jackman, Mollenberg, & Brabson, 1987; Lagowski, 1987; Lunetta & Hofstein, 1981; Rivers & Vockell, 1987). These goals should be optimized when a guided-discovery instructional design (Gagne & Merrill, 1991; Reigeluth & Schwartz, 1989) is used to teach the empirical approach to problem-solving activities (Rivers & Vockell, 1987). The theoretical basis for this approach combines the discovery method of Burner (1971) with the conditions of learning of Gagne (1985), which describes the pedagogic relationships between the external conditions (instruction) and the learner's internal processes while allowing for individual differences. The interactive medium of computer-based instruction can provide all of the attributes for guided discovery learning, such as student control options, guidance in learning, various types of feedback, and branching based on student self-evaluation of performance (Gagne, Wager, & Rojas, 1981; Martin & Szabo, 1990).

Two instructional sequences, inductive and deductive, can link together empirical data and scientific principles. In the deductive sequence, the principle is presented to the learner who then applies it to a given specific problem situation, whereas in the inductive sequence, the learner discovers the principle after interacting with several specific situations within the domain of that principle. Using a single high school chemistry lesson on stoichiometry, Hermann and Hincksman (1978) found that the deductive-treatment group scored significantly higher than the inductive group on the immediate retention test, but their superiority disappeared on the delayed retention test. Sakmyster (1974) found no significant main effects due to instructional method on the immediate or delayed tests of achievement on the concept of chemical equilibrium. She found several significant interactions between method and student abilities (reading ability and algebra ability). Thus, aptitude-treatment interactions may merit further study.

The cognitive-developmental level of students can affect their problem-solving ability, in general, and chemistry achievement, in particular. Several studies have found that formal reasoners achieve significantly more than concrete reasoners in both high school chemistry (Howe & Durr, 1982; Morris, 1991) and in college-level chemistry courses (Ward & Herron, 1980).

Gender differences in science achievement in favor of the males have been found in several large studies and reviews (Becker, 1989; Humrich, 1989; Steinkamp & Maehr, 1984). This difference increases with age, beginning with adolescence, and it is largest in physics and chemistry (Boli, Allen, & Payne 1985) with a slight difference in biology. The origin of this achievement difference appears to be related to a cluster of factors: spatial ability (Linn & Petersen, 1985; Zimowski & Wothke, 1987), previous experiences (Linn, DeBenedicts, DeLucchi, Harris, & Stage, 1987; Piburn & Baker, 1989), and personality traits (Martinez, 1992).

The instructional method used in teaching science may interact with the gender differences in science achievement. Girls, but not boys, benefit from verbal information given in a discovery situation (Ogunyemi, 1971). However, Sakmyster (1974) found no significant differences due to inductive or deductive method. Staver and Halsted (1985) found a three-way interaction of reasoning, method (model usage and no usage), and gender on achievement in chemical bonding. When models were used, high-reasoning females achieved more than lower-reasoning females, but when no models were used, lower-reasoning females outperformed higher-reasoning females. Higher-reasoning males did better than lower-reasoning males regardless of whether or not models were used. On mathematical problem-solving performance measures, Garrard (1982) found that females benefitted from visual adjuncts while males did not. In summary, females seem to be more affected by instructional method than males, and they tend to prefer more verbal or visual information than do males.

Purposes

The primary purpose of this research report was to determine the effect of inductive and deductive instructional sequences in a set of computer-simulated experiments on chemistry achievement and gain in reasoning ability. Secondary purposes were to determine the effects of a subject's gender, cognitive-developmental level, and any interactions between the main effects on the dependent variables. Given an entire semester of simulated experiments, it was expected that the inductive group would outperform the deductive group on the problem-solving dependent variables. Formal-level subjects should achieve more than transitional subjects who should, in turn, achieve more than concrete-level subjects. Males should achieve higher than females, but females should be more affected by any interactions with instructional method. The overall goal was to improve the problem-solving abilities of students by giving them the needed prerequisite skills and knowledge, letting them practice with guidance and feedback during the CSE's, and evaluating their *transfer* of acquired abilities on the problem-solving measures of the comprehensive final examination.

Procedures

This research report was conducted in three stages: the *pilot study*, revision of the simulations, and the *main study*. All of the instructional materials, procedures and statistical analyses were designed (or selected), developed, and implemented by the authors.

Instructional Materials

The pedagogic purposes for inclusion of the computer-simulated experiments, CSE, in Chem 301, Introductory General Chemistry, were to give students experience at empirical decision-making and to teach the empirical basis for the most important chemical principles taught in their lecture section. For logistical reasons this course does not include a corresponding laboratory section, thus students first exposure to college chemistry lacks inclusion of the experimental component of the discipline. The topics of the 10 computer-based lessons covered a wide range of topics normally taught in the first semester course, Figure 1. Six computer-simulated experiments were designed to link empirical phenomena to principles taught in the lecture hall and 4 programs provided tutorial problem-solving practice.

As shown in Figure 2, the computer-simulated experiments actively engaged students in the three stages of scientific investigation: *organize* a problem-solving strategy in the Pre-lab Stage, *execute* the strategy in the Experimental Stage, and *evaluate* their results in the Post-lab Stage. The students were thus actively involved in most of the 12 heuristics of scientific investigation (Suits, 1986,1992). The guided discovery approach (Bruner, 1971; Gagne, 1985; Landa, 1976) was selected because it provides only the essential instructional prerequisite knowledge and guidance (external conditions) to allow the learning (internal conditions) of problem-solving skills and strategies. The extent of learning varied among students due to their individual differences, but nearly all were able to attain at least a minimal level of competency as indicated by the post-lab evaluation stage of the CSE.

The investigators used a think aloud approach in which experts and novices articulated their frustrations and/or reasoning strategies while responding to the instructional frames of a simulation. Modifications were then made as needed to allow novices to be challenged but not overwhelmed when processing the prerequisite knowledge needed to solve the problem posed in the simulation.

Procedures, Pilot Study

The subjects for the *pilot study*, $N = 428$, were all enrolled in the same lecture section of Chem 301 at a large state university in the Southwest. Each subject was randomly assigned to one of three groups, inductive-simulation, deductive-simulation, and control-CAI group (tutorial computer-assisted instructional units). The simulation groups alternated with the control group in using the computers on a two-week cycle over the entire semester. When a group was not using the computer, students were given pencil-and-paper homework assignments. During the first week of the semester, a reasoning instrument, the IARC (see *Instrumentation, Reasoning Ability* in the next section), was used to determine the cognitive-developmental level of subjects who were classified in approximately equal-sized groups based on cutoff scores, i.e. 33.5 % of the sample were concrete-level reasoners (raw score below 33), 34.0 % transitional reasoners (33 to 36), and 32.6 % formal-level reasoners (above 36). The *pilot study* sample was 63.1 % male.

The dependent variables used in the *pilot study* were chemistry achievement and gain in reasoning ability. Chemistry achievement was measured by a subject's score on the comprehensive final examination in the course (see *Instrumentation, Achievement Measures).* The IARC was given as both the pretest (first week of semester) and the post-test (last week) with gain in reasoning ability being

Figure 1:
Computer-based Lessons for Introductory General Chemistry.

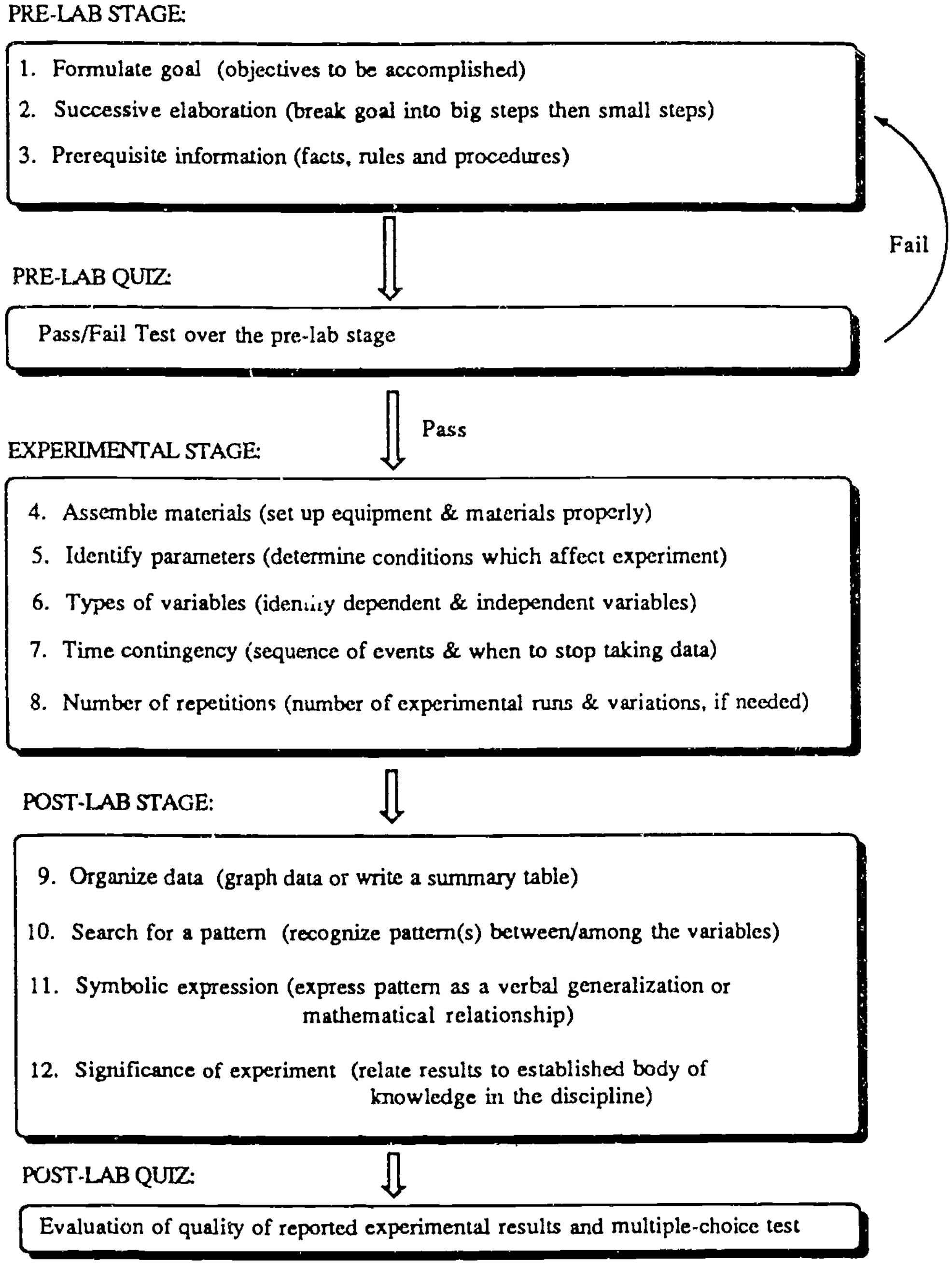
Title	Type	USAGE *Pilot Study*	 *Main Study*
CL # 1: Mixtures & Pure Substances	Simulation	*Ind & Ded*[*]	*Ind & Ded*
CL # 2: Combining Volumes of Gases	Simulation	*Ind & Ded*	*Ind & Ded*
CL # 3: Reactions of Chlorine	Tutorial	Control	- - - **
CL # 4: Atomic Structure	Tutorial	Control	- - - **
CL # 5: Ionization Potential	Simulation	*Ind & Ded*	*Ind & Ded*
CL # 6: Nature of Chemical Compounds	Simulation	*Ind & Ded*	*Ind & Ded*
CL # 7: Nature of Chemical Reactions	Tutorial	Control	*Ind & Ded*
CL # 8: Aqueous Solution Chemistry	Tutorial	Control	*Ind & Ded*
CL # 9: Identification of Metals	Simulation	All Groups	*Ind & Ded*
CL #10: Combustion of Organics	Simulation	All Groups	*Ind & Ded*

* *Ind & Ded* refer to the inductive- and deductive-simulation treatment groups, respectively

** CL #3 & 4 were not used in the *main study*

Figure 2:

The main stages of the computer-simulated experiments and the 12 heuristics of scientific investigation (Suits, 1986, 1992).



PRE-LAB STAGE:

1. Formulate goal (objectives to be accomplished)
2. Successive elaboration (break goal into big steps then small steps)
3. Prerequisite information (facts, rules and procedures)

PRE-LAB QUIZ:

Pass/Fail Test over the pre-lab stage

EXPERIMENTAL STAGE:

4. Assemble materials (set up equipment & materials properly)
5. Identify parameters (determine conditions which affect experiment)
6. Types of variables (identify dependent & independent variables)
7. Time contingency (sequence of events & when to stop taking data)
8. Number of repetitions (number of experimental runs & variations, if needed)

POST-LAB STAGE:

9. Organize data (graph data or write a summary table)
10. Search for a pattern (recognize pattern(s) between/among the variables)
11. Symbolic expression (express pattern as a verbal generalization or mathematical relationship)
12. Significance of experiment (relate results to established body of knowledge in the discipline)

POST-LAB QUIZ:

Evaluation of quality of reported experimental results and multiple-choice test defined as post-test minus pretest. Many subjects, 40.9% of the class, did not participate in all three data gathering stages, especially in the IARC post-test, thus their data could not be used in the statistical analysis. Results of a statistical method to determined effects of experimental mortality (Jurs & Glass, 1971) indicated that the study possessed internal validity (similar characteristics among dropped and retained subjects in the treatment groups, the genders and reasoning groups) but not external validity (generalization from the study sample, *N* = 254, to the original sample, *N* = 428).

A 3 x 3 x 2 factorial design was used in the *pilot study.* The three factors were instructional method (inductive-simulation, deductive-simulation, and control-CAI group), cognitive-developmental level (concrete, transitional, formal), and gender (male, female). The following null hypotheses were generated to determine the main effects and interactions upon the dependent variables (chemistry achievement and gain in reasoning ability):

1. There are no significant differences between inductive-simulation, deductive-simulation and control-CAI instructional methods on the dependent variables.
2. There are no significant differences between concrete, transitional, and formal subjects on the dependent variables.
3. There is no significant difference between male and female subjects on the dependent variables.
4. There is no significant interaction between instructional method and cognitive-developmental level on the dependent variables.
5. There is no significant interaction between instructional method and gender on the dependent variables.
6. There is no significant interaction between cognitive developmental level and gender on the dependent variables.

These null hypotheses were investigated using the analysis of variance, ANOVA, statistical method with the .05 alpha level selected. The ANOVA procedure of the *Statistical Analysis System,* SAS (Helwig & Council, 1979) was used with the MANOVA option which tests for overall effects on more than one dependent variable.

Revision of the Simulations

In the time period between the two studies (spring and summer), the simulations were revised to increase their effectiveness as self-instructional units. Briefly, the simulations were redesigned to blend the characteristics of CAI, which facilitate student learning, with the characteristics of meaningful problem-solving, which allow student participation in activities resulting in an understanding of chemical principles. The scheduling format was changed from one-hour session followed by a half-hour session the next week to three half-hour sessions per simulation. This change gave students time to think about what they learned in the pre-lab session and to speculate on the simulated experiment and subsequently on the post-lab analysis before interacting with these latter stages. The success criterion for the revised simulations was as follows: If the same format and sequence are used repeatedly to solve different content problems over a period of time, then students can internalize those cognitive structures which could allow them to do open-inquiry problem solving.

Procedures, Main Study

The *main study*, conducted one year after the *pilot study*, also used subjects, *N* = 438, from an intact lecture section of Chem 301. Subjects were randomly assigned to either the inductive- or deductive-simulation groups. They were not aware of their assignment to the groups, and instruction was identical in all aspects except for the instructional sequence within the series of CSE's over the entire semester. During the first week of the semester, the IARC reasoning instrument was used to determine the cognitive-developmental level of subjects based on the cutoff scores from the *pilot study*, i.e. 28.2 % of the sample were concrete-level (raw score below 33), 37.2 % transitional (33 to 36), and 34.6 % formal-level reasoners (above 36). The *main study* sample was 66.4 % male.

The dependent variables used in the *main study* were chemistry achievement and gain in reasoning ability. Chemistry achievement was measured by three cognitive levels (dependent variables) on the comprehensive final examination (see *Instrumentation, Achievement Measures).* As in the *pilot study*, many subjects, 57.3% of the class, did not participate in all three data gathering stages, especially in the IARC post-test. The results on the effects of experimental mortality (Jurs & Glass, 1971) also indicated that the *main study* possessed internal validity but not external validity (generalization from the study sample, *N* = 187, to the original sample, *N* = 438).

A 2 x 3 x 2 factorial design was used in the *main study*. The three factors were instructional method (inductive-simulation, deductive-simulation), cognitive developmental level (concrete, transitional, formal), and gender (male, female). The null hypotheses for the *main study*: (1) were identical to those listed for the *pilot study* with the exception of the first hypothesis, i.e. no control-CAI group was used in the *main study*; and (2) were used to determine the main effects and interactions upon the four dependent variables described in the above paragraph. The *main study* used the same statistical procedures and alpha level as the *pilot study*.

Instrumentation

Instrumentation, Achievement Measures

In both studies, the course final examinations included test items from a standardized test (Wolfe & Heikkinen, 1979), the Test of Higher Cognitive Learning in Chemistry (THCLC). The THCLC incorporated four levels of the cognitive domain with the highest level combining analysis, synthesis and evaluation (Wolfe & Heikkinen, 1979). The validity of the THCLC was based on the construct of "student understanding of chemistry" (3 higher levels) within the content areas normally covered in introductory general chemistry. The construct validity of the THCLC has been reported (Wolfe & Heikkinen, 1979).

For the comprehensive final examination in the *pilot study*, the course instructor combined 31 THCLC items with 19 items that he wrote. The intact THCLC was not used because some THCLC items were not listed among the topics covered in the course syllabus (e.g. the gas laws), and many of the instructor-written items covered topics not included on the THCLC (e.g. molecular geometry). The resulting instrument emphasized problem-solving and understanding, 78 % of the test items, rather than memorization and low-level comprehension, 22 %. The criterion measure for chemistry achievement was percentage correct on the entire final examination.

The comprehensive final examination used in the *main study* also included both instructor-selected THCLC items, 16 items, and instructor-written items, 32 items. Chemistry achievement was partitioned into three levels: lower cognitive, 10 % of test items (knowledge and comprehension), middle cognitive, 63 % (application), and higher cognitive, 27 % (analysis, synthesis and evaluation). The criterion measure was percentage correct for each level of achievement. Higher-cognitive items were more difficult than middle-cognitive items which, in turn, were more difficult than lower-cognitive items. Both problem-solving measures (middle- or higher-cognitive items) had higher item discrimination means that did the lower-cognitive items . Low correlations between each of the three cognitive level subtests in the final examination suggests that the subtests are relatively independent and, thus, measure different constructs. These results are very similar to the results reported for the original THCLC (Wolfe & Heikkinen, 1979).

Instrumentation, Reasoning Ability

The reasoning instrument used in these studies was the *Inventory of Attitudes and Reasoning Characteristics*, IARC. Its purpose was two fold: (1) to distinguish between concrete- and formal-thinking subjects in the Piagetian sense, and (2) to further distinguish between formal-level subjects who are capable and not capable of applying their formal thinking to problems presented in either a verbal-logic or a verbal-mathematical context. To accomplish the first purpose, half of the items (36 of 72 items) on the *Inventory of Piaget's Developmental Tasks*, IPDT (Milakofsky & Patterson, 1979) were incorporated into the IARC. The second purpose was accomplished by selection of 9 items from the 27 item *Practice in Thinking Test*, PTT (Good, Mellon, Kromhout, 1977). This combination should overcome the limitations of the two component instruments, i.e., the IPDT items measure reasoning without the confounding variables of verbal and mathematical abilities, and the PTT items should eliminate the ceiling effect found with the IPDT for college-level subjects (Milakofsky & Patterson, 1979). Reasoning ability was measured by raw score on the combined segments rather than by classification of subjects based on Piaget's construct.

The IARC instrument used in this research report consisted of 36 items from the IPDT and 9 items from the PTT. For both studies data from the IARC pretest of the pilot-study subjects, *N* = 433, was used to classify subjects into reasoning-ability groups. The raw scores of *pilot study* subjects on the 45 items were ranked from highest to lowest score and were divided into three equal-sized groups (See *Procedures, Pilot Study).* These same cutoff values were used in the *main study.*

The descriptive statistics for subjects in the two studies were as follows: (1) for the *pilot study*, the mean was 34.30 (76.22 %) with a standard deviation of 4.27, and (2) for the *main study*, the mean was 34.19 (75.98 %) with a standard deviation of 3.42. Males scored slightly higher than females in the *pilot study* (male *M* = 35.12; female *M* = 33.05) and in the *main study* (male *M* = 34.53; female *M* = 33.48).

The reliability of the IARC was established using a coefficient of internal consistency (even and odd, r = 0.7863) and rational equivalents (KR-21, r = 0.5651). A second measure of internal consistency was determined (r = 0.8492) for a test-subtest (an "early formal" 10-item subtest) measure of reliability. The validity of the IARC as a reasoning ability measure was assumed to roughly correspond to the validities of the two component instruments, the IPDT and the PTT. The construct validity of the IARC was based on its two-fold purpose, as described above, in which the construct was the reasoning ability of college students. When confronted with a new subject matter area (Chiappetta, 1976; Herron,1978) or a deeper level of a familiar subject formal-level students tend to regress to a concrete mode of reasoning. Thus, it follows that transitional or early formal thinkers should be more likely to regress than those who possess a greater degree of formal thinking across a wider set of contexts.

Results

Pilot Study

The multivariate and univariate analysis of variance results for the *pilot study* are shown in Table 1. Cognitive-developmental level produced the only significant F-values for both MANOVA and ANOVA. Formal-level subjects (*n* = 91, *M* = 64.28) achieved significantly higher than transitional subjects (*n* = 90, *M* = 51.07), who, in turn, scored higher than concrete-level subjects (*n* = 73, *M* = 44.60). Concrete-level subjects (*M* = +1.42) exhibited a significantly greater gain in reasoning ability than did the transitional- (*M* = -0.53) or formal-level subjects (*M* = -0.79). In regard to gender differences, male subjects (*n* = 167, *M* = 55.48) scored significantly higher than female subjects (*n* = 87, *M* = 50.98) on the chemistry achievement final examination measure (ANOVA, Table 1).

An interaction effect between instructional method and cognitive-developmental level approached significance for the univariate ANOVA on gain in reasoning (Table 1). Concrete-level subjects in the inductive group (*n* = 23, *M* = +2.61) showed a greater gain in reasoning ability than those in the deductive group (*n* = 22, *M* = +1.32) who, in turn, gained more than those in the control-CAI group (*n* = 28, *M* = +0.54).

Table 1
Multivariate and Univariate Analysis of Variance for the Pilot Study

	MULTIVARIATE				*UNIVARIATE* ANOVA				
Source	df	*F*	Significance of *F*		df	SS	*F*	Significance of *F*	
Method	4	0.45	0.7707	NS					
Final Exam					2	107.10	0.19	0.8298	NS
Gain in Reasoning					2	13.13	0.75	0.4723	NS
Level	4	22.48	0.0001	* *					
Final Exam					2	16826.90	29.34	0.0001	* *
Gain in Reasoning					2	229.72	13.16	0.0001	* *
Gender	2	2.31	0.1012	NS					
Final Exam					1	1162.45	4.05	0.0452	*
Gain in Reasoning					1	3.18	0.36	0.5469	NS
Method x Level	8	1.35	0.2187	NS					
Final Exam					4	529.24	0.46	0.7640	NS
Gain in Reasoning					4	77.46	2.22	0.0676	NS
Method x Gender	4	0.63	0.6443	NS					
Final Exam					2	62.16	0.11	0.8973	NS
Gain in Reasoning					2	17.19	0.98	0.3751	NS
Level x Gender	4	0.23	0.9183	NS					
Final Exam					2	0.00	0.00	1.0000	NS
Gain in Reasoning					2	7.60	.44	0.6477	NS
Residual									
Final Exam					240	68815.72			
Gain in Reasoning					240	2094.72			

* Significant at 0.05 level   ** Significanct at 0.0001 level

Main Study

The multivariate and univariate analysis of variance results for the *main study* are shown in Table 2. Only cognitive-developmental level produced significant F-values for both MANOVA and ANOVA. On gain in reasoning ability, concrete-level subjects (*n* = 51, *M* = +0.96) outgained transitional subjects (*n* = 85, *M* = +0.42) who, in turn, outgained the formal-level subjects (*n* = 51, *M* = -0.12). On middle-cognitive achievement, formal reasoners (*M* = 51.90) outscored concrete reasoners (*M* = 45.08) but not transitional reasoners (*M* = 48.94). All other main effects and interaction effects were not significant.

Discussion

Primary Purpose

The primary purpose of this research report was to determine the effect of inductive or deductive instructional sequence (method) in a set of computer-simulated experiments on the dependent variables used in these two studies. On the chemistry achievement variables, instructional sequence did not produce any significant main effects or interactions in either study. In other studies involving effects of sequence on chemistry topics, Sakmyster (1974) also found no main effects, whereas Hermann and Hincksman (1978) noted that the superior performance of the deductive group on the immediate retention measure disappeared on the delayed retention test.

On the gain in reasoning ability variable, instructional sequence produced a method-level interaction which approached significance in the *pilot study* (Table 1). Concrete reasoners in the inductive group posted a larger gain in reasoning (*M* = +2.61) than their counterparts in the deductive group (*M* = +1.32) who, in turn, out-gained those in the control group (*M* = +0.54). Other studies have also reported gains in reasoning ability due to inquiry treatment (Marek, 1981) or learner control (Wirt, 1987) over the gains of the respective control groups.

In these studies a confounding variable may have lessened any treatment effects because the inductive and deductive subjects intermingled within the computer lab room. Obviously, an improved experimental design would involve a multi-section class in which each lab/recitation section is assigned to a particular treatment group rather than mixing the groups within the same section.

Secondary Purposes

In regard to the secondary purposes, the subjects' gender or reasoning ability produced several significant differences on the dependent variables. In the *pilot study*, there were significant differences on the final examination measure of chemistry achievement due to reasoning level and gender (Table 1). Formal reasoners (*M* = 64.28) outperformed transitional reasoners (*M*= 51.07) who, in turn, scored significantly higher than the concrete reasoners (*M* = 44.60). This result is expected because many of the concepts and problem-solving applications in chemistry require abstract thought (Chandran, Treagust & Tobin, 1987; Keig & Rubba, 1993; Sawyer, 1986; Lawson, McElrath, Burton, James, Doyle,

Table 2

Multivariate and Univariate Analysis of Variance for the Main Study

	MULTIVARIATE				UNIVARIATE				
Source	df	*F*	Significance of F		df	ANOVA SS	*F*	Significance of F	
Method	4	0.54	0.7053	NS					
Lower Cognitive					1	431.82	0.93	0.3350	NS
Middle Cognitive					1	39.10	0.13	0.7166	NS
Higher Cognitive					1	141.32	0.39	0.5312	NS
Gain in Reasoning					1	15.48	1.41	0.2364	NS
Level	8	1.94	0.0537	*					
Lower Cognitive					2	338.25	0.37	0.6940	NS
Middle Cognitive					2	1196.72	2.02	0.1353	NS
Higher Cognitive					2	573.93	0.8	0.4512	NS
Gain in Reasoning					2	119.32	5.44	0.0051	*
Gender	4	1.82	0.1273	NS					
Lower Cognitive					1	1419.47	3.07	0.0814	NS
Middle Cognitive					1	50.17	0.17	0.6810	NS
Higher Cognitive					1	784.60	2.19	0.1411	NS
Gain in Reasoning					1	0.25	0.02	0.8807	NS
Method x Level	8	0.56	0.8138	NS					
Lower Cognitive					2	0.00	0	1.0000	NS
Middle Cognitive					2	0.00	0	1.0000	NS
Higher Cognitive					2	482.26	0.67	0.5121	NS
Gain in Reasoning					2	20.10	0.92	0.4018	NS
Method x Gender	4	0.71	0.5864	NS					
Lower Cognitive					1	189.40	0.41	0.5228	NS
Middle Cognitive					1	285.28	0.96	0.3274	NS
Higher Cognitive					1	255.32	0.71	0.4002	NS
Gain in Reasoning					1	13.73	1.26	0.2638	NS
Level x Gender	8	1.47	0.1661	NS					
Lower Cognitive					2	716.04	0.77	0.4623	NS
Middle Cognitive					2	1021.25	1.73	0.1809	NS
Higher Cognitive					2	913.09	1.27	0.2829	NS
Gain in Reasoning					2	14.59	0.67	0.5154	NS
Residual									
Lower Cognitive					177	81785.89			
Middle Cognitive					177	52354.64			
Higher Cognitive					177	66685.23			
Gain in Reasoning					177	1940.99			

* Significant at 0.05 level

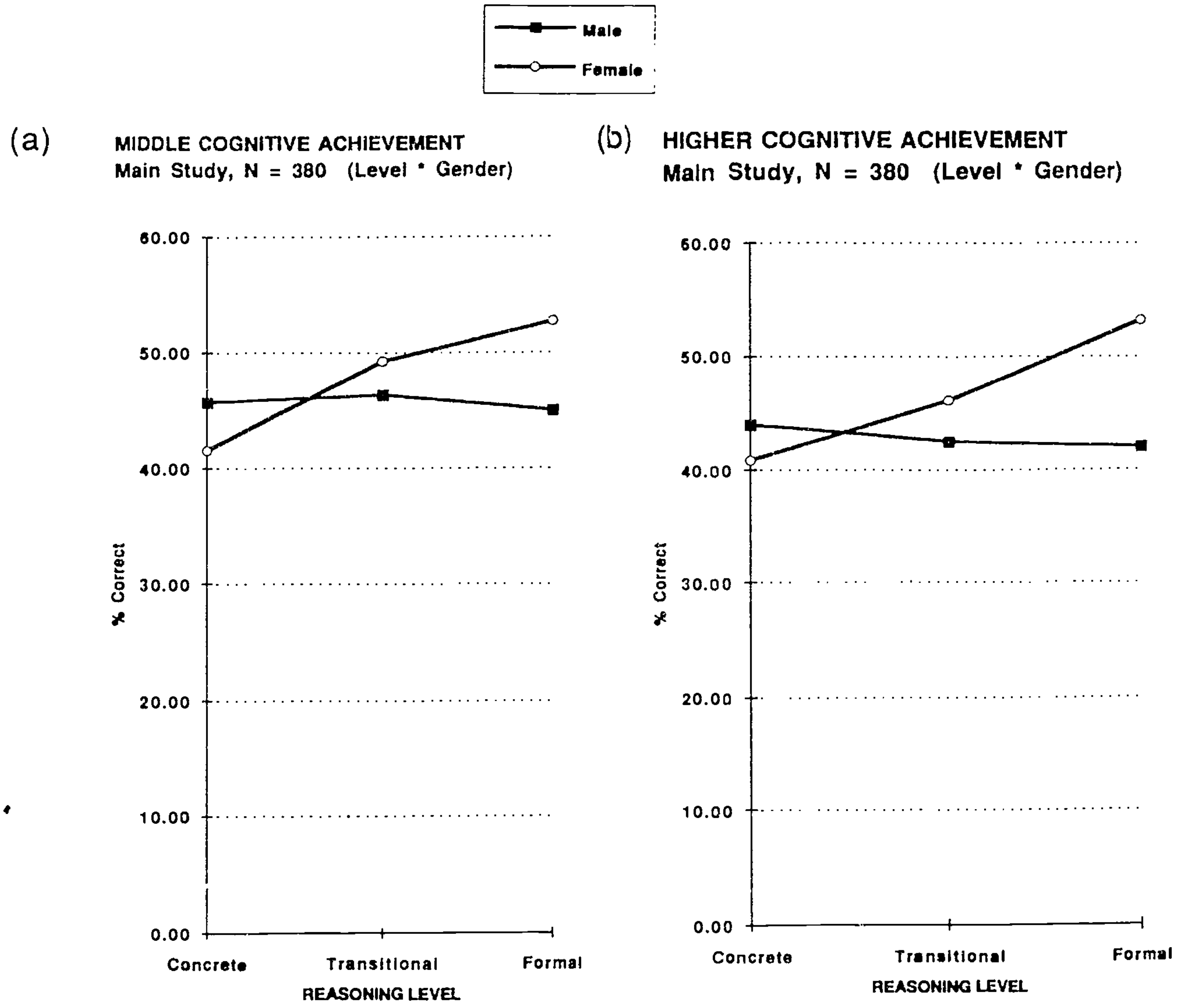
Woodward, Kellerman, & Snyder, 1991; Wirt, 1986). *Pilot study* males ($M = 55.48$) outperformed females ($M = 50.98$) on the final examination measure of chemistry achievement as expected from the reported results of several large national and international studies. However, it is interesting to note that this difference tended to be due to the superior performance of the transitional-thinking males ($n = 54$, $M = 52.22$) over their female counterparts ($n = 32$, $M = 48.94$) because the means of males and females in each of the two other groups, i.e., concrete reasoners or formal reasoners, were essentially equal.

In the *main study*, the females equaled the males on middle cognitive problem-solving achievement (Table 2). On higher cognitive items, females ($n = 73$, $M = 49.26$) score higher than males ($n = 114$, $M = 45.06$) although not at a significant level (Table 2). These problems require reasoning ability and other non-algorithmic skills for successful solutions. It is noteworthy that the higher-cognitive means for transitional- and formal-thinking females ($M = 49.39$ and 56.93, respectively) tended to be higher than that of their male counterparts ($M = 45.42$ and 45.58, respectively) although not at a significant level.

To determine whether this unusual tendency in gender differences was spurious or valid, a separate analysis ($N = 380$) was performed with the larger sample, which included the examination scores of those subjects dropped ($n = 193$) from the study due to missing post-IARC test scores. A significant reasoning level-gender interaction was found (MANOVA, $F(6,734) = 2.51$, $p = 0.0207$). As shown in Figure 3(a), the middle-cognitive achievement (ANOVA, $F(2,370) = 3.91$, $p = 0.0209$) of females progressively increases from concrete- ($n = 61$, $M = 41.51$) through transitional- ($n = 30$, $M = 49.23$) to formal-reasoners ($n = 34$, $M = 52.68$), whereas the achievement of males remains constant over all three reasoning levels (concrete $n = 82$, $M = 45.70$; transitional $n = 80$, $M = 46.31$; and formal $n = 93$, $M = 44.95$). As shown in Figure 3(b), this same interaction pattern was found for higher-cognitive achievement (ANOVA, $F(2,370) = 4.92$, $p = 0.0078$) in which female scores increased with level (concrete $M = 40.82$; transitional $M = 46.13$; and formal $M = 52.15$), whereas male scores registered a slight decline with increase in reasoning level (concrete $M = 43.99$; transitional $M = 42.52$; and formal $M = 42.01$). Apparently, the nonconcrete-thinking females could successfully apply their reasoning skills within a chemistry problem-solving context, whereas the males could not apply theirs.

No published study has found this reversal of the expected gender differences in general chemistry courses at the university level. The only studies of chemistry achievement that have reported superior female achievement were found at the ninth grade level on immediate retention (Hermann & Hincksman, 1978) and at a high school in Thailand (Klainin, et al., 1989). Conversely, at the university level, Carter, LaRussa, & Bodner (1987) reported superior male achievement in one section and no differences achievement in the other section at Purdue University. While noting a larger rate of female attrition, Sieveking and coworkers (Sieveking & Larson, 1969; Sieveking & Savitsky, 1969) found no significant differences in achievement *($N = 707$)* as measured by a standardized pretest and college

Figure 3:
Main study (*N* = 380) achievement interaction between reasoning level and gender for (a) middle-cognitive achievement items, and (b) higher-cognitive achievement items.



course grade at Vanderbilt University. In a recent study, Suits (unpublished data) found that the males ($n = 228$, $M = 53.42$) scored significantly higher ($t = 2.31$, $p = 0.02$) than the females ($n = 127$, $M = 49.09$) on a comprehensive final examination at Southern Illinois University at Carbondale. Among high ability males and females (Boli et al., 1985) enrolled in the first quarter of general chemistry at Stanford University, males received higher grades than females ($M = 3.00$ and 2.60, $t = 6.39$, $p < .01$), but when they controlled for SAT mathematics score and same sex role model (subject's high school chemistry teacher) this difference was reduced to zero. At the high school level, Keig and Rubba (1993) also found that when factors such as reasoning ability, spatial ability, and prior knowledge were factored out that the gender effect on chemistry achievement was reduced to near zero.

Several factors discourage females in science courses at the college/university level. First, when faced with the same learning environmental stimuli, males and females exhibit distinctly different physiological responses (Dunn & Reddix, 1990) or learning styles (Baxter-Magolda, 1988). Second, stimuli in complex scientific subjects may encourage males to enhance their reflective learning strategies while discouraging most females especially those who employ more concrete-type learning styles (Baxter-Magolda, 1988). This feminine style may have developed during elementary school due to the differential perceptions of female teachers (Shepardson & Pizzini, 1992) and parents (Raty & Snellman, 1992) that may result in the differential prior instruction and science achievement (Linn et al., 1987). Third, beginning with adolescence when the sexes develop their identities with regard to college majors and careers, males and females generally consider chemistry, along with physics and mathematics, to be a male domain that is competitive (Hollings, 1991), which further discourages females (Kerr, 1989).

In summary the females were attempting to succeed in a male-dominated discipline, chemistry, given a slight disadvantage in reasoning ability and a large disadvantage in social acceptability. However, they were in possession of the prior knowledge (82.55% took high school chemistry) needed to compete with their male classmates (80.20%), and the CAI learning environment may have benefitted them (Petersen, Johnson, & Johnson, 1991) rather than force them to adapt to a learning style which typically triggers distinct male patterns of problem-solving success.

Instructional Structure

A comparison of the results of these two studies suggests that the difference in structure of the simulations between the studies may have differentially affected males and females and the three types of reasoners. In the *pilot study*, the more implicit structure (larger steps between instructional frames/sections) of the CSE's may have contributed to the expected differences in problem-solving abilities in which males outperformed females and formal reasoners outperformed transitional reasoners who, in turn, outperformed concrete reasoners. The CSE's in the *pilot study* apparently challenged students in a manner similar to the way in which lecture material in general chemistry traditionally challenges students. Thus the expected results of higher achievement by males and formal reasoners over their respective counterparts was obtained.

Conversely, in the *main study*, the more explicit, systematic structure (Reif, 1987) of the CSE's (smaller instructional steps and clearer organization of instructional components) may have allowed females and concrete reasoners to learn chemistry problem-solving skills without being frustrated by missing information or strategies (McKenzie, 1979), which can obscure the empirical-abstract relationships. An explicit strategy in the *main study* CSE's may have allowed females and concrete reasoners to participate in problem-solving conceptualization, whereas the presented strategy was of less value to formal-reasoning males, who may have preferred a self-generated generic but less powerful strategy. In other words, during the formative stages of instruction and evaluation, if females and concrete reasoners are given instruction with an explicit cognitive structure taught within a supportive, cooperative learning environment (Dickman, 1991; Petersen et al., 1991), they can learn to solve relatively complex chemistry problems (Linn, 1983) . Upon encountering complex problems in the summative stages of evaluation, they can use their problem-solving abilities on a level comparable to the traditionally successful males and formal reasoners (Ayoubi, 1986).

Instruction and Cognitive Styles

Four implicit statements are necessary to establish the causality between the instructional structure of the CSE's and chemistry achievement on the final examination: (1) The direct learning outcomes of the CSE's focused on the use of empirical *cognitive processes* to develop selected chemical principles, whereas chemistry problem-solving achievement was composed of specific *cognitive products* (i.e., mostly abstract applications of a variety of chemical concepts and principles). (2) An essential feature of problem-solving ability involves the transfer of information from the context of acquisition to different contexts of application (Perkins, 1987). (3) The conscious effort of the learner is necessary in seeking generalizations beyond the obvious cognitive processes of the CSE's to applications of a diverse array of chemical concepts and principles, i.e., high-road transfer (Perkins, 1987). (4) Females were able to overcome the well established disadvantages due to sociobiological factors (Hacker, 1992) such as differential collegiate social roles, and differences in spatial and numerical abilities, in order to excel in high-road transfer to an equal/greater extent compared to the males.

Evidence from several research studies supports the plausibility of each of these four statements. Female elementary school teachers perceive that their female students possess greater cognitive process skills, whereas the male students have higher cognitive intellectual skills, and this perception results in differential instructional treatment that usually results in greater science achievement for males (Shepardson & Pizzini, 1992). However, computer-based instruction (Hativa, 1988) can develop the cognitive skills of females through the guidance of precise feedback and multiple solutions (Hodes, 1984; Linn, 1983) that allows them to interact in a complex, changing environment. Thus, the explicit structure of the CSE's may have provided the guidance that the females needed to develop their cognitive process skills while engaged in the mental manipulation of chemical phenomena/information which produced chemical principles that were meaningful to them because it matched their cognitive style (Stringfellow, 1975). This instructional advantage based on matching cognitive styles may not have extended equally to their male counterparts, who tend to rely on a more intellectual cognitive style (Baxter-Magolda, 1988), e.g. understanding abstract relationships with very few if any concrete referents. Therefore, the normal differential instructional advantage of the males (Linn et al.,1987) in science achievement may have been reversed by instruction which emphasized cognitive processes within a context rather than the decontextualized cognitive products normally taught and assessed in science courses. The females may have been able to transfer skills learned in the development of selected chemical principles (acquisition) to many other diverse principles (application) in a meaningful manner that matched their cognitive style.

Implications

The two studies of this research report should be viewed as exploratory studies in which the results suggest the need for a more sophisticated study in which the treatment variable includes all four types of simulations, i.e. inductive and deductive loosely structured simulations as well as inductive and deductive concretely/explicitly structured simulations. The optimal experimental design would necessitate the use of a large lecture section that is divided into a number of recitation sections with each treatment assigned to one section as the unit of analysis. The replacement of one of the dependent variables, gain in reasoning ability, with micro-level dependent variable(s), e.g. post-lab evaluation of simulations, would allow a more accurate determination of instructional effectiveness and its contribution to the multiple regression equation used to predict achievement. The post-lab evaluation, in turn, could be improved by the inclusion of a two-step process: (1) confronting a learner with the specific consequences of their incorrect solution strategy, and (2) having them explain or identify why their strategy was less effective or nonproductive.

In regard to gender and problem-solving simulations, some advocates of computers usage have based their arguments primarily on the cost-effectiveness of this form of empirical or conceptual investigation. They suggest having a group of students collaborate together and enter the consensus on one computer terminal. This idea runs counter to the results of this report in which females could listen to the dominant male (Barbieri & Light, 1992; Moody, 1991) and then accept or reject all or part of his logic when she entered her response on her own computer. The first author observed one such interaction in which the female simply and correctly stated that she was assigned a different sample of matter, and that his logic may apply to his specific sample but not necessarily to hers.

The extent to which these results were due to instructional factors may be attributed to the theoretical basis for these studies, i.e. an *interactive approach* (Borsook & Higginbotham-Wheat, 1991). This approach focuses on the interaction of the learner's cognitive structures (internal conditions) within an instructional context (external conditions) that can adapt to individual differences in both learning styles, e.g. gender differences, and cognitive abilities, e.g. reasoning ability. The criteria used to program these simulations were based on a synthesis of several theories of learning (Ausubel, Novak, & Hanesian, 1978; Bruner, 1971; Gagne, 1985; Landa, 1976; Mayer, 1983) and instructional design (Gagne et al., 1981; Gagne & Merrill, 1991; Reif, 1987; Reigeluth & Schwartz, 1989) rather than that of optimal programming efficiency in the computer science sense or the problem-solving efficiency of chemists who use a simulation as a problem-solving tool. Relative to the latter criteria, these simulations were inefficient and contained a large amount of verbal baggage. However, the resulting gender equality on problem-solving measures may have been due to these "verbal handles" (Ross, 1990) and "spatial pictures" (animated graphics) that allowed students to understand the problem (Nielsen, 1984) in all of its verbal and spatial dimensions.

In conclusion, the traditional instructional heuristic that the only way to "learn to problem solve" is to *solve problems without explicit guidance* (Bruner, 1973) during the formative stages only applies to students for whom a challenge is needed to engage them in the subject matter, i.e. formal-reasoning males. Meanwhile, females and concrete reasoners may benefit from a more explicit structure in which help is given as prerequisite knowledge, cues and feedback but only when needed to avert a nonproductive strategy which leads to an instructional dead-end. They can enhance their problem-solving abilities in a learning environment which is both supportive and flexible, i.e. can offer several alternative pathways based on the learner's decisions (learner control) or can adapt to the learner's characteristics (program control with advisement).

The implication of these results for science teaching is that simulated experiments can adapt to the diverse, conflicting learning needs of a variety of individuals who differ in reasoning ability and cognitive style, especially gender-related differences. That learners can be challenged to solve complex empirical-abstract chemistry problems with different adapted instructional pathways, based on initial input of their reasoning level and gender or cognitive style. This adaptability is not possible with conventional lecture presentations, textbook assignments or laboratory work.

The implication for future studies is that studies should integrate the use of two probes to evaluate student understanding and achievement: (1) an objective, quantitative probe which uses a complex experimental design to investigate potential aptitude-treatment interactions that may reveal an optimal pathway for each type of learner, and (2) the think-aloud technique in which the investigator(s) listens to how experts and novices/students conceptualize during their interaction with the instructional program and make changes in that program as needed. The development and evaluation of user-adapted simulated experiments is a worthwhile goal which should be a national priority for science education research.

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