Computerized Molecular Modeling as a Tool To Improve Chemistry Teaching

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The use of molecular models to illustrate and explore phenomena in chemistry teaching is widespread. However, only one type of model is usually used, and not enough emphasis is put on its meaning. The advantage of computerized molecular modeling (CMM) stems from the convenience and simplicity of building molecules of any size and color in a number of presentations. To expose chemistry teachers to the use of CMM we developed a 14 h workshop on models. It consists of an introduction to the model concept, using various types of models (including CMM) and experiencing ways to use them for illustrating chemical structure and bonding via team projects. This workshop has been incorporated into pre- and in-service training at the Department of Education in Technology and Science at the Technion since 1994. As a final project, teachers were asked to plan a session of 1−2 lessons by building a miniature database of molecules along with working instructions. The new methodology is based on using CMM through a special booklet, designed in a constructivist approach. During 1995, it was implemented in three tenth grade experimental classes with two other classes serving as a control group. Overall, teachers' attitudes toward using molecular modeling to improve chemistry teaching were favorable. The effect of using molecular modeling on students' understanding and constructing new concepts was investigated in relation to chemical structure and bonding as well as to geometric and symbolic representation. In two representative questions related to three-dimensional molecule structure, the experimental group performed better than the control group. Students' attitudes toward the use of CMM have also been found to be positive. Most of the students enjoyed using the new methodology and indicated it helped them understand concepts in molecular geometry and bonding.

INTRODUCTION

Alternative conceptions held by students who study chemistry seem to be associated with difficulties students have visualizing matter in terms of a particulate model (Garnet, Garnet, and Hackling[1]). The difficulties students experience are due to the abstract, unobservable, particulate basis of chemistry. Several authors have suggested using concrete models to help students visualize the particulate nature of matter (Gabel and Sherwood;[2] Garnet, Tobin, and Swingler;[3] Herron[4]). Indeed the use of models of molecules in chemistry teaching is widespread (Gabel and Sherwood[2]). It is aimed at simplifying, illustrating, and exploring chemical structure, phenomena, and processes in a stepwise fashion. The models are usually rigid, and their limited availability for students in the classroom restricts their use to the construction of only small molecules. The use of balls and sticks is common, but a limited number of ball sizes and colors is supposed to characterize all the elements. These limitations impose inaccuracies in bond lengths and angles between atoms in the molecule.

Many teachers who use models do not emphasize the fact that the models are a simulation of theory and that no molecule looks exactly like any one of the models. Teachers usually use only one type of model. Consequently, students' perceptions of the model are sometimes partial and wrong (Gilbert;[5] Ingham and Gilbert[6]). Furthermore, Johnstone[7] and Gabel[8] have pointed out the difficulties students have with rapid transfer between the three levels of thought—the macroscopic, submicroscopic, and symbolic. While chemists and chemical educators operate across the various levels quickly and easily, students have difficulties creating links across these levels and must therefore use models, analogies or computer graphics. Scientists are currently investigating molecular properties in organic chemistry, biochemistry, and drug industry with the aid of computer programs that simulate the molecular structure and calculate their properties (Glaser, Hug, and Michel[9]).

The advantage of computerized molecular modeling (CMM) over the use of rigid models lies in the fact that through the use of software, molecules of any size, number, and model type can be conveniently constructed, with each atom type having a different color pattern and a precise size, making the presentation more accurate. Atomic symbols can be added to (or removed from) the figure at will to enhance the model understanding. Indeed, several research groups have started to take advantage of this technology, especially with undergraduate students (Aduldeka, Akhter, Field, Nagle, O'Sullivan, O'Connor and Hathaway;[10] Campanario, Bronchalo, and Hidalgo;[11] Chapman;[12] Dori;[13] Moore[14]), and have shown a positive effect of students' increased understanding (Ziedler and McIntosh;[15] and Williamson and Abraham[16]).

These findings are supported by the constructivist learning theory, which proposes that students actively construct new meaning when they interact with physical events and phenomena (von Glaserfeld[17]). Millar[18] indicates that the most important change in the curriculum must be increasing the active involvement of students. Students' achievements and performance should be enhanced by modern technologies through the use of metacognitive strategies, where students reflect on their understandings and take responsibility for

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their learning (Gunstone[19]). The study presented in this report focuses on integrating computerized molecular modeling into chemistry teaching and learning in a constructivist manner. Through simulation students observe the particulate nature of matter in various representations. These activities challenge students to determine the generalizations by themselves and relate macroscopic, submicroscopic, and symbolic levels to each other.

RESEARCH AIMS

Our study had two objectives:

1. Exposing chemistry teachers to the use of CMM as a tool to improve chemistry teaching and examining their views and attitudes.
2. Implementing CMM in high school chemistry by using a constructivist learning approach and examining its effect on students' achievements and attitudes.

RESEARCH POPULATION

The research included two stages. The first stage involved teachers' training which consisted of pre- ($N = 30$) and in-service ($N = 40$) chemistry teachers.

In the second stage the new methodology was implemented in an urban high school in Haifa. It involved five classes ($N = 169$) of tenth graders (age 15). These students studied chemistry for the first year, and their science and mathematics qualifications were heterogeneous. The experimental group—three classes ($N = 97$)—worked on the subject of geometric shapes of molecules with the molecular modeling software and a special designed working booklet, while two other classes, which served as a control group ($N = 72$), studied the subject in the traditional way. Four teachers were involved in the research; two worked with the experimental group and the other two—with the control group. All four teachers were familiar with CMM, and the assignment to the experiment and control groups was done with their agreement.

RESEARCH METHOD

The "Bonding and Structure" subject is usually taught in schools by using the deductive method. Students learn the rules of the Valence State Electron Pair Repulsion Theory and then try to determine the basic shapes of exemplary molecules. Teachers use plastic ball and stick models for this purpose, but, as noted, there are usually not enough parts available for every student in the class and not enough types to distinguish among different atoms. Our new inductive approach is described in detail below. This approach has been implemented in pre- and in-service teachers training as well as in teaching chemistry in high school. In this section we describe the instructional material and research tools used in the study.

Instructional Material. The instructional material consisted of the CMM software and a specially designed working booklet for individual learning.

The CMM Software. The software tool used in the study was the "Desktop Molecular Modeler[26] (DTMM)" (Crabbe and Appleyard[20]), a PC-compatible package which enables three-dimensional molecule visualization through the use of red/green eyeglasses to view stereo paired lines display. It also provides colored lines, space filling, quick filling, and ball and stick representation options. The most powerful features of the software are molecular synthesis and energy minimization (Gulinska, Lewicki, and Burewicz[21]). The energy minimization routine optimizes the geometry of the newly created molecule by using an algorithm that calculates bond, angle, van der Waals, and charge energies to create a viable three-dimensional conformation. For every bond, DTMM minimizes the energy by rotating it in an effort to find a better conformation. The minimization process is shown both graphically, as the display changes, and in a box at the bottom of the screen which counts the number of iterations done. The minimization process takes a few minutes, and its length depends on the size of the molecule. The software is controlled through pull-down menus, which are easy to master. A special school version of DTMM has been designed and is available for a nominal fee. A computer laboratory session of 60−90 min is needed to become acquainted with the software. During the first session students view and manipulate familiar molecules.

The Working Booklet. As part of the research we have designed and written a self-study booklet, which fosters a constructivist learning approach of various geometric shapes of molecules. At first, students view four or five different molecules that share the same geometry. They then measure and compare bond angles and lengths. The student is asked questions of the following nature.

a. How many electron pairs surround the central atom of the molecule?
b. How many ligands are connected to the central atom?
c. How many nonbonding electron pairs are there?
d. Is there any symmetry in the molecule?
e. Do you think this molecule is polar or nonpolar?

Using these questions the student tries to find a common description of the structures by building their Lewis formulas.

These activities lead students to discover the rules of the Valence State Electron Pair Repulsion Theory and to explain whether molecules are polar or not when they change one or more ligands. Instead of telling students the theory, they construct their own theory. This is in accordance with the constructivist approach, which proposes that students actively construct new meaning by using their present conceptual frameworks to interpret new information they have received during their active involvement in the lesson (von Glaserfeld[17] and Millar[18]).

After each geometric shape is studied in this way, the student completes a worksheet containing questions or tables that summarize what has been studied so far. Some examples are presented in Chart 1.

Research Tools. The research tools included a teachers' views questionnaire on using CMM, a students' achievement test on structure and bonding, and students' attitude questionnaire.

Teachers' Views on Using CMM. An open questionnaire on using CMM was administered to the teachers following their workshops. Teachers were asked to list advantages and disadvantages of using computerized molecular modeling for teaching chemistry.

Students Achievement Test on Structure and Bonding. We have developed the Structure and Bonding Achievement Test to identify conceptual change and alternative concepts held by 10th graders. The test, which contains eight

Chart 1

Lesson No. 3.

Molecules whose central atom is from Col. 4 of the Periodic Table

1. Enter the library "Exercise" and load the molecule CH4. View the molecule in various representations available and rotate it in all the directions.
Do you think this molecule is symmetric? Explain.
Do you think this molecule has a three dimensional structure?
2. Measure the bond lengths and angles, and write them in your notebook. Do all the bonds have the same length? Are all the angles the same?

Conclusion:

In the molecule CH_4 the length of all C-H bonds is _____ Angstroms; all H-C-H angles are of _____ degrees.

A molecule in which four ligands are connected to the central atom, and the angles among the bonds are 109° has a tetrahedral structure.

* Repeat the same activities for the following molecules: CCl_4, $CHCl_3$, CH_2Cl_2, CH_3Cl.
* What is the shape of each molecule?
* Do all the C-H bonds have the same length?
* Do all the C-Cl bonds have the same lengt ?
* What, in your opinion, causes the difference in bond length between C-Cl and C-H?
* Is there a similarity in bond angles for all the four molecules?
* What is your conclusion from the data you have collected?
* Draw Lewis formulae for all the molecules you have examined.
* Is there a common Lewis structure to all the tetrahedral molecules ?
* Can you think of other molecules that may have a tetrahedral geometry ?

Fill in the missing sentences:

Each molecule that was built has _____ couples of bonding electrons around the _____ atom. Electron _____ part to create the _____ distance among them. When the central _____ is surrounded by _____ electron pairs they form a _____

questions, at the knowledge, comprehension, application, and evaluation levels of Blooms' [22] taxonomy focuses on the following five topics.

- ionic and covalent bonds
- polarity of a chemical bond
- molecule geometry and relation to polarity
- lattices
- inter- and intramolecular forces

Six of the eight questions in the test are multiple choice type and two are open ended. For each multiple choice question the student is also asked to provide an explanation. Each response was categorized and standardized such that the score for each question ranges between 0 to 2, hence the score for the entire questionnaire ranges from 0 to 16.

The content validity of the test items was established by a group of experts in chemistry and science education ($N = 5$) and by high school teachers ($N = 5$). The reliability was calculated and the α Cronbach coefficient for all the items was 0.91.

The two exemplary questions in Figure 1 deal specifically with the geometric shapes of molecules and consist of five items each. Question 1 requires the ability to relate the molecule's symbolic representation to its shape. The second question (question 8 in Figure 1) calls for identifying the graphic representation of five different molecules and determining their polarity.

Students' Attitude Questionnaire. Students in the experimental group responded to an attitude questionnaire which included the following two open questions.

1. Did you enjoy working with computerized molecular modeling? Explain
2. Do you think that the new method enhanced your understanding? Explain.

Students wrote whether they enjoyed working with CMM and expressed their opinion on the ability of this methodology to improve their understanding and achievements.

RESEARCH METHODOLOGY

The research consisted of two major stages: chemistry teachers training and implementation of the CMM approach within 10th grade chemistry curriculum.

Stage 1—Chemistry Teachers Training. Before teachers use CMM as a tool for chemistry teaching in their classrooms they have to become familiar with it (Dori and Barnea[23]). This can be done by integrating the study of CMM into preservice courses and conducting in-service training. To this end, we have developed a 14 h workshop on Models in Chemistry. The workshop consists of an introduction to the model concept through a discussion on different types of models, both physical (plastic, wood, metal) and computerized. Teachers learn about new ways to use models for illustrating chemical structure and bonding and familiarize themselves with the molecular modeling software.

We have incorporated this workshop into a 56 h chemistry teaching methodologies course and into in-service training at the Technion in the Department of Education in Technology and Science since Spring 1994 semester.

During the workshops, the pre- and in-service chemistry teachers use the existing molecule libraries to view and modify molecules. They rotate molecules (see Figure 2, for example), change their representation among ball-and-stick, space-filling, and cylindrical models (as in Figure 3), and use stereoview glasses to get a 3-D perception of molecules. They build and manipulate molecules by applying such operations as breaking bonds, lengthening or shortening them, changing, and deleting or joining atoms and molecule fragments. Using energy minimization, they are able to optimize the geometry of the newly created molecules. Following the minimization procedure, they examine the quantitative measurements of distances, angles, and torsion angles of the models they create and compare them to their prior knowledge. We found that even teachers are enthusiastic to be engaged in such activities as measuring different properties and solving related problems.

The teachers who took part in the study also worked using the specially designed self-study booklet prepared for the high school students. They provided feedback on the booklet as well as suggestions for additional exercises, which were very instrumental in the formative evaluation. The teachers' feedback on the booklet validated the subject matter, the activities, and the learning approach. Their recommendations were implemented and used later for improving the booklet.

As a final project, teachers were asked to plan a session of one to two lessons with the computerized software. The goal of this mini-project was to introduce teachers to the capabilities of CMM and encourage them to implement it in their classrooms by involving them in the creation of the working unit. Their task was to build a miniature database of molecules along with working instructions for using it in chemistry lessons. As subjects for their projects, the teachers chose a variety of topics taken from high school chemistry curriculum. These included molecular geometry, isomers of organic compounds, such as alkanes, alkenes, alcohols,

1. Point out which of the following molecules have a three dimensional structure and explain, either in a graphic or a verbal mode.

a. H_2S b. COF_2 c. SiF_4 d. PCl_3 e. HCN

8. Name each of the following geometric shapes and state if the molecule is polar or nonpolar.

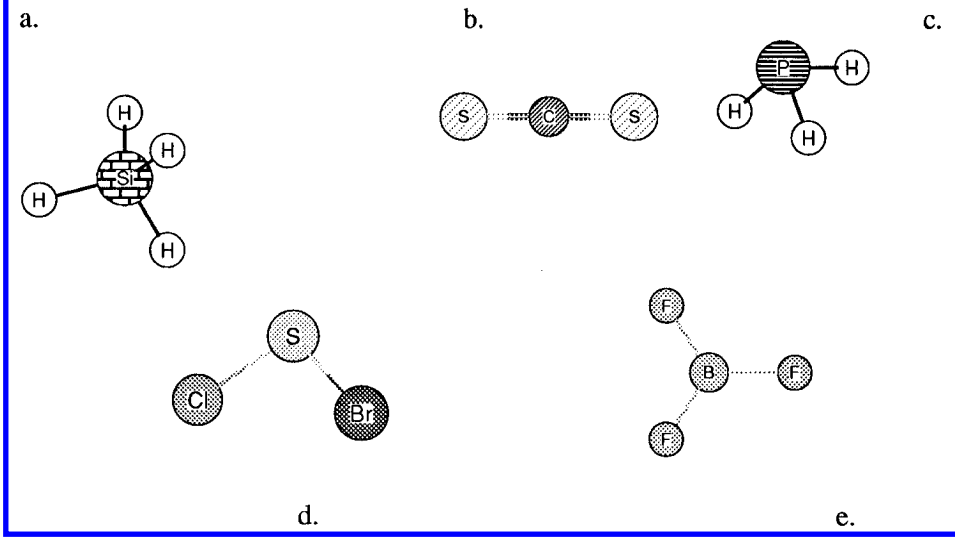

Figure 1. Two exemplary questions from the final exam.

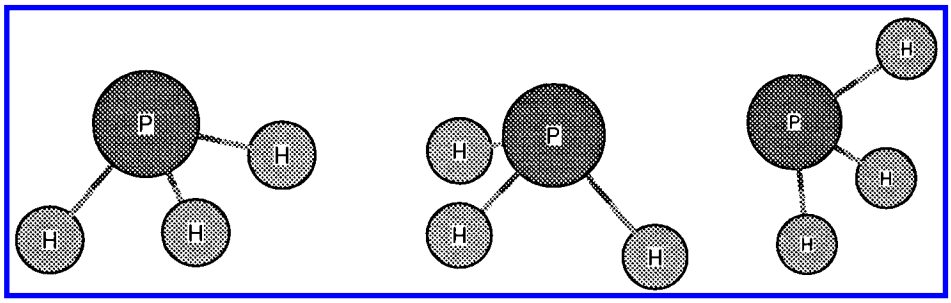

Figure 2. Three different rotations of the molecule PH_3 in "ball and stick" representation.

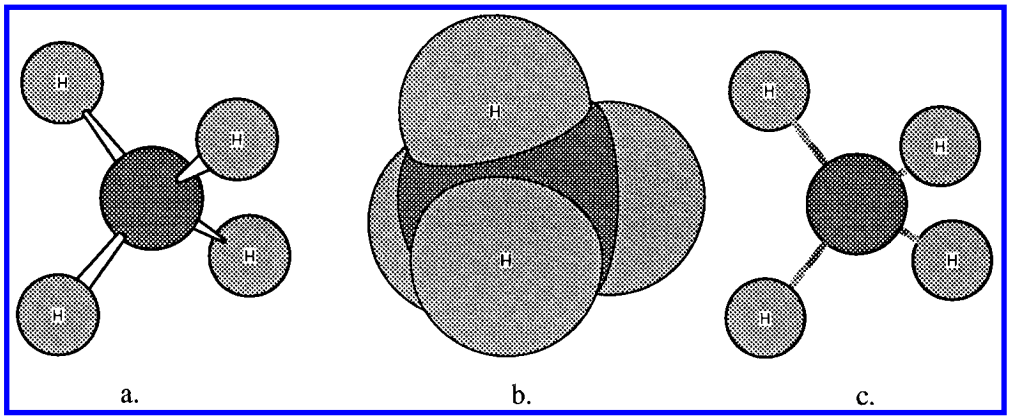

Figure 3. Three different representations of CH_4: a. cylindrical bonds, b. space filling, and c. ball and stick.

organic acids, cycloalkanes, and halomethanes. Other teachers created large molecules, such as polysaccharides and synthetic polymers from their monomers.

Stage 2—School Implementation. During the academic year 1995 we carried out an experiment in one high school as Stage 2 of the research. Students from both the experimental and control groups studied the topic of molecular geometry during the same period of time in different ways. Students of both groups answered pre- and post-course questionnaires on molecule structure and character. The experimental group students also answered two open questions on their attitudes toward the new method.

The Experimental Group. The experimental group—three classes of 10th graders—participated in three computer laboratory sessions of 2 h each and used the self-study booklet described above. Since the computer laboratory had only ten workstations, students worked in pairs and had the opportunity for interactions and group work. Students chose molecules from the library (a database which included molecules designed to work with the booklet), measured their bond length and angles, rotated them, and watched them in various modes: bonds only, stereolines, ball and stick, and space filling.

After the information gathering stage, students decided what geometric shape those molecules had. Later, they found out the similar properties of molecules that shared the same structure by building their Lewis formula. These students could identify the graphic representation easily, and, this, in turn, helped them decide whether the molecule is polar or nonpolar. Sometimes, the teacher used rigid models in order to clarify some misunderstandings. During the sessions students were very enthusiastic and concentrated on their work, discussed the results and conclusions with their peers, and called for assistance or approval of the teacher only when they disagreed or could not find a proper answer. Even students who are usually not active in chemistry laboratory cooperated and performed the required tasks. Students did not feel at the time the lesson was over that they were ready to stop and wanted to continue their work even during break time.

The Control Group. The control group studied the same subject during the same time duration according to the conventional frontal method—a deductive approach, in which the teacher explains the Valence State Electron Pair Repulsion Theory and demonstrates molecular structures in the classroom using a blackboard and rigid models. Students' practice was done through written exercises and the use of plastic models.

RESULTS

Teachers' Views on Using CMM. The main advantages the teachers listed were the following:

1. Working with computers motivates most students. It enables learning in an individualized pace, independent of the teacher and other students' pace.
2. Students working with computerized molecular modeling are more active than in conventional, frontal teaching methods. They are able to visualize molecules in a variety of display modes, thereby internalizing the idea that different models are just different ways of representing the same substance.
3. The fact that molecular modeling is three-dimensional, as opposed to the two-dimensionality of chalk and board, enables students to manipulate the molecules. This ability potentially improves their spatial perception.
4. Building molecules using software is quicker and easier. Unlike working with plastic models, there is never a problem of lack of parts to construct any number of isomers of the same molecule and keep them for the sake of comparison. In using computerized models, shortage of parts is no problem even when building large molecules, such as polymers or proteins.
5. The ability of the software to apply energy minimization to newly constructed molecules provides an excellent demonstration of this principle. It enables one to obtain models that reflect the spatial arrangement of atoms within a molecule as stated in the literature.

Table 1. Means of the Pre- and Post-Test Results of the Structure and Bonding Achievement Test

group	N	pre-test mean score	N	post-test mean score	N	net gain
exptl	97	26.3	84	61.61	79	33.34
control	72	14.63	65	43.58	59	29.32

The disadvantages of using CMM teachers mentioned were as follows:

1. The cost of a molecular modeling package may be prohibitively expensive for many schools (later we found out that there is a school version of DTMM at an affordable price).
2. There is a setup time involved in getting acquainted with the molecular modeling software.
3. In the particular modeling package we used, no consideration is given to molecule polarity or intermolecular bonds, such as van der Waals or hydrogen bonds.
4. Sometimes, when replacing hydrogen atoms with polar radicals in organic molecules, the angles between atoms do not change to reflect torsion.

Overall, teachers' attitudes toward using molecular modeling as a tool to improve chemistry teaching were favorable. The questionnaire also included a question regarding whether the teacher would be willing to incorporate molecular modeling in the classroom. Responding to this question, only ten teachers from the in-service group ($N = 40$) expressed their readiness to integrate the new methodology in their classes.

THE STRUCTURE AND BONDING ACHIEVEMENT TEST

The experimental group consisted of three classes, while the control group consisted of two classes. We have analyzed the mean score of each group for the pre- and post-questionnaire. Table 1 shows pre-test, post-test, and net gain mean scores for the two groups. All the students improved their scores, but the improvement of the experimental group was higher. Although there was a significant difference between groups in the pre- and post-test score ($p < 0.01$), the t-test showed no significant difference between the two groups ($p = 0.337$) for the net gain between the two phases.

Since the difference between the experimental and control groups was not significant we analyzed the differences between the two groups on their answers to the two questions that deal especially with molecular geometry (see Figure 1). We estimated that experimental group students could benefit from the new method and might score better especially in these questions because the questions deal with the particulate nature of molecules and require transfer across the three levels of representations discussed earlier. Each question has five items, and the score has two components: a number between 1 and 5 which counts the number of correct items

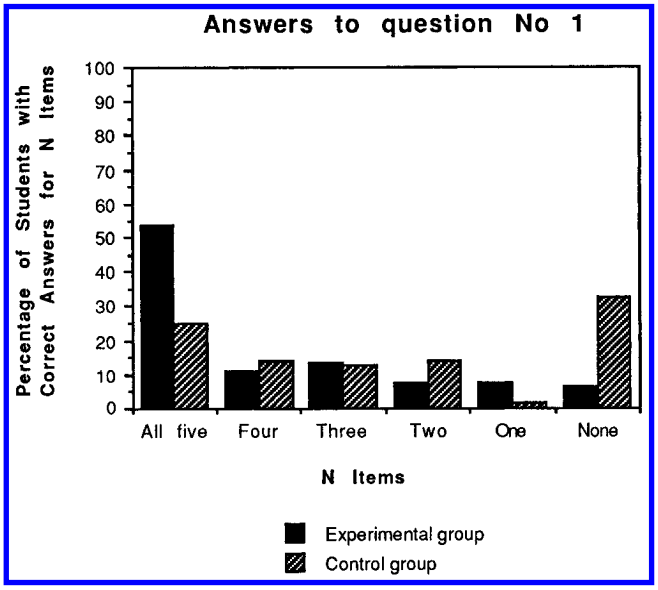

Figure 4. Percentage of students who answered question 1 correctly.

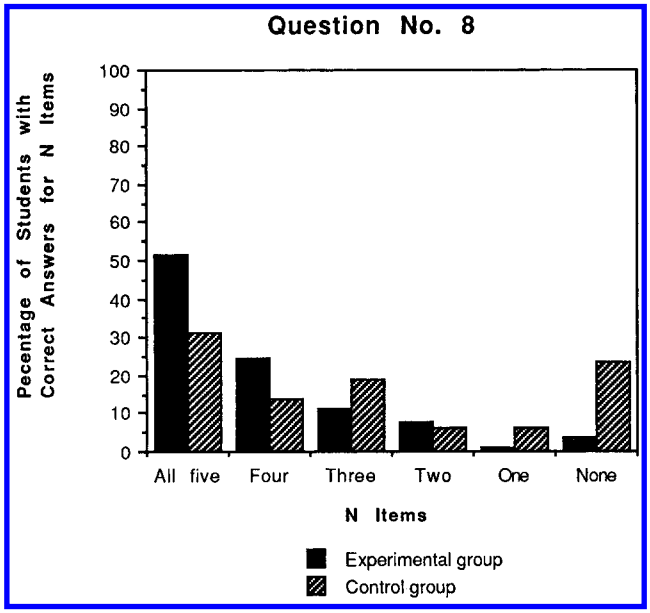

Figure 5. Percentage of students who answered question 8 correctly.

answered, and a number between 0 and 2, which relates to the explanation provided by the student.

The correct answer for question 1 (Figure 1) is that molecule c—SiF_4, which is tetrahedral, and molecule d—PCl_3, which is pyramidal, have both a three dimensional structure.

We examined these two questions further and analyzed typical wrong answers students provided for these questions. Some typical wrong answers students gave for this question are as follows. Students thought that COF_2 (which is planar) is three-dimensional. Some of them thought that it has a pyramidal shape and some explained that it must be three-dimensional because it includes four atoms. Another common mistake was indicating PCl_3 as having a trigonal planar structure. All the answers were accompanied by Lewis structures of the molecules which students used to decide which molecules are three-dimensional and which are not. Most of the mistakes occurred when the corresponding Lewis structure was wrong.

As noted, each question consisted of five items. A bar diagram of the student percentage who answered correctly *n* items ($n = 1, 2, 3, 4$, or 5) is presented in Figure 4. While 54.3% of the experimental group answered correctly all five items, only 25% did so in the control group. There is no big difference between the experimental and control groups in the percentage of students giving correct answers to two, three, and four items. However, there is a great difference—6.2% vs 32.8%—in the percentage of students who did not answer even one correct item between the experimental and control groups, respectively.

In question no. 8 (see Figure 1) the correct answers were as follows:

a. SiH_4—tetrahedral and nonpolar, b. CS_2—linear and nonpolar, c. AsH_3—pyramidal and polar, d. SClBr—bent planar and polar, and e. BF_3—trigonal planar and nonpolar.

Some students did not think that PH_3 and SClBr are polar. Some thought that AsH_3 is trigonal planar and therefore nonpolar. Since the representation of the molecules were already provided in the questions, students did not think it was necessary to draw Lewis formulas to confirm their answers, an activity which could help them realize the correct shape those molecules have.

Table 2. Linear Regression Model for Explanation of the Post-Test Score for Question 1

parameter	estimate	T for H_0: parameter = 0	p
intercept	1.476	7.98	0.0001
ques.1-pre	0.912	1.13	0.263
treatment	−0.232	−1.93	0.055
ques.1-pre group	−0.502	−0.77	0.442

Figure 5 shows that 50.8% of the experimental group gave a fully correct answer, while only 31.25% did so in the control group. A similar effect is found in the percentage of students answering four correct items, 24.7% vs 14% in the experimental and control groups, respectively. There is not a big difference between the experimental and control groups with respect to the level of correct answers of two and three items. The percentage of students who did not answer even one correct item has a similar pattern to that of question 1: in the experimental group only 3.7% had zero correct answers, while in the control group 23.4% did not know the correct answer even for one item.

Question 8 was somewhat easier for the control group. Of this group 32.8% did not answer even one item correctly in question 1, while in question 8 only 23.4% had zero correct items. In the experimental group, both questions were of about the same difficulty level, as can be seen from the percentage of students providing a completely correct answer: 54.3% and 50.8% for questions 1 and 8, respectively.

To explain the differences in post-test scores for these two questions, we applied a linear regression model for each question and found out that the treatment was the variable that accounted for the significant differences in the post-test scores for these questions (see Tables 2 and 3). Neither the pre-test score nor the interaction between the pre-test score and the treatment provided any explanation.

Tables 2 and 3 demonstrate that the treatment was the cause for the difference in the post-test score for both questions, while the pre-test score could not explain it. This

Table 3. Linear Regression Model for Explanation of the Post-Score for Question 8

parameter	estimate	T for H_0: parameter = 0	p
intercept	1.859	10.04	0.0001
ques.8-pre	−0.580	−0.44	0.658
treatment	−0.347	−2.87	0.005
ques.8-pre group	0.818	0.69	0.493

Table 4. Pearson Correlation among Post and Net Gain Scores of Questions 1 and 8

	post score no. 8	net gain score no. 8
post score no. 1	$r = 0.3887$ $p = 0.0001$ $N = 138$	$r = 0.3976$ $p = 0.0001$ $N = 138$
net gain score no. 1	$r = 0.3952$ $p = 0.0001$ $N = 138$	$r = 0.4178$ $p = 0.0001$ $N = 138$

may be attributed to the fact that the pre-test was administered before this subject was taught.

We performed a t-test for these two questions because the score is a continuous variable, and only the treatment was found to be an explaining variable. The t-test analysis showed a significant difference between the experimental and control groups in the pre-test, post-test, and net gain scores. The net gain of the experimental group was significantly higher than that of the control group. A possible cause is the initial difference between the groups, but it could also result from the treatment. After examining the correlations between questions 1 and 8, (Table 4), we found out significant correlation between the post-test and the net gain scores for these questions.

ATTITUDE QUESTIONNAIRE

The majority of the students enjoyed experiencing the new methodology and thought that this method enhanced their understanding of the bonding and structure of matter topic, as the results below show.

The first question of the students' attitude questionnaire concerned enjoyment. Of the students 76.5% enjoyed using the CMM, 19.8% did not enjoy it, and 3.7% did not answer the first question. The second question related to understanding. Of the students 77.8% thought that CMM helped to enhance understanding the subject matter, 19.8% thought that the CMM did not help at all, and 2.4% did not answer this question.

Students' explanations for their answers were categorized. The main reasons mentioned by the students were the following:

Understanding

1. CMM explains molecular structure.
2. CMM is a good way to demonstrate graphically what molecules look like.
3. CMM improved my spatial understanding.
4. CMM made me understand the relation between structure of a molecule and its properties.
5. I understood better because I worked individually on my own pace.

Enjoyment

1. I liked to use the special (spatial) eye glasses.
2. I enjoyed the program because I understood the topic a lot better.
3. I liked working with the computer and I had a lot of fun.
4. This was an innovative and interesting way to study chemistry.

SUMMARY AND DISCUSSION

A 14 h workshop on models and the use of CMM has been incorporated into pre- and in-service training at the Department of Education in Technology and Science at the Technion since 1994. Overall, teachers' attitudes toward using molecular modeling to improve chemistry teaching were favorable. The fact that only 25% of the in-service teachers are willing to implement the CMM in their classroom can be attributed to teachers anxiety to work with computers and/or to the lack of suitable equipment (Barnea[24]).

During 1995, the workshop methodology and learning materials were implemented in three 10th grade experimental classes with two classes serving as control. We investigated the effect of using molecular modeling on students' understanding of concepts related to chemical structure and bonding as well as geometric and symbolic representation.

The results demonstrate that the experimental group scored higher than the control group in both questions. This may be attributed to better understanding of chemical bonding and improved three-dimensional perception of molecular structure. The workshop experience of students in the experimental group with different models of molecules improved their perception of various geometrical shapes and the relation between the molecular formula and the geometric structure.

Alternative explanations may be based on the motivation difference between groups, the difference among the teachers, and the difference in scores in the pre-test. However, the fact that the experimental group, which consisted of three different classes, scored higher than the control group, which consisted of two other classes, is best explained by the effect of the new method, which is also reflected in the students' attitude questionnaire.

Experimental group students succeeded well in the difficult task called for in question 1. This question required three levels of transfer, from the symbolic (formula) level to the molecular representation level (submicro) and from it to the graphical representation and the phenomena level (Dori, Gabel, Bunce, Barnea, and Hameiri[25]). Students in the control group, who had not taken part in the CMM workshop, could not perform this required series of transfers.

Question 8 was easier for the control group since it required only one transformation—from graphic to verbal representation. The difference in difficulty between questions 1 and 8 was reflected in the relatively better performance exhibited by the control group in solving question 8. For the experimental group, however, there was no real difference between the degrees of difficulty of the two questions.

Students' attitudes toward the use of CMM were favorable. Most of the students enjoyed learning by using the new methodology, and many of them thought that it helped them understand better and improve their spatial ability.

The results obtained so far indicate that the CMM workshop methodology is potentially very effective. We plan to implement our constructivist approach in additional

schools and further investigate its effect on students' spatial ability and three dimensional molecular structure.

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