ZVIA KABERMAN AND YEHUDIT JUDY DORI

QUESTION POSING, INQUIRY, AND MODELING SKILLS OF CHEMISTRY STUDENTS IN THE CASE-BASED COMPUTERIZED LABORATORY ENVIRONMENT

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ABSTRACT. A new learning unit in chemistry, *Case-based Computerized Laboratories* (CCL) *and Computerized Molecular Modeling* (CMM) was developed at the Technion. The CCL and CMM curriculum integrates computerized hands on experiments and molecular modeling with an emphasis on scientific inquiry and case studies. Our research aimed at investigating the effect of the CCL and CMM learning environment on students' higher-order thinking skills of question posing, inquiry, and modeling. The experimental group included 614 honors 12th grade chemistry students from high schools in Israel who studied according to this learning unit. The comparison group consisted of 155 12th grade chemistry honors students who studied other chemistry programs. Pre- and post-tests questionnaires were used to assess students' higher-order thinking skills. Students' responses were analyzed using content analysis rubrics and their statistical analysis. Our findings indicated that the scores of the experimental group students improved significantly in question posing, inquiry and modeling skills from the pre-test to the post-test. The net gain scores of the experimental group students were significantly higher than those of their comparison peers in all three examined skills. In modeling skills, experimental group students significantly improved their achievements in making the transfer from 3D models to structural formulae, but only about half of them were able to transfer from formulae to 3D models. By presenting a case-based chemistry assessment tool and content analysis of students' responses in this paper, we enable teachers and educators to analyze their students' higher-order thinking skills both qualitatively and quantitatively.

KEY WORDS: chemistry laboratory, computerized learning, environment, inquiry, modeling, question posing, thinking skills

Introduction

One of the main goals of science educators is the development of students' higher-order thinking skills (Bransford, Brown & Cocking, 2000; Dori, 2003; Dori, Barak & Adir, 2003; Dori & Tal, 2000; Dori, Tal & Tsaushu, 2003; Zohar & Dori, 2003). In most high schools in Israel, matriculation examinations have been the primary instrument for assessing students' knowledge in chemistry. Since teachers were preparing their students to pass this examination, they neglected developing their higher-order thinking skills (Dori, 2003).

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Until last decade, there was little opportunity for the students to engage in such activities as planning experiments, resolving conflicts, or thinking reflectively. Laboratory activities were not planned to create new knowledge, but to confirm already known theories. Typically, students followed a recipe for data collecting in order to confirm facts or laws, which they were exposed to in their previous studies (Tobin, 1990). Reforming the Israeli honors chemistry curriculum meant developing higher-order thinking skills and integrating the laboratory as a mandatory part of the five units, which students study for the national matriculation examination (Barnea, 2002; 2004). The reform in chemistry instruction in Israel included embedding computerized environments into school classes and laboratories.

Researchers claimed that chemistry is still taught using a narrow range of methods, while it should be taught using a variety of methods (Gilbert, De Jong, Justi, Treagust & Vav Driel, 2002). Other approaches, such as computer-based simulations, project work, and cooperative learning, need to be developed, implemented, documented and evaluated. Gilbert, De Jong, Justi, Treagust & Vav Driel (2002) noted that computers may help students relate the macro, micro, and symbolic representation levels of chemical entities to each other. However, there has not been sufficient research into how effective such strategies are and how students' knowledge, skills, and attitudes change in computer-based environments. The learning unit we have developed consists of two parts: *Case-based Computerized Laboratory* (CCL) and *Computerized Molecular Modeling* (CMM). It was developed at the Technion, Israel Institute of Technology, in response to the need for a variety of methods in chemical education in general and in computerized laboratory and molecular modeling learning environments in particular.

In this paper, we explain the meaning of higher-order thinking skills in the context of our research and discuss the specific thinking skills that we targeted, namely, question posing, inquiry, and modeling. We then present the principles of the learning unit *Case-based Computerized Laboratory* (CCL) and *Computerized Molecular Modeling* (CMM) that we developed within the chemistry syllabus reform framework in Israel. After describing the research objective and settings, we provide detailed examples of students' assignments and responses. Finally, the statistical findings concerning modeling skills and the comparison we made between the students who studied in the CCL & CMM program and their counterparts who experienced chemistry in other teaching methods is described and discussed. The case-based approach which is introduced in this paper, brought changes into the national chemistry matriculation examination in Israel since 2005. Nowadays, it includes students' assessment of higher-order thinking skills along with their content knowledge and practical laboratory skills.

Theoretical Background

Higher-order thinking skills describe cognitive activities more complex than knowledge, understanding or application (Bloom, 1956). Based on Bloom's taxonomy, memorization and recall of information are classified as lower order thinking skills, while analysis, synthesis, and evaluation are classified as high order thinking skills. Zoller (1993) defined question posing, problem solving, and critical thinking as higher-order thinking skills. Constructing arguments, generating research questions, making comparisons, dealing with contradictions, identifying hidden assumptions, and scientific inquiry skills are additional examples of cognitive activities that are classified as higher-order thinking skills (Zohar & Dori, 2003).

Question Posing

Young children are inherently curious, frequently asking a stream of questions. However, many elementary school students have stopped asking questions, and they do not articulate a desire to discover, debate, or challenge (Becker, 2000).

Dillon (1988) found that when students did ask questions, the questions were seldom designed for increasing their personal knowledge or understanding. Rather, they were procedural, informational, and focused on the content covered in the next test.

Emphasis on students' questions conveys the message that inquiry is a natural component in a variety of science disciplines and that questions need to be constantly raised (Woodward, 1992). The value of student questioning has been emphasized in the National Science Education Standards, which stated that "inquiry into authentic questions generated from student experiences is the central strategy for teaching science" (NRC, 1996, p. 31). It is not generally possible to define the quality of students' posed questions, but it is possible and desirable to provide teachers with research-based sets of working criteria for guiding their students (Arzi & White, 1986). For students to be active learners and independent thinkers, they must generate questions that shape, focus, and guide their thinking (Singer, 1978).

Inquiry Skills

In the laboratory, students are exposed to the scientific inquiry method and acquire inquiry skills. Inquiry refers to diverse ways in which scientists study the natural world, propose ideas, and explain and justify assertions based upon evidence derived from scientific work (Hofstein & Lunetta, 1982). Inquiry also refers to more authentic ways in which learners can investigate the natural world, propose ideas, and sense the spirit of science (Hofstein & Lunetta, 2004). According to NRC (1996; 2000), inquiry is an activity that involves making observations, posing questions, examining sources of information, planning investigations, using tools to gather, analyze and interpret data, and proposing answers and explanations. Tobin (1990) suggested that meaningful learning is possible in the laboratory if students are given opportunities to manipulate equipment and materials in an environment suitable for them to construct their knowledge about phenomena and related scientific concepts.

Modeling Skills

Understanding chemistry relies on making sense of the invisible and untouchable. Much of what is chemistry exits at a molecular level and is not accessible to direct perception. Consequently, chemistry is a field of study that is inherently representational or symbolic (Kozma & Russell, 1997). Modern chemistry cannot be taught without models, and according to Harrison & Treagust (1998), constructing and manipulating atomic and molecular models are a necessity in chemical education.

Keig & Rubba (1993) and Furio, Calatayud, Barcenas & Padilla (2000) argued that high school students are frequently unable to make electron configuration-to-model translations or model-to-formula translations. They face difficulties drawing ball-and-stick models and determining molecular structures when empirical formulas are given. Coll & Treagust (2003) also claimed that students are required to interpret a variety of representations of chemical bonds (e.g., chemical formulae or ball-and-stick models) and chemical bonding is a topic that students commonly find problematic and for which they develop a wide range of alternative concepts.

Representational competence is described by Kozma & Russell (1997, 2005) as a set of skills and practices that allow a person to reflectively use a variety of representations or visualizations, to think about, communicate, and act on chemical phenomena in terms of underlying physical entities and processes. Thus, it is likely that learning chemistry involves students' visuo-spatial abilities that support students in performing certain cognitive operations spatially. Therefore, being able to comprehend and mentally manipulate chemical configurations is critical for students to understand the content and conduct advanced scientific research (Wu & Shah, 2004). Modeling ability is a thinking skill that cannot be learned like content.

Learning to become a skilled modeler can only be achieved through much practice over a long period. Teachers should therefore teach modeling skills, encourage students to use multiple rather than isolated analogical models, and take the time to discuss and critique the models used in class (Harrison & Treagust, 2000).

Barnea & Dori (2000) developed a computerized molecular modeling (CMM) environment for high school students and conducted a training program for the teachers. The researchers investigated the effect of the training program on teachers' and students' perception of the nature and function of models. The findings indicated the effectiveness of the program on high school students' conceptualizing the meanings of models, especially in the domain of chemistry.

In this paper, we refer to modeling skills as the understanding of correct 3D representation of spatial structures of molecules and the ability to transfer between different molecular representations.

Research Setting: The Case-based Computerized Laboratory Environment

A new chemistry learning unit *Case-based Computerized Laboratories* (CCL) *and Computerized Molecular Modeling* (CMM) was developed at the Technion, Israel Institute of Technology (Dori, Sasson, Kaberman & Herscovitz, 2004). The target audience was honors 12th grade chemistry students from high schools in Israel. The honors curriculum in Israel consists of five learning units, and the CCL & CMM learning unit is one of the elective units in this curriculum. Another elective inquiry laboratory unit was developed at the Weizmann Institute of Science (Hofstein, Levy Nahum & Shore, 2001; Hofstein, Shore & Kipnis, 2004). The curriculum, developed within the framework of reforming the Israeli honors chemistry studies, integrates computerized hands-on experiments with emphasis on scientific inquiry and case studies.

The CCL & CMM learning unit activities included case studies, question posing, computerized inquiry laboratories, and molecular modeling. The CCL laboratory activities included data collection using temperature, pH, and conductivity sensors, graphs construction in real time, and interpretation of the results (Dori & Sasson, 2008).

The organic chemistry part of the unit was taught in the CMM environment, where students could investigate daily-life organic molecules using two CMM software packages downloaded from the Internet. Using the first software package, students were able to construct the molecules by determining the kinds of atoms and their numbers, as well as the covalent bonds between them (single, double or triple). The molecule is built according to the bonding rules. At the end of the construction process, the students get a 2D structure of the molecule. Using the second software package, students could view the molecule they had constructed in 3D representation modes. The software enables the transfer of the 3D drawing between three molecular representation modes: line, ball-and-stick, and space-filling.

To emphasize the importance of constructing 2D molecular models and then transferring them into 3D models, we present an example of students' assignment while working with CMM. The students were asked to construct cyclohexane and benzene rings and then investigate their properties after transferring them from 2D to 3D models. Figure 1 presents the different models that the students constructed.

Research Objective, Questions, Participants and Tools

One of the most important goals that guided the developers of this learning unit was designing educational disposition aimed at developing higher-order thinking skills.

This research aimed at investigating the effect of case-based hands-on experiments and computerized molecular modeling on three higher-order thinking skills: Question posing, inquiry, and modeling.

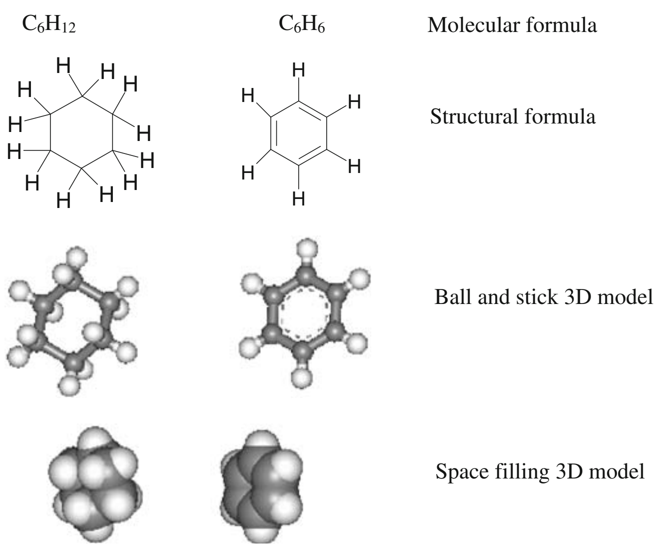


Figure 1. Multiple representations of cyclohexane (*left*) and benzene (*right*)

The research questions were formulated as follows:

1. Are there any differences between CCL & CMM students' higher-order thinking skills and their comparison group peers?
2. What is the effect of the CMM environment on students' modeling skills with respect to (a) Transferring between models and structural formulae, and (b) Drawing a 3D model?

Research Participants

The research described here was part of a longitudinal study that investigated chemistry students studying in the CCL & CMM environment. In the first year of the research only the CCL part of the learning unit was taught. The first year study findings are described in Dori, Sasson, Kaberman & Herscovitz (2004). A year later, the CMM portion became an integral part of the larger learning unit. Our research participants in the second and third (2nd and 3rd) stages consisted of experimental students who studied the whole CCL & CMM program (2nd stage participants N=224; 3rd stage participants N=390) and a comparison group students (N=155). Both research groups included honors 12th grade chemistry students from high schools in Israel. Each academic year was defined as an experimental stage, so the experimental and comparison groups consisted of different students in each stage.

The comparison group students studied chemistry via means other than the CCL & CMM learning unit. Most of the comparison group students (70%) studied in inquiry- or industry-oriented laboratories. In these programs, students performed laboratory activities and read modified scientific articles with an emphasis on inquiry or industrial issues. The rest of the comparison group students studied in a traditional, teacher-centered style, where theoretical sessions were accompanied by few laboratory activities.

Our study is longitudinal, based on the notion of White & Arzi (2005), who defined a longitudinal study as one in which two or more measures or observations of a comparable form are made of the same individuals or entities over a period of at least one year. Our case-based pre-tests were handed to the students at the beginning of the academic year, while the case-based post-tests were administered at the end of the academic year. As noted by White & Arzi (2005), while loss of subjects can affect any research, the length of longitudinal studies makes attrition particularly likely. We faced this very problem, but since the initial number of our experimental subjects was much higher than that of the comparison group, the problem was more noticeable for the latter group.

The teachers of both research groups participated in a summer training program and were familiar with the CCL & CMM learning unit and its characteristics. However, only the experimental group teachers participated also in an ongoing training program throughout the academic year. They received further help and got answers to questions that were raised while they instructed the new CCL & CMM learning unit. The experimental group teachers fully cooperated with the researchers, who, in turn, supported the teachers. Other teachers, who decided not to implement the CCL learning unit, were asked to be part of the comparison group. Lacking the same level of commitment for the research as the experimental teachers, only a small part of the teachers in the comparison group ended up participating in both the pre- and the post-test questionnaires. This was mainly due to time pressure to prepare the students for the upcoming matriculation examinations at the end of the academic year.

To analyze the effect of students' academic level on their thinking skills, we divided the experimental and the comparison group population using Duncan's Multiple Range Test into three academic levels–low, intermediate, and high, based on their total pre-test scores. The total score of the pre-test questionnaire was calculated based on average scores of all the thinking skills examined in the CCL & CMM program–question posing, inquiry, modeling, chemical understanding–retention, graphing skills and transfer (Dori & Kaberman, submitted; Dori & Sasson, 2008; Kaberman & Dori, submitted; Sasson & Dori, 2006). According to the pre-test, we found a similar distribution of the participants in low and high academic levels, with no regard to the teaching methods in their classes. No significant differences in achievements were found in the pre-test between the experimental group participants and the different sub-groups participants.

Research Tools

We used pre- and post-test questionnaires to assess students' higher-order thinking skills. The questionnaires included a case study related to a chemical story and a variety of assignments for investigating various thinking skills, notably question posing, inquiry, and modeling skills.

The questionnaire was of two types, A and B, each containing a different case study. The questions in both questionnaire types were related to the story in each one of the case-studies and examined the same thinking skills. About half of the students responded to type A in the pre-test and then took type B in the post-test. The other half of the students responded to type B in the pre-test and to type A in the post-test. Statistical analysis of the results revealed no significant differences between the two test types.

The pre-test questionnaire was administered to both the experimental and the comparison group students in the beginning of the academic year. The experimental group students studied the CCL & CMM unit for about ninety sessions. The post-test questionnaire was administered to the whole population towards the end of the year.

A chemical case study from the questionnaire used in the 2nd stage is presented in Figure 2.

Examples for assignments which examined the different thinking skills are presented in Table I.

New assessment tools were designed especially for the CCL & CMM learning unit in order to encourage the development of students' higher-order thinking skills. These assessment tools consisted of a detailed rubric for each skill that enabled us to diagnose students' different thinking skills. Using our rubrics and applying content analysis on students' responses, we categorized the responses to the three examined thinking skills and normalized the scores to a 1–100 scale for each thinking skill. The questionnaires were analyzed in two phases. In the first, qualitative phase, we applied content analysis of students' responses to extract categories and use them to characterize students' responses. In the second, quantitative phase, we scored each student's response using the rubrics and statistically analyzed the results. Scoring students' answers to the examined skills in the pre- and post-test questionnaires provided us with a broad picture of the students' thinking skills before and after studying the CCL & CMM learning unit.

Assessment of Students' Responses to Higher-Order Thinking Skills Assignments

The criteria used to assess each of the three examined thinking skills were as follows.

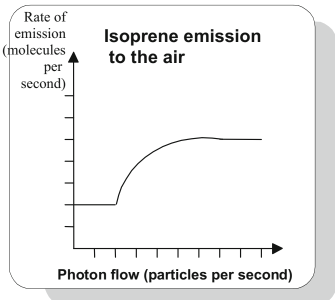
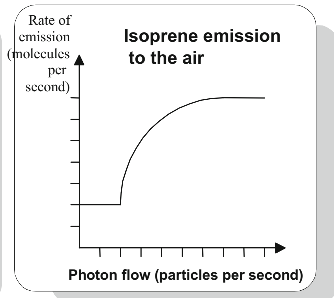
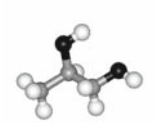
Trees cause air pollution – Is this possible?

Volatile hydrocarbons are naturally emitted from various types of trees. Isoprene (C_5H_8) is the most common organic compound that oak and sycamore trees emit at daylight. Researchers assume that isoprene emission is part of the tree's heat protection mechanism. Updated research emphasizes the role of isoprene in the process of smog formation. Due to photochemical reactions, which involve nitrogen oxides and hydrocarbons emitted from vehicles, oxidant materials such as ozone (O_3) disperse in air and create the smog effects – Haze, inadequate visibility and bad odor.

Figure 2. An example of a case study from a questionnaire–2nd stage

TABLE I

Examples of assignments for each of the examined thinking skills

Examined thinking skill	Assignment
Question posing	Pose two questions to which you did not get a direct answer in the case study.
Inquiry	An experiment that examined isoprene emission to the air focused on the connection between the emission rate of isoprene and parameters of the leaves from which it is emitted. The inquired parameters were: intensity of light radiated on the leaf, leaf temperature, and leaf humidity. Examining isoprene emission rate as a function of the intensity of light radiated on the leaf (based on photon flow), the graphs below were obtained.  **Experiment 1**  **Experiment 2** Scientists carried out experiments 1 and 2 in order to examine the influence of a certain factor on the dependent variable. 1. Write down the scientistsí goal in carrying out the experiments by formulating a research question. 2. What are the independent and depended variables? 3. What are the control variables? Why were they left constant? 4. What was the scientistsí conclusion in your opinion?
Modeling	The molecular formula of isoprene is C_5H_8. 1. Write a possible structural formula for the molecule (a non cyclic formula). 2. Draw a model for the structural formula of C_5H_8 you suggested. 3. Write the structural formula of propylene glycol - a product of a reaction between propene (another hydrocarbon air pollutant), $KMNO_4$ and water. 

Question Posing Skill

The CCL & CMM environment exposed the students to case studies and modified scientific articles and to metacognitive knowledge on question posing strategies, supported by a question classification taxonomy. The metacognitive aspect of the question posing higher-order thinking skill is described in detail elsewhere (Kaberman & Dori, submitted). The taxonomy we designed especially for this research has provided us with the ability to examine different aspects of the questions posed in relation to a given chemical text.

We used this taxonomy, presented in Table II, to define what constitutes a “good and complex” question in this context. A student who knows the teacher's strategic preferences in question posing, is better able to adapt to the demands of this teacher’s classroom (Pintrich, 2002). Based on this, the taxonomy was presented to the teachers in a training program, and the teachers exposed their students to the taxonomy in class.

Three of the four chemistry understanding levels—macroscopic, microscopic, and symbolic—were identified by Johnstone (1991) and Gabel (1998). The process level was suggested and investigated by Dori & Hameiri (1998, 2003) and by Barak & Dori (2005). Understanding at the process level requires understanding the way substances react with each other. The process level can explained in terms of one or more of the first three levels.

According to Chandrasegaran, Treagust & Mocerino (2007), students’ ability to use the macroscopic, microscopic, and the symbolic representations is essential for understanding chemistry concepts and phenomena. Even though, students do not have sufficient understanding of the macroscopic and microscopic representations on one hand, and significance of the symbols and formulae in chemical equations, on the other hand.

TABLE II

The classification taxonomy of chemical questions

The aspect	Criteria
Content	The question should not only focus on the phenomenon described in the text. It should involve such aspects as potential hazards and possible solutions.
Thinking level	The question requires a response at a thinking level higher than knowledge or understanding.
Chemistry understanding levels	The question calls for a response that requires the invocation of at least two out of the four chemistry understanding levels—symbolic, macroscopic, microscopic, and process.

Questions at different complexity levels that two students posed after reading the Isoprene case study are presented next. Their content analysis based on the taxonomy is provided in Table III.

Inquiry Skills

We focused on four inquiry sub-skills which the teachers had to emphasize in their teaching in each inquiry experiment they conducted: (1) The generation of an inquiry question, (2) the identification of the dependent and independent variables, (3) the control variables and (4) the conclusion(s) that can be drawn. We analyzed students' responses based on the work of Tamir, Nussinovitz & Friedler (1982). The content analysis of students' responses is provided in Table IV.

Modeling Skills

The software in the CCL & CMM environment enables the transfer of a 3D drawing between three molecular representation forms: wire-frame (line), ball-and-stick, and space-filling. In addition, there are options of rotating the molecules, measuring bond lengths and angle sizes between different atoms in the molecule. Students investigated molecules used in daily-life and tried to make connections between the measurements they took (at the microscopic level) and the properties of the substances (at the macroscopic level). The students were trained to transfer between molecular representations and the teachers emphasized the spatial structure of organic molecules (see Tables V and VI).

Findings

Descriptive statistics indicated that students in the experimental group improved their scores in their question posing, inquiry, and modeling skills. The pre-test scores in the three examined higher-order thinking skills were relatively low (less than 50) in both stages of the experiment. A significant improvement was found in the post-test relative to the pre-test in all three skills. The inquiry and modeling skills scored in the post-test much higher than in the pre-test. These results were consistent in both stages.

In order to respond to the first research question, we investigated the improvement in students' scores from the pre-test to the post-test before and after studying the CCL & CMM learning unit. The comparison to other chemistry students was aimed at investigating the attribution of students' cognitive development or of theoretical chemistry lessons in

TABLE III

Analysis of questions posed by students after reading the Isoprene case study

Student's question	Content	Thinking level	No. of chemistry understanding levels
A low complexity question–student M.'s question: Where do nitrogen oxides come from?	The question deals with a fact appearing in the case study and is partly answered.	The response is at the knowledge and understanding level, and it can be found in textbooks or in scientific papers.	The response to the question concerns one level of chemistry understanding: Macro-nitrogen oxides are emitted from vehicles.
A high complexity question – student R.'s question: Is Isoprene emission more intensive when air temperature is higher?	The question concerns a problem that does not appear in the case study. The question elaborates on the heat protection mechanism mentioned in the case study.	An inquiry question - an evidence of making an assumption and trying to draw a conclusion from the text. The question raises the need to conduct an inquiry experiment.	The response to the question concerns two levels of chemistry understanding: Macro–more isoprene in the air because of high temperature. Process–the effect of temperature on the amount of isoprene production and on emission rate.

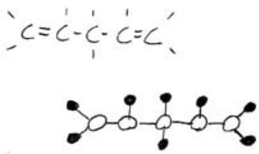
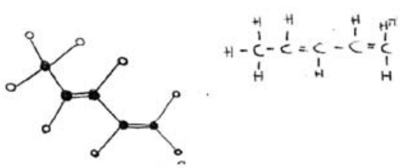
TABLE IV

Analysis of students' responses to the inquiry skills assignments

Student's response	Analysis
An insufficient response–student C.'s question: What is the effect of photon flow on the emission rate of isoprene? Dependent variable–Rate of emission Independent variable–Photon flow (intensity of light) Control variables–Leaf temperature, leaf humidity, pressure Conclusion–The intensity of the photon flow increases with the emission rate of isoprene.	The question could be a good one if only one graph was presented. Since there is an obvious difference between the two experiments, there has to be another parameter that affects the isoprene emission rate. The independent variable has to be other than the photon flow, e.g., leaf temperature, leaf humidity, or leaf's surface area. Even though an incorrect inquiry question was posed, the photon flow – the independent variable – suits the inquiry question that was posed and gets a full score. The control variables are fine according to the independent variable that the student chose. The conclusion is very partial and indicates that the student did not understand the two experiments.
A high level response–student A.'s Question: How is emission rate of isoprene affected by the surface area of the leaf? Dependent variable–Rate of emission Independent variable–The surface area of the leaf Control variables–Leaf temperature, leaf humidity, light intensity, leaves from the same tree Conclusion–The isoprene emission rate increases with the leaf surface area. In experiment 2 the surface area is wider, the leaf is more exposed to the heat and emits isoprene at a higher rate.	A well generated inquiry question, containing suitable dependent and independent variables based on the two graphs, four relevant control variables, and most importantly – a connection between the conclusion and the two experiments. The student was able to decide which of the graphs suits the wider surface area of the leaves and to explain the reason for his decision.

TABLE V

Analysis of students' responses to the model drawing assignment – questions 1 and 2

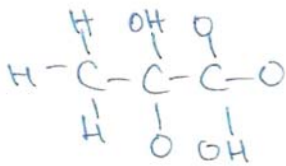
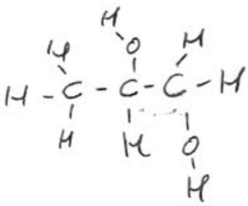
Student's response	Analysis
An insufficient response written by student B. 	All bonds and atoms in the structural formula match the molecular formula and the bonding rules. There is good representation of atoms in the drawn model but reference to angles and spatial representation is incorrect and there is no distinction between single and double bonds. There is only partial match between the structural formula and the model.
A high-level response written by student D. 	All the bonds and atoms in the structural formula match the molecular formula and the bonding rules. A correct model with right angles that make the distinction between 2D and 3D is drawn, and a distinction is made between single and double bond. There is complete match between the structural formula and the model.

class. To this end, we compared the students in the experimental group and the comparison group, sorted by academic levels to low and high.

We used the General Linear Model Procedure for comparing average net gain scores of experimental students vs. comparison students at the low and high academic levels. This statistical analysis showed that there was no significant difference between the pre-test scores of the students in the experimental group and in the comparison group for any one of the two academic levels. The findings are presented for both stages combined since the scores in the second and the third stages were very similar. Figures 3, 4 and 5 present a comparison between students' scores in the experimental and in the comparison group for each of the thinking skills, sorted by academic level. The number of students who responded to the pre-test was higher than the number of those who responded to the post-test. The numbers of students reported in the graphs account only for low and high academic level students who responded to both the pre- and the post-test questionnaires. We elected to present the high and low academic level groups since this makes the differences between academic levels most obvious. Omitting the data regarding the intermediate group for some of the findings is the reason for the lower number of students for those issues, compared with the initial number of subjects.

TABLE VI

Analysis of students' responses to the transfer from a 3D model to structural formula – question 3

Student's response	Analysis
An incorrect response of student F. 	The student confused between hydrogen and oxygen atoms, and made more than two mistakes while transferring from the model to the structural formula. The student drew the formula without considering the bonding rules (score 0).
A high level response written by student N. 	A correct structural formula for propylene glycol with accurate relation between the model and the structural formula (score 2).

As Figure 3 shows, the net gain (post- minus pre-test score) of the experimental group students' question posing skill was significantly higher than that of their comparison peers (t=3.71* [1] for low academic level students and t=3.96** for high academic level).

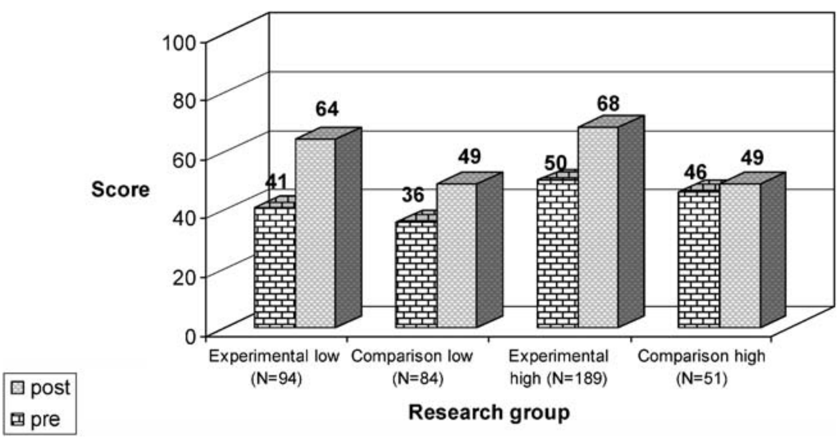


Figure 3. Scores of experimental vs. comparison students in question posing

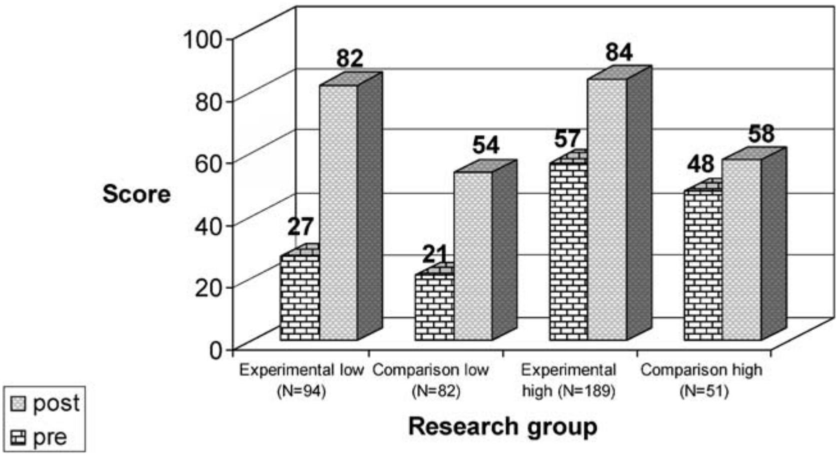


Figure 4. Scores of experimental vs. comparison students in inquiry

Figure 4 shows that the net gain of the experimental group students' inquiry skill was also significantly higher than that of their comparison peers. For low academic level t=3.71** and for high academic level t=5.26***[1].

Finally, the net gain of the experimental group students' modeling skill, shown in Figure 5 was also significantly higher than that of their comparison peers. For low academic level t=4.06** and for high academic level t=4.13***.

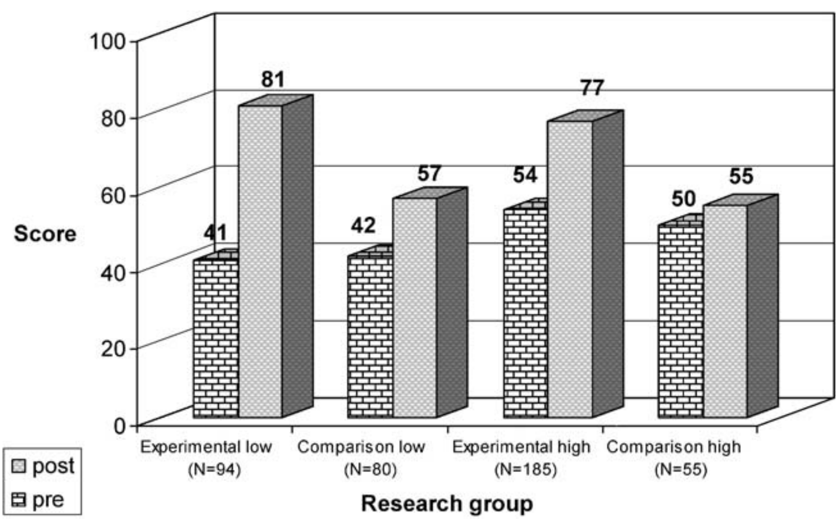


Figure 5. Scores of experimental vs. comparison students in modeling

Low academic level students' net gain scores were much higher than those of their high academic level peers in both the experimental and the comparison group, probably due to the ceiling effect.

Our second research question concerned the effect of the CMM learning environment on students' modeling skills. The modeling skills included a variety of sub-skills, and we found out that these sub-skills can be ranked hierarchically based on students' difficulties to conduct the various transfer assignments that require these sub-skills. We present the findings of the experimental group students for two of the sub-skills. The first is transferring a 3D model to a structural formula, which turned out to be an easy assignment. Hence the corresponding sub-skill is low in the hierarchy. The inverse operation, i.e., drawing a 3D model given a molecular or a structural formula was found to be a more difficult assignment.

In order to find out whether the students could reconstruct the structural formula from a given unfamiliar 3D model, we gave the students the following assignment: "Write the structural formula of propylene glycol". This is question 3 in the modeling assignment (See Table II). The students were given a ball-and-stick model of the propylene glycol molecule. The findings of this assignment are presented in Figure 6.

Examining Figure 6, we see that in the pre-test, about one quarter of the students did not carry out the task at all, over 40% of them made an incorrect or a partially correct transfer from the model to the structural formula, and less than one third of them made the transfer correctly. In the post-test, about 75% fully made the transfer from the 3D model to the structural formula correctly.

We also examined the drawing of the model from two aspects: (a) the quality of the drawing (bonds, angles, linear/spatial) and (b) the quality of

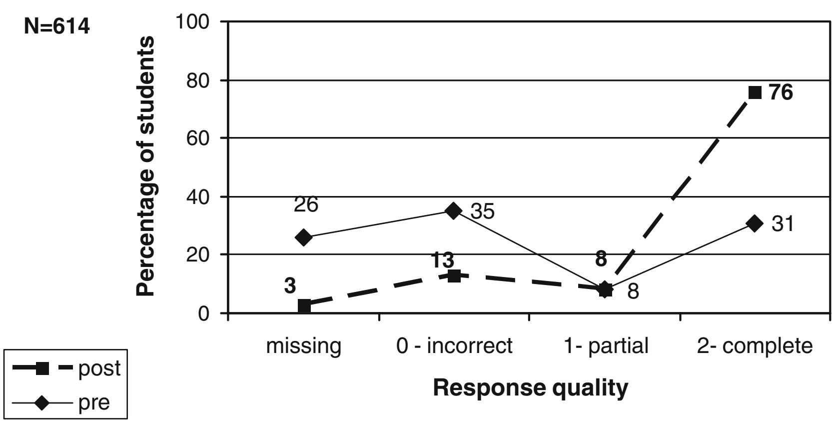


Figure 6. Distribution of students who performed transfer from model to structural formula

transfer between the structural formula the student suggested and the model she/he drew, as well as the extent to which the student understood the linkage between the two (as expressed by matching the kind and number of atoms and the covalent bonds between them).

To examine the drawing of the model, we gave the student the following assignment: Draw a model for the structural formula of C_5H_8 that you suggested". This is question 2 in the modeling assignment (See Table I).

Figure 7a and b present the results of the model drawing quality and transfer quality from structural formula to model. Half of the students did

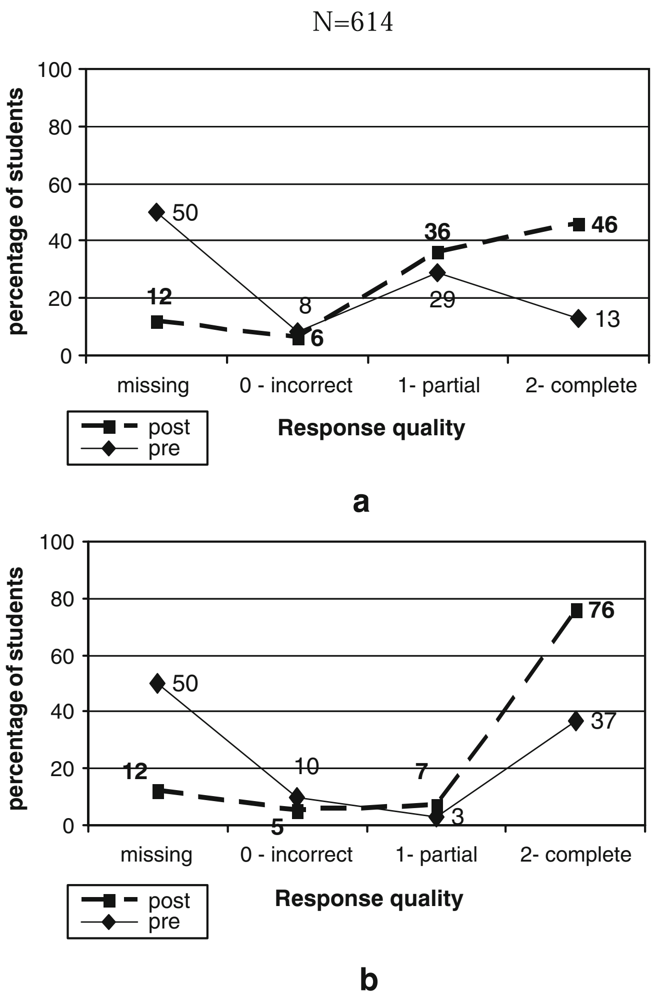


Figure 7. (**a**): Model drawing quality (**b**): Transfer quality from structural formula to model

not draw any model at all in the pre-test, while in the post-test most of them (about 85%) performed that task.

Comparing the quality of the models that students drew, we found out that while in the pre-test, only about tenth of the students drew a completely correct model, in the post-test about 45% of the students drew a correct model. In both the pre-test and the post-test, most students who carried out the drawing model task could transfer between representations quite well (Figure 7b). In the pre-test, only 37% made a correct transfer between the structural formula they wrote and the model they drew. While in the post-test about 75% of the students made a complete transfer between the two representation types.

Discussion

Our research has introduced a new learning mode, which combines case studies with computerized inquiry laboratory activities and molecular modeling. This learning environment has improved the experimental group students' scores in a variety of higher-order thinking skills examined, as reported previously (Dori, Barak & Adir, 2003; Dori & Kaberman, submitted; Dori & Sasson, 2008; Dori, Sasson, Kaberman & Herscovitz, 2004; Kaberman & Dori, submitted; Sasson & Dori, 2006). These findings were reinforced in a comparison between the experimental and the comparison group students. Experimental students' net gain scores in both the low and high academic levels were significantly higher than those of the comparison group students. While part of the comparison students in the inquiry-oriented laboratories scored higher than the two other sub-groups in all three examined skills, these differences were not significant.

Question Posing

The question posing assignment called for posing questions to which the answer could not be found in the adapted scientific article. The findings show that students significantly improved their question posing skill. Both the number of questions students posed in the post-test and their complexity were significantly higher than those in the pre-test. These findings are in accordance with Dori & Herscovitz (1999), who found that the Air Quality project, in which students were taught how to generate "good and complex" questions, brought about a significant increase in students' question posing capability in the aspects of number of questions, their orientation, and their complexity.

Our taxonomy exposed the students to higher-order thinking aspects, and as a result, students posed questions at the application, analysis, and assessment levels. Many judgmental questions were generated and an incline in inquiry questions was found as well. A similar phenomenon, which strengthens this finding, was reported by Marbach-Ad & Claasen (2001) and Marbach-Ad & Sokolove (2000). In our research, teachers exposed their students at the beginning of the semester to a question classification taxonomy which emphasized what "good and complex" questions were. At the end of the semester, students' questions were characterized by deep insights and understanding, and the best questions were inquiry questions. Our question taxonomy was partly based on previous question analysis tools, which were used by other researchers in STS high school programs (Dori & Herscovitz, 1999), in biology college classes (Marbach-Ad & Sokolove, 2000), and in-service science teachers training (Dori & Herscovitz, 2005). The innovation of our contribution is related to the chemistry understanding aspect. Our question taxonomy analyzes the complexity of the questions posed after reading case studies that have chemical characteristics according to the levels of understanding in chemistry: symbol, macroscopic, microscopic, and process.

In both the pre- and the post-tests, many questions students posed were in the macroscopic level only. After experiencing the chemical understanding aspect of our taxonomy, students posed questions also at the microscopic level, relating to the atomic and molecular structure of the substance, and at the process level (Kaberman & Dori, 2008).

Inquiry Skills

In inquiry skills, the post-test results of the experimental group students were significantly higher than the pre-test results in formulating a research question, defining the dependent and independent variable, defining the control variables, and drawing conclusions. The students conducted six guided and semi-guided experiments, as well as two open-ended experiments, in which they had to go through the whole scientific inquiry process. The inquiry skills could be well assimilated during the months of intensive inquiry laboratory work. German, Aram & Burke (1996) also found that explicit and gradual teaching of science process skills, including inquiry question generation, assumption raising, and variables defining, embedded with examples in each inquiry stage, could make it easier for the students to develop their inquiry skills. Most students (70%) in the comparison group studied in inquiry- or industry-oriented laboratories. These programs integrated laboratory activities with emphasis on inquiry or industrial issues. Nevertheless, those students did not experience computerized experiments and much of the laboratory work time was devoted to collecting data and measurement techniques as well as documenting the results and conclusions in portfolios. The CCL & CMM students, who worked with sensors and computer software, were not concerned with data collection, as it automatically appeared on the computer screen as graphs showing the connection between the variables (Dori & Sasson, 2008). Hence, these students could focus on the inquiry skills necessary for planning their experiments and analyzing their results. As a result, experimental group students' scores were significantly higher than the comparison group students' scores. Another advantage of the experimental group students was their familiarity with reading case studies and with carrying out the assignments that followed. Throughout the whole year, the CCL & CMM students were assessed in a way similar to their assessment in the post-test. The inquiry-oriented laboratory students (about 50% of the comparison group) were used to planning, conducting the experiments, and analyzing the data in the laboratory. Despite this, they were assessed based on "hot" reports they wrote during the laboratory sessions (Hofstein, Shore & Kipnis, 2004). Those students were not used to respond to case-based questionnaires. This may explain why the improvement in their inquiry skills, although noticeable, was not as significant as the improvement of the experimental group students' inquiry skills.

In this study we did not investigate the net gain in the inquiry skill as expressed in the experimental students' portfolios. It may well be that comparing this skill of students in the inquiry-oriented and industry-oriented comparison group, as manifested through their portfolios rather than through their case study assignments, might have shown an advantage of the comparison group over the experimental group.

Modeling Skills

The experimental group students also improved their modeling skill achievements significantly in both stages. The starting point of the students was quite low, scoring on average less than 50 in both stages. When the students responded to the pre-test questionnaire, they had not been exposed to the CMM environment yet. Their knowledge at that point in time was mainly based on organic chemistry they had studied a year earlier and on occasional work with plastic models in a few class sessions. After experiencing processes of inquiry and exploration of molecular models using computerized media, students were more skillful in manipulating the diverse representations of molecules, drawing models spatially, understanding what they were doing, and making connections between the different levels of chemistry understanding, the symbol, microscopic, macroscopic and process levels.

Our findings are in accordance with Small & Morton (1983), who argued that direct training or practice on visuo-spatial tasks could improve chemistry achievements. Students who received training on visualization skills achieved significantly higher scores on questions that required the use of 3D models in a retention test. Dori, Barak & Adir (2003) and Barak & Dori (2005) also reported that undergraduate chemistry students, who elected to undertake a Web-based computerized molecular modeling project (the experimental group) study, performed significantly better in both the post-test and the final examination of the course than those who elected not to carry out the project (the control group). Dori & Barak (2001) investigated the effect of using virtual and physical models while teaching organic chemistry on high school students' understanding new concepts as isomerism and functional groups and the spatial structure of new molecules. They also found that experimental students who worked with two kinds of models gained a better understanding of the model concept and were more capable of defining and implementing new concepts, and able to transfer between the four understanding levels of chemistry: symbol, macroscopic, microscopic and process.

Students who worked in the CMM environment were exposed to many 3D models while inquiring different molecules. The students constructed the molecules and then transferred them to 3D models. Consequently, in the post-test about 75% of the students made a correct and complete transfer from the model of propylene glycol to its structural formula, while in the pre-test only one third of the students handled that assignment properly.

According to Mathewson (1999), visual-spatial thinking ought to be a systematic and integral part of planning, teaching, teacher preparation, and research in education. In chemical education in Israel, prior to studying with the CMM, the students were not familiar with model drawing tasks since drawing models in general, and 3D models in particular, was never emphasized in class, and the teacher was the one who drew 2D structural formulae on the board. Only after the teachers had participated in training programs (Barnea & Dori, 2000) for assimilating CMM, they became aware of the need to draw 3D models with their students.

The teachers emphasized the spatial structure of the molecules in class discussions, after the students had taken measurements of the angles between the different atoms, such as the 109.5° angle between a carbon atom and two hydrogen atoms in a tetrahedral spatial structure. Most of the molecules that were investigated were organic compounds, built up of carbon atoms, and we expected that students would represent their models in the questionnaires the way they had seen them on the computer screen. Yet, there were students who drew linear models without taking into consideration the need to emphasize the spatial characteristics of the model in their drawing. Since the assignments were computerized and the students had to submit mostly printed responses, they did not have much paper and pencil practice in drawing molecular models. This can explain the remaining difficulties in drawing spatial models that students were left with after practicing CMM.

Keig & Rubba (1993) investigated translation of representation performance between formula, electron configuration, and ball-and-stick model through think-aloud interviews. No treatment was provided and students' performance on translation was poor. Many students were unable to infer the formula from the ball-and-stick model of a simple substance. Students were also unable to complete model-to-formula translations, to prepare an adequate ball-and-stick model from the formula, and to translate tasks involving electron-configuration notation.

While designing the CMM environment, we assumed that our students would encounter the same difficulties described by Keig & Rubba (1993). The treatment in our case was immersing the students in the CMM environment. As a result, these students improved significantly their ability to make the transfer between molecular formula and spatial models, and vice versa.

Wu, Krajcik & Soloway (2001) investigated students who constructed molecules and viewed them in three types of representations: wire-frame, ball-and-stick, and space-filling using a visualization tool called eChem. The authors reported that high school students' ability to make transformations between 2D and 3D models improved after studying with eChem. Our students also worked with CMM visualization tools and improved their ability to conduct the different transformations.

The innovative aspect of our research is the case-study-based assessment tool that was developed specifically for this research and which enabled us to examine the extent of students' improvement in modeling skills. In addition to the content analysis, we also quantified students' responses and scored them. This assessment tool is adequate for carrying out research on large-scale populations as well as a means for chemical educators to analyze difficulties their students encounter while they engage in modeling molecules.

Outlook: A Policy Perspective

Higher-order thinking skills, such as question posing, critical thinking, argumentation, and system thinking, have been examined in previous studies in Israel (Zohar & Dori, 2003; Zohar & Nemet, 2002; Zoller, 1993). These researchers have shown that those skills can be learned even by low achieving students. Zoller (2002) called to move chemistry and science instruction from an algorithmic and factual recall orientation dominated by algorithmic, lower order cognitive skills to a decision making, problem-solving and critical thinking approach dominated by higher-order cognitive skills. Responding to this challenge, we developed the CCL & CMM environment for studying chemistry in a way that enables students to develop diverse higher-order thinking skills, including question posing, modeling, inquiry, graphing, and transfer skills (Dori & Kaberman, submitted; Dori, Sasson, Kaberman & Herscovitz, 2004; Kaberman & Dori, submitted; Sasson & Dori, 2008). Throughout the academic year, students experienced case-based formative assessment and were aware of the criteria their teachers were using. The rubrics we built in order to assess students' achievements in the questionnaires were presented to the students during chemistry lessons, so students knew how to respond to the assignments and which aspects need to be emphasized. The transparency in the assessment criteria was an important component in students' learning and teachers' instruction. Since chemistry instruction and the assessment of the learning quality were embedded as part of the chemistry learning process, students' higher-order thinking skills improved significantly. The embedding of a plethora of higher-order thinking skills that were applied and assessed in chemistry in the same research is yet another innovative aspect of this research.

Gilbert, De Jong, Justi, Treagust & Vav Driel (2002) reported, from their experience, that the consensus among chemistry teachers is that chemical education research has little impact on the development of theory, policy, or classroom practice. Our research had been proven to have a significant impact on the Israeli Ministry of Education policy: Our Case-based Computerized Laboratory (CCL) and the Computerized Molecular Modeling (CMM) learning unit brought about changes in the national chemistry matriculation examination in Israel. Students are now tested for their higher-order thinking skills in addition to their content knowledge. A case-study-based question is embedded nowadays in the matriculation examination and students are required to pose questions, analyze graphs, demonstrate inquiry skills, and transfer between molecular representations.

Another new element in the embedded assessment, which has become part of the Israeli matriculation examination in chemistry, is the portfolio. It has been included in the new examination format as a result of the inquiry-oriented laboratory learning unit and the research concerning this unit (Hofstein, Shore, & Kipnis, 2004).

This reform was made possible thanks to the cooperation between the Ministry of Education in Israel, the academia, and the teachers in the field (Barnea, 2004). The developers of the new laboratory learning units that were included in the reform constantly supported the teachers, ran long and demanding training programs in the summers and during the academic year, and constantly visited and supported the teachers at schools. As a result, all the teachers of the different laboratory programs were motivated to update and improve their teaching methods, further contributing to the success of the assimilation process of the laboratory unit in Israel (Dori, Barak, Herscovitz & Carmi, 2006; Hofstein, Levy Nahum & Shore, 2001).

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Note

[1] * = $p < 0.05$, ** = , $p < 0.01$, *** = $p < 0.001$

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Education of Tec. & Sc., Technion, Technion City, Haifa 32000, Israel
E-mail: yjdori@technion.ac.il