Chemical Understanding and Graphing Skills in an Honors Case-Based Computerized Chemistry Laboratory Environment: The Value of Bidirectional Visual and Textual Representations

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Abstract: The case-based computerized laboratory (CCL) is a chemistry learning environment that integrates computerized experiments with emphasis on scientific inquiry and comprehension of case studies. The research objective was to investigate chemical understanding and graphing skills of high school honors students via bidirectional visual and textual representations in the CCL learning environment. The research population of our 3-year study consisted of 857 chemistry 12th grade honors students from a variety of high schools in Israel. Pre- and postcase-based questionnaires were used to assess students' graphing and chemical understanding–retention skills. We found that students in the CCL learning environment significantly improved their graphing skills and chemical understanding–retention in the post- with respect to the prequestionnaires. Comparing the experimental students to their non-CCL control peers has shown that CCL students had an advantage in graphing skills. The CCL contribution was most noticeable for experimental students of relatively low academic level who benefit the most from the combination of visual and textual representations. Our findings emphasize the educational value of combining the case-based method with computerized laboratories for enhancing students' chemistry understanding and graphing skills, and for developing their ability to bidirectionally transfer between textual and visual representations. © 2008 Wiley Periodicals, Inc. J Res Sci Teach 45: 219–250, 2008
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A growing body of research is concerned with the contribution of external representations to high-level cognitive processing of information (Kozma & Russel, 1997; Larkin, 1983; Munneke,

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van Amelsvoort & Andriessen, 2003; Roth & McGinn, 1998; Toth, Suthers, & Lesgold, 2002). Following the dual-channel processing principles of cognition, humans process information concurrently via a visual channel and a textual-verbal channel (Mayer, 2002a).

Visual-based learning involves exposure to richly illustrated texts, multimedia, visual computer interfaces, and hands-on activities, in which students observe, form mental images, and analyze graphs and visualizations of scientific phenomena. ''Visible thinking'' involves making explicit or concrete the structure of knowledge or the mental models learners and experts use (Jacobson, 2004). Vision and imagery are different yet complementary concepts. Vision is the process of using the eyes to identify, locate, and think about objects, processes, and systems. Imagery is concerned with the formation, inspection, transformation, and retention of images in one's mind in the absence of a visual stimulus (Mathewson, 1999). Software interfaces enable users to construct, examine, and manipulate representations of their knowledge (Dori & Belcher, 2005a; Suthers, 2001). Our visual representation of knowledge includes hands-on experiments and real-time graph construction in a computerized chemistry laboratory environment.

The complementary medium through which concepts and ideas are conveyed is text. Our textual representation includes case studies, also known as case narratives, which are ''stories with a message'' or ''stories to educate'' (Herreid, 1997). Originating from business and medical schools, the case study method provides a context for exploring particular principles or problems (Sykes & Bird, 1992). Case studies are usually real stories, examples for us to study and apply and can make science more relevant to the students' daily lives (Herreid, 1994). They can be closed-ended or open-ended; they might require not only a single correct answer, but also various resolutions of a dilemma. Because open-ended cases may contain scientific aspects that involve emotions, ethics, or politics, they can present unresolved dilemmas or yield multiple solutions (Dori, Tal, & Tsaushu, 2003). Another source of ambiguity, which is purely physical, stems from incomplete specification of the problem conditions (http://www.physics.umn.edu/).

The objective of the research described in this article was to investigate 12th grade honors students' bidirectional visual and textual chemical understanding in the computerized chemistry laboratory (CCL) learning environment. Students were exposed to visual representations, which included hands-on experiments and real-time graph construction and interpretation, and textual representations of case studies.

The article is structured as follows. We start with a theoretical background on learning through inquiry in a laboratory environment. Next, we discuss visualizations in general and graph representations in particular, and conclude with case-based methods as teaching and learning tools. We then describe the CCL environment, the research objective, setting, population, and instruments. The results are presented in two parts: (1) outcomes of a 3-year study of experimental students' graphing skills and chemical understanding–retention, and (2) a comparison with control students' performance over the course of the last 2 years of the study.

Theoretical Background

Researchers have emphasized the benefit of incorporating laboratory activities into science teaching (Dori, Sasson, Kaberman, & Herscovitz, 2004; Hofstein & Lunetta, 1982; Lazarowitz & Tamir, 1994; Mintzes, Wandersee, & Novak, 2005; Redish, Saul, & Steinberg, 1997). Nakhleh, Polles, & Malina (2002) claimed that the most important potential contribution of the laboratory lies in developing and sustaining motivation for constructing chemical understanding rather than simply helping students memorize facts. Inquiry-based laboratories involve students in the process of conceiving scientific problems and questions, formulating hypotheses, designing experiments, gathering and analyzing data, and drawing conclusions (Hofstein & Walberg, 1995). The *National Science Education Standards* (NRC, 1996) indicated that inquiry is central to students' scientific literacy. Inquiry pertains to both content understanding on one hand, and thinking skills on the other hand. In the content aspect (Lunetta, 1998), students are encouraged to explain their experience and mentally construct concepts (such as mole or energy) and processes (such as acid-base chemical reactions). In the thinking skills aspect, Bybee (2000) and Hofstein and Lunetta (2004) included identifying and posing scientific questions, forming hypotheses, designing and conducting investigations, formulating and revising explanations, and defending scientific arguments. Laboratory activities enable students to learn and engage in a process of constructing knowledge while doing science (Tobin, 1990). According to Hofstein and Lunetta (2004) when science assessment doesn't include a component of practical knowledge, students do not value the contribution of the laboratory activities. The researchers also indicate that the ''cookbook'' laboratory activities do not foster the development of students' higher order thinking skills. However, in inquiry-based laboratory students are more involved, and usually have positive attitudes regarding their laboratory experience (Abd-El-Khalick et al., 2004).

CCL activities researched in this study include two components: the visua—real-time graphing, and the textual—case-based learning; both components were studied in the inquiry-based approach.

Visualization and Real-Time Graphing Technologies

Ausubel, Novak, and Hanesian (1978) claimed that humans have a genetic potential for representational learning, which is usually expressed by the end of the first year of life, when children acquire the insight that it is possible to use symbols. When a particular new proposition of representational equivalence is presented, the child is able to relate it to the already established and more generalized version of the same proposition in his or her cognitive structure.

Researching students and adults, Mayer (2002a) presented a cognitive theory that includes three theory-based assumptions about how people learn from words and pictures: (1) people use two channels in learning: the visual-pictorial channel and the auditory-verbal channel; (2) the channels can become overloaded when a lot of spoken words and pictures are presented; (3) meaningful learning occurs when learners engage in active processing within the channels, including selecting relevant words and pictures, organizing them into coherent pictorial and verbal models, and integrating them with each other while incorporating prior knowledge.

Designing visualization-rich learning environments, which foster meaningful learning, seems to be one of the main goals of educators and curriculum developers. Computerized laboratories and molecular modeling in schools have gained recognition as important instruments in this effort (Barnea & Dori, 1999; Dori, Barak, Herscovitz, & Carmi, 2006; Jones & Atkins, 2000; Kozma, Chin, Russel, & Marx, 2000).

Graphs are visual displays that depict the relationships between continuous variables in pictorial form (Mckenzie & Padilla, 1986). Real-time graphing, formerly known as MBL—Microcomputer Based Laboratory, occurs when data is measured and calculated in real time and is dynamically displayed on a graph. The value of real-time graphing lies in the ease with which data can be collected with various probes and stored in a computer or a calculator (Kown, 2002; Nakhleh et al., 2002). The observer perceives the measurements to be displayed at exactly the same instant as the phenomenon is occurring (Ainsworth & VanLabeke, 2004). Allowing for frequent repetition, this technology provides opportunities to vividly experience graphical, chemical, and physical phenomena.

The ability to access data over time intervals of varying durations and the power to rapidly process and display the collected data alleviates students from these mundane tasks, leaving them more time to test hypotheses, manipulate variables, and explore relationships (Russell, Lucas, &

McRobbie, 2004). One might expect science major students to apply mathematical skills into scientific content knowledge assignments (e.g., application of graphing skills in chemical equilibrium). Investigating the way physics students apply mathematical understanding in graphing skills assignments, Woolnough (2000) suggested that students encounter difficulties connecting between three worlds: the science world—the theories and principles of science, the mathematical world—the domain of symbol manipulations, and the real world—the investigated phenomena.

Indeed, although graph construction and interpretation have been identified as important skills in science education, many students do not succeed in acquiring these skills (Beichner, 1994, 1996; McDermott, Rosenquist, & Van Zee, 1987; Padilla, McKenzie, & Shaw, 1986; Roth, Bowen, & Mcginn, 1999). However, computerized technology may positively affect students' graphing skills, leading to better understanding of science phenomena (Adams & Shrum, 1990; Beichner, 1996; Dori et al., 2004; Nakhleh & Krajcik, 1994; Kown, 2002; Redish, 2003).

The effect of real-time graphing technology on learning processes was investigated in several science disciplines, especially in physics. The presentation of graphs in real time plays a central role in addressing specific science concepts. By linking the displayed graph image to the simultaneously observed phenomenon, real-time graphing helps teaching the basics of how to interpret graph images produced in real-time experiments, thereby improving students' graphing skills (Brasell, 1987; Sassi, Monroy, & Testa, 2005; Thornton & Sokoloff, 1990). Comparing the relative effect of traditional laboratory with real-time graphing on fostering students' conceptual change, Svec (1999) investigated students' ability to interpret and use graphs to improve grasping kinematics concepts and apply them to new nongraphic problems. Using specialized tests he found significant differences in favor of real-time graphing compared with traditional laboratory students.

The effect of graphs' generating and interpreting as well as real-time graphing on students' learning outcomes was investigated in chemistry by Nakhleh and Krajcik (1994).

The importance of integrating real-time graphing and simulation as visualization tools into physics education for supporting students' active learning is well established (Dori & Belcher, 2005b; Scheker, 1998; Thornton & Sokoloff, 1990). In chemistry education, research has established that computerized molecular modeling is valuable to students in high school and higher education (Barnea, 2000; Barnea & Dori, 1999; Dori, Barak, & Adir, 2003; Wu & Shah, 2004). However, research regarding the effect of real-time graphing as part of inquiry-based laboratory on students' chemistry understanding has been sparse (Russell & Kozma, 2005).

The Case Study Teaching Approach

Case studies have been viewed as ''windows into science classrooms'' and as contributors to professional development and teacher preparation (Tobin, Kahle, & Fraser, 1990). According to Kobballa and Tippins (2000), the use of case studies features several themes: cases as a tool for professional preparation and development, cases as a discipline-based teaching method, cases for facilitating critical thinking and exploring dilemmas, and cases as an assessment tool. Several researchers (Dori, 2003; Dori & Herscovitz, 1999, 2005; Tal & Hochberg, 2003) emphasized the use of case studies as science-based teaching and assessment tools and argued that the case-based method helps the development of students' and teachers' higher order thinking skills.

Lohman (2002) and Mayer (2002b) have characterized the case study as a semistructured, expert-oriented, nonroutine problem, which requires the reader to list and evaluate possible causes and solutions. They claimed that learning outcomes of students who study using the case-based method include transfer of content knowledge and skills, and the ability to solve authentic problems. The case study method fosters a constructivist learning environment and provides for evaluating students' higher order thinking skills (Dori, 2003; Wassermann, 1994). Heller, Keith, and Anderson (1992) and Heller and Hollabaugh (1992) define context-rich problems as short stories that include a reason for calculating some quantity about a real object or event. The problem statement does not always explicitly identify the unknown variables, information may be missing, and reasonable assumptions may be needed. They found that groups were more likely to use an effective problem-solving strategy when given context-rich problems than when given standard textbook problems.

Higher order thinking skills have been described as complex skills with no simple algorithm for constructing a solution path (Resnick, 1987). Solving assignments that require higher order thinking skills are also referred to in the literature as ill-structured problems (Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004). These assignments are based on real-world issues and call for a variety of thinking patterns that are not well defined and have no definite single correct response. Zoller (1993) claimed that a major goal of chemical education is the development of students' reasoning, critical thinking, problem solving, and decision-making abilities. Achieving this requires appropriate teaching and examination strategies and implementing assignments that call for higher order cognitive skills. Students should construct a deep conceptual understanding of any scientific topic they study rather than simply learning to apply algorithms to problem sets (Zoller & Tsaparlis, 1997).

Each one of the CCL components surveyed above was aimed at fostering students' higher order thinking skills in both the visual and the textual channels. Lunetta and Tamir (1979) included in graphing skills the abilities to process data, construct graphs, describe and interpret graph representations, compare between graphs, and draw conclusions. In the visual channel, graph construction and analysis, which requires chemical understanding, is considered a higher order thinking skill. Each inquiry-based CCL session started off with an environmental, biological, or industrial case study. Using the textual channel, students had to apply previous chemical understanding in new learning situations and transfer their knowledge across domains.

Research Setting

Since the early 1950s, Israeli high schools have been accustomed to preparing their students to pass the national matriculation examinations. Therefore, at least until the last decade, emphasis was put on students' required knowledge to the external tests rather than the implementation of variety of teaching strategies and assessment modes. During the recent years, when alternative assessment approaches have begun attracting researchers' and educators' attention, the chemistry matriculation examinations in Israel started to be supplemented with new modes of assessment. The reform in the chemistry curriculum included (1) specializing in inquiry-based laboratory activities; (2) changes in the content of the high school chemistry syllabus such as a reduction in the compulsory topics, providing teachers with more flexibility; and (3) changes in the way students are assessed regarding their progress and achievements (Barnea, 2002; Dori, 2003; Hofstein, Shore, & Kipnis, 2004).

A CCL study unit that we developed at the Technion was designed for 12th grade honors chemistry students with embedded assessment in mind (Dori et al., 2004). The honors students' curriculum in Israel consists of five units (the maximum), which students study for the national matriculation examination. The CCL curriculum, developed within the framework of reforming the Israeli honors students' chemistry curriculum, integrates computerized desktop experiments with emphasis on scientific inquiry and case studies. The CCL activities included case studies, data collection using temperature, pH, and conductivity sensors, graphs construction in real time, and interpretation of the results.

Three goals guided the CCL study unit developers: integrating laboratories activities as an important tool to foster inquiry skills, designing educational disposition aimed at developing higher order thinking skills, and using advanced data collecting method based on computerized sensors. The study unit contains five independent laboratories units, with total 13 computerized experiments. Each laboratory unit includes five (45-minute) lessons. All the topics of the laboratories are based on previous chemical knowledge students gained. The CCL learning contents include: liquids and solutions, colligative properties, salts precipitation, acids and bases, energy, diffusion and osmosis (Dori et al., 2004, 2006). Table 1 demonstrates the CCL unit structure and presents several examples of the various components.

The assignments in the study units emphasized the need to deal with and to transfer between four chemistry understanding levels: (a) the symbol level that contains formulae, equations, and graphs; (b) the macroscopic level that includes the observable/tangible phenomena; (c) the microscopic level in which the student need to give explanations at the particle level (Gabel & Bunce, 1994; Johnstone, 1991; Nakhleh & Krajcik, 1994; Treagust, Chittleborough, & Mamiala, 2003). [Gabel and Bunce (1994) and Treagust et al. (2003) used the term submicroscopic. We prefer the term microscopic since using current technological advances it is possible to visualize molecules and atoms using variety of microscope types]; (d) the process level, which deals with the way substances react with each other (Dori & Hameiri, 2003; Dori et al., 2003, 2004). The process level can be explained in terms of one or more of the first three levels.

Table 1
The CCL structure

CCL Learning Stages	Components	Example
Theoretical inquiry	Case study that deals with the topic of the laboratory	'Hygiene demands: No more dental cavities!'—The chemical aspects of the cavity generation process and the chewing-gum effects
	Assignments aimed at developing higher order thinking skills	Inquiry skill assignment:
		Plan a simple experiment aimed at evaluating the claim: 'chewing a sugar- free gum decreases the mouth acidity after meal.' What is your research question? What are the investigated variables (dependent and independent)? What is your hypothesis?
Laboratory-guided inquiry	Guided inquiry process. Students conduct a computerized experiment	How does the acid strength affect the acid-base titration curve?
	Data analysis with emphasis on chemical understanding	The graphs present in Figure 1 describe the results of acid-base titration
Further investigation-Independent inquiry process	Students are asked to suggest ideas for further investigation. An independent stage for a new open-ended experiment that they are required to conduct by themselves	In which ways do the titration curve and the equivalent point differ when different acids are in use?

Our research combined textual and visual representations to enhance students' chemical understanding. As part of the learning environment, both representations had to be applied bidirectionally. Students were provided with textual knowledge representations, mainly in the case studies, and were required to express their chemical understanding in both text and graph construction; for example, they had to describe and explain the relationships between two investigated variables and to predict the shape of the curve of the corresponding graph. Conversely, students were provided with graphs that were constructed in real time while they were carrying out inquiry-type experiments. They were asked to textually describe, interpret, and reason about the generated graphs using as many levels of chemistry understanding as possible.

During the CCL class assignments teachers frequently request that their students describe and explain various regions on a given graph and determine the curve trend. This was done both verbally in class discussions and in writing as part of a laboratory report either individually or as a group. Teachers also encouraged their students to compare a variety of graphs (derived from their own experiments or provided in the learning unit) with a specific focus on similarities and differences.

The research includes two parts: (1) a 3-year study of experimental students' graphing skills and chemical understanding–retention, and (2) a comparison of CCL students with control students over the course of the last 2 last years of the study.

Research Objective and Questions

The main visualization component in the case-based computerized laboratory is graph representations in real time, while the "hands-on" aspect of the experiments adds another important component. The research objective was to investigate 12th grade honors' chemical understanding and higher order thinking skills using both visual and textual means in the CCL learning environment. The research questions included:

1. What is the effect of the CCL environment on students' ability to bidirectionally express visual and textual chemical knowledge via: (a) describing, interpreting, constructing, comparing, and analyzing graphs, and (b) expressing their chemical understanding through both graphs and text?

2. What are the differences (if any) between experimental group and the control group in chemical understanding–retention and graphing skills?

3. What are the characteristics of the visualizations aspects in the CCL environment as expressed by students' reflection on the learning processes?

Research Population

The Experimental Group

About 800 chemistry 12th grade honors students from 15 high schools in Israel participated in this 3-year study. These students elected to study chemistry at an honors level when they entered high school (10th grade) and made a commitment to specialize in chemistry during 3 years (until the 12th grade).

Sixteen teachers who were trained to use the computerized laboratory tools and the case-based method in their classrooms taught these students. The teachers came from a variety of schools and geographic areas. In the first year, the research focused on 196 12th grade honors students who studied the CCL curriculum—experimental group first stage. In the second and third year, we investigated 599 honors students who studied the CCL curriculum—experimental group second and third stages. Students in all the research stages were evaluated for chemical understanding and graphing skills. Teachers of all the research stages participated in a week-long CCL summer training program at the Technion. The teachers of the experimental group also participated in an on-going training program throughout the academic year. Because they received support in teaching the CCL study unit, they fully cooperate with the researchers.

The Control Group

The control group consisted of 62 12th grade honors students who studied chemistry in other teaching modes in parallel to the experimental group second and third stages. Most of the control group students studied in inquiry-based laboratory (labeled Control I) with emphasis on reading and interpreting scientific articles with industrial orientation. Students in this group used Microsoft Excel to draw graphs off-line but did not focus on developing graphing skills. The rest of the control group students studied in a traditional setting (labeled Control T) without routine laboratories activities. These students were exposed to graphs in books and assignments but there was no emphasis on analyzing graphs.

As the research was conducted in real-life classrooms, we were faced with limitations that affected the ideal statistical random sample (Rennie, 1998).

Due to lack of suitable equipment or for other reasons, such as the need for time to prepare the student for the matriculation examinations, some of the teachers who participated in our summer training decided not to implement the CCL learning unit. These teachers were asked to serve as the control group. Lacking the same level of commitment for the research as the experimental teachers, only four of them ended up participating in the research with their students as two control groups. Each one of these teachers had at least 10 years of chemistry teaching experience and taught in honors classes. Most of the experimental teachers had the same level of experience, but some were relatively new to the profession (for more details see Dori et al., 2006).

In both the experimental and the control classes, teachers emphasized the same topics, such as chemical structure and bonding, acids and bases, and energy. Students were exposed to graphing skills in both the experimental and the control classes, but the emphasis and the pedagogical approach were different. The experimental students studied the CCL program, which is based on real-time graphing and case studies. They were exposed to real-time graph representation and engaged in inquiry activities aimed at developing their higher order thinking skills with emphasis on graphing. The case studies matched the subject matter taught in the laboratories activities. The control I students, who used the Excel software, generated graphs after gathering data during inquiry based activities. They also engaged in activities based on modified scientific articles, which were not necessarily related to the laboratory activities. The control T students, who learned in a traditional teacher-centered style with a few laboratory activities, were exposed to graph representations only during theoretical activities with assignments that included interpretation of graph images. The teachers of the two control groups did not systematically emphasize the graphing skills during their laboratories activities. Table 2 presents the research design at the second and third stages, sorted by classes and teaching methods.

Table 2
Research population sorted by classes' type and teaching methods

Research Group	Main Teaching Characteristics	Exposing Students to Graphing Skills	Main Topics
Experimental Group	Case-Based Computerized Laboratories	Theoretical and Practical Activities Using MBL-Type Experiments	
Control group I	Integrating laboratory activities and modified science articles with emphasis on inquiry	Theoretical and practical activities using Excel software	Implementation of Chemical Structure and Bonding, Acids and Bases, and energy
Control group T	Traditional teacher-centered teaching style with a few laboratory activities	Theoretical activities	

Methodology

Research data from the pre- and postcase-based questionnaires were gathered and calculated for the experimental and control group students alike. However, because the number of control students was small compared with the number of the experimental students, in the comparison between these two research groups we used only the low and high performers (and not the entire experimental group). We refer to this research limitation as well as to others in the discussion.

To gain a broad view of the CCL environment, we used both quantitative and qualitative research tools (Denzin & Lincoln, 2000; Johnston & Onwuegbuzie, 2004). In this article we present the results of case-based questionnaires and part of a reflection questionnaire. In an upcoming article (Sasson & Dori, submitted) we present results of students' interviews.

Case-Based Questionnaires

Pre- and postcase-based questionnaires were designed to assess the students' higher order thinking skills. In addition to graphing skills and retention, the questionnaires included a variety of assignments for investigating various thinking skills, such as question posing and inquiry (Dori et al., 2004). In this article we focus on investigating graphing skills and chemical understanding–retention. However, to determine the students' academic levels in the precase-based questionnaire, the assignments for all the thinking skills were accounted for. The case-based questionnaires were each year of two types: A and B. These two types contained similar questions with slight variations but different case studies (to avoid the effect of prior exposure in the pretest to questions that would later appear in the posttest). About half of the students from each class responded to type A pretest and then took type B in the posttest. The other half of the students responded to type B pretest and to type A in the posttest. Statistical analysis of the results revealed no significant differences between the two test types.

The questionnaires were analyzed in two phases. In the first, qualitative phase, we applied content analysis of students' responses to extract categories, and used them to characterize students' responses. In the second, quantitative phase, we scored each student's response using rubrics (see, e.g., Tables 3 and 12) and statistically analyzed the results. The potential maximum normalized total score for all the assignments in the case-based questionnaire was 100.

Aimed at responding to research questions A and C, we focused on graphing skills, while for research question B we looked into students' chemical understanding and its retention. The latter skill also served as a baseline in the comparison between the three modes of teaching in the different research groups: experimental, Control T, and Control I.

Because the CCL study unit emphasizes comprehension and transfer across the four chemistry understanding levels, we evaluated students' chemical understanding by their comprehension of and transfer across these levels. The graphing skills assignments differed each year according to the subject presented in the case study. However, all the questions shared the same characteristics. The students were asked to process data and identify the relationship between variables, construct a graph that explains this relationship, describe and interpret the

Table 3
Rubric for assessing students' graphing ability

Chemistry level Score	Symbol—Graph	Macroscopic—Textual response	Microscopic—Textual response	Bidirectional transfer between graphical and textual representations
0	Wrong or irrelevant graph	Wrong or irrelevant reference to macro level	Wrong or irrelevant reference to micro level	Correct hypothesis (textual representation) but no graph, correct graph but no hypothesis or the graph is not suitable to the hypothesis
1	Partial performance of the graph (correct curve, but the variables are not well defined or vice versa)	Partial reference to macro level (correct variables but wrong relationship or vice versa)	Reference to one aspect of the micro level	Partial connection between the hypothesis and the graph
2	Correct curve, which properly describes the relationships between variables. The variables are well identified. Units for variables are indicated	Correct reference to the relationship between the two variables: the water temperature and the organic compound solubility	Reference to at least two aspects of the micro level: An increase in the particles' kinetic energy, breaking off hydrogen bonds between water molecules, a decrease in water molecules polarity, Van Der Vaals interactions between water and organic molecules	The hypothesis suits the graph representation

Organic solvents - OUT, Green solvents - IN

Many organic solvents are commonly used in industry. For example, carbon tetrachloride, CCl_4 is a non-colored liquid, which is commonly used as a solvent for some oils and resins. Terpentine is volatile oil, which is composed mainly of non-saturated hydrocarbons derived from Isoprene (C_5H_8).

Many organic solvents have been found to be hazardous for human health and for the environment, so finding new green solvents has become essential.

Two common alternative solvents are water (H_2O) and carbon dioxide (CO_2).

The use of water as an efficient solvent for a variety of chemicals in industry was limited due to the high polarity of water molecules at room temperature.

Superheating of water, achieved by high levels of pressure and temperature (between 100°C to 374°C), decrease the water polarity. The solubility of superheated water (below 210 °C) is similar to the solubility of a methanol (CH_3OH) and water mixture.*

Figure 1. An example of a case study—second stage.

*The effect of entropy on solubility of superheated water was not included in this case study.

*Based on the case study you read, write a possible hypothesis about the solubility of an organic compound in water as a function of the water temperature. Explain your hypothesis and draw a suitable graph.**

Figure 2. An example for graphing assignment type B—second stage.

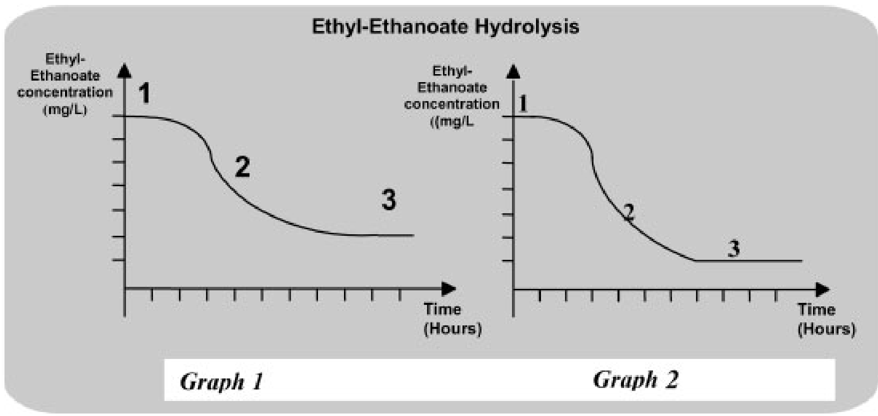
*Figure 1 presents only the opening paragraph of the case study. For replying the assignment presented in Figure 2, students used further information from the case study and chemical understanding based on their previous chemistry learning.

graph, compare between two graphs, and draw conclusions. Figure 1 presents an opening paragraph from one of the case-based questionnaires, in which students were presented with text describing the use of solvents in industry. We show the assignments for this case study and describe the characteristics of the graphing skills required in these assignments in Figure 2 (for type B assignment) and Figure 3 (for type A assignment).

Content analysis of students' responses to both type A and B assignments was carried out according to two aspects: subcategories of the graphing skills and the invocation of a maximal possible subset of the four levels of chemical understanding—symbolic, macroscopic, microscopic, and process—to respond to a chemical question or explain a phenomenon. We evaluated the type and frequency of the different chemistry understanding levels students invoked in their answers and the quality of their explanations. In addition, we investigated the compatibility between their verbal and graphical representations. Figure 4 summarizes the way we evaluated students' graphing skills while carrying out the case study assignments.

In the chemical understanding–retention assignment, the students were asked to recall and apply previous knowledge related to the case study (see Fig. 5).

Ethyl-ethanoate is an organic solvent, which was used in the past for extracting caffeine from coffee. In ethyl-ethanoate hydrolysis, which occurs in acid solution, the products are ethanol and acetic acid. The two graphs below describe two hydrolysis experiments, conducted in different conditions.



1. *Describe and explain the regions on graph 1 marked as 1, 2, and 3.*
2. *Is it possible to calculate the maximum quantity (in grams) of the Ethanoic acid (Acetic acid) produced by the hydrolysis process? (Assume that data on the graph axis are presented in specific numbers). Explain your answer.*
3. *Compare between the two graphs and indicate their similarities and differences.*
4. *Explain the differences between the two graphs. What was the researchers' conclusion?*

Figure 3. An example for graphing assignment type A—second stage.

The retention assignment required students' previous understanding of inter- and intramolecular bonding. Students studied this subject, mainly theoretically, as part of the chemical structure and bonding topic, which was taught a year earlier. They were tested on this topic at the end of 11th grade as part of the basic (three units) chemistry matriculation examination. The students responded to the pre- and the postcase-based questionnaire about 5 (pre) and 12 (post) months after this topic was taught.

Data Analysis of the Case-Based Questionnaires

To assess students' responses to the assignments in the case-based questionnaire, we developed rubrics. One-tenth of all the students' responses were scored and validated by five

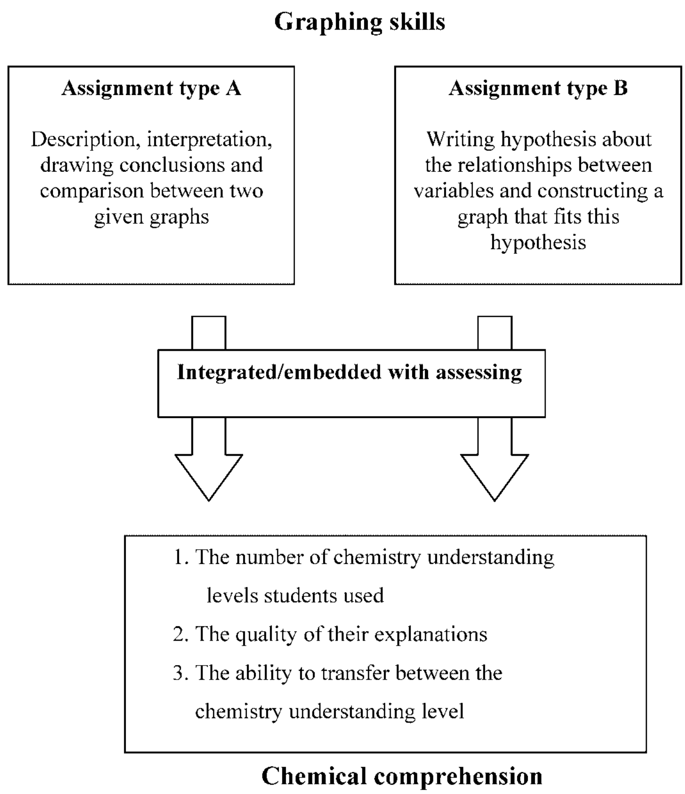


Figure 4. Assessment of the graphing skills in type A and B assignments.

chemical educators (two researchers and three doctoral students), achieving 90% interraters reliability. The examples, which we present in the sequel, were taken from the “Organic solvents—OUT, Green solvents—IN” case study (see Fig. 1). Students were asked to hypothesize about the solubility of an organic compound in water as a function of the water temperature (assignment type B). They were required to provide both an explanation for the hypothesis and a suitable explanatory graph. An example of an excellent response for this assignment is one that contains the symbol, macroscopic, and microscopic chemistry understanding levels. We also evaluated the compatibility between the hypothesis (textual representation) and the graphing (visual) representation.

Table 3 presents an example of a rubric we used to assess students’ ability to describe the hypothesis and to construct a suitable graph (assignment type B).

Figure 6 presents a response written by student C., which is representative of type B assignment (shown in Fig. 2).

Using the rubric presented in Table 3, one can see that student C drew the correct curve, in which she correctly identified the variables and properly described the relationships between

Based on the molecular structure explain why isoprene (C_5H_8) dissolves well in carbon tetrachloride (CCl_4) but not in water (H_2O) at room temperature.

Figure 5. A chemical understanding–retention assignment given in the second stage.

"When the water temperature increases, the hydrogen bonds between water molecules become weaker and more water molecules are tied to organic molecules by Van Der Vaals interactions. As the temperature increases, the water molecules polarity decreases."*

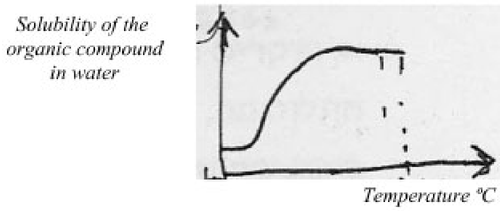


Figure 6. Student C's response to graphing assignment type B.

*In the classroom language it means that part of the hydrogen bonds is broken down.

them. Units for the variables were mentioned partially. Her textual explanation included the correct reference to the relationship between the two variables: the water temperature and the organic compound solubility. Two aspects regarding the microscopic level were mentioned. There was only partial connection between the hypothesis and the graph, because the student did not describe and explain textually the plateau in the curve. As Table 4 shows, student C gained six points out of eight in this assignment.

Table 5 presents the calculation of the score of student L's response (see Fig. 7) to type B assignment as well. His score was three points out of eight.

Student C and L scores in this assignment expressed their performance in the graph construction skill, one of the categories of graphing skills, which were identified by Lunetta and

Table 4
Student C score calculation

Chemistry Level	Symbol—Graph	Macroscopic—Textual Response	Microscopic—Textual Response	Bidirectional Transfer between Graphical and Textual Representations
	Correct curve, which properly describes the relationships between variables. The variables are well identified. Units for variables are partially mentioned	Correct reference to the relationship between the two variables: the water temperature and the organic compound solubility	Two aspects regarding the microscopic level were mentioned	Partial connection between the hypothesis and the graph because the student didn't describe and explain in words the plateau in the curve
Score	1/2	2/2	2/2	1/2

Table 5
Student L score calculation

Chemistry Level	Symbol—Graph	Macroscopic—Textual Response	Microscopic—Textual Response	Transfer between Graphical and Textual Representations
	The variables are not well identified. Units for variables are not mentioned.	Correct reference to the relationship between the two variables: the water temperature and the organic compound solubility	No aspect related to the microscopic level was mentioned	The graph presents tendency that is contrary to the hypothesis. While presenting the correct ratio between the temperature and the solubility in the textual representation, the student drew the curve in the reverse direction.
Score	1/2	2/2	—	0/2

Tamir (1979). These categories include data processing, graph construction, description and interpretation, comparison, and drawing conclusions. The assignments types (A and B) described in Figure 4 focused on students' performance in these categories.

Content analysis of students' responses for all the graphing assignment types in the case study was based on the same method. Question scores and category scores were calculated (see Table 12 in Appendix 1 for the rubric of description and interpretation skill).

In chemical understanding–retention assignments, students had to recall and apply previous knowledge. For example, in the retention skill assignment students were asked to explain why isoprene—C_5H_8—is highly soluble in carbon tetrachloride—CCl_4—but not in water—H_2O (see Fig. 5). Here, most of the students (95%) used only the microscopic level in their responses. Table 6 presents several examples of student responses to the retention assignment.

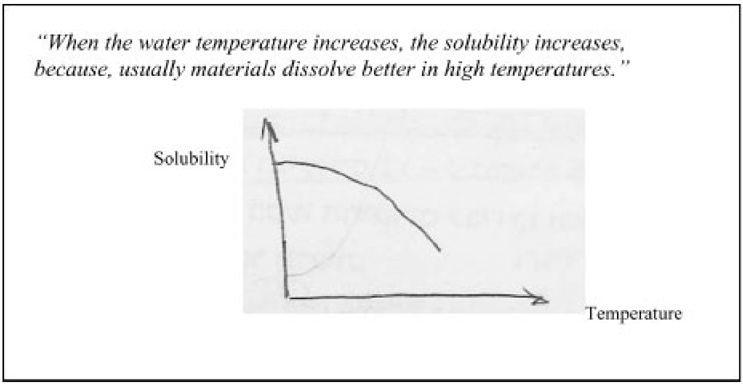


Figure 7. Student L's response to graphing assignment type B.

Table 6
Examples of students' responses to chemical understanding–retention assignment—second stage

	Students' response	Assessment features
Example 1: Adequate response	CCl_4 and Isoprene are not polar molecules. Between these molecules there are Van Der Vaals interactions and that's why Isoprene is well soluble in CCl_4. Due to its angle shape, H_2O is a polar molecule. Between the water molecules there are hydrogen bonds. Only polar materials can generate intra-molecules forces with water molecules, and that's why Isoprene is not soluble in water	Correct reference to both inter and intramolecules forces. In the response the student mentioned the isoprene solubility in CCl_4 and insolubility in water.
Example 2: Insufficient response	'Isoprene is well soluble in CCl_4 because both of these materials have Van Der Vaals interactions between molecules. Van Der Vaals interactions are generated between the isoprene and the CCl_4 molecules. Isoprene is not soluble in water because there are hydrogen bonds between the water molecules.'	Partial reference to the microscopic level without mentioning intermolecular forces types. He mentioned only the intramolecular forces between the molecules
Example 3: Insufficient response	'CCl_4 molecule has tetrahedral shape. Both the CCl_4 and Isoprene are not polar molecules and they have weak bonds between molecules. That's why the Isoprene is soluble in CCl_4. water molecule has a bent shape and polarity characteristic. That's why the isoprene is not soluble in water.'	Partial reference to the microscopic level without mentioning intramolecular forces types. Correct reference to the symbol level. The student integrated correct molecular structural models of CCl_4 and H_2O (missing the pair of nonbonding electrons).
Example 4: Wrong response	'Isoprene molecules create covalent bonds with CCl_4. Isoprene can't create hydrogen bonds with the water molecules.'	Wrong reference to microscopic level. Confusion between intramolecular bonds and intermolecular bonds.

Qualitative Tool—Reflection Questionnaire

Students were asked to respond to an open-ended reflection questionnaire, which dealt with their perceptions on the learning processes in the CCL environment. In this research we focused on two questions (out of six): "Explain in what way, if any, the case-based computerized laboratory contributed to your understanding of chemical phenomena?" "Describe components in the case-based computerized laboratory learning unit that you liked and disliked, and explain why."

Content analysis of students' responses focused on analysis of sentences that reflect on the contribution of the visualization components and the CCL program as a whole.

Findings

Our findings are presented in the following order. First, we refer only to the net gain (i.e., posttest minus pretest scores) in the graphing skills as a whole for the experimental group students in each one of the three experiment stages (years). Second, we present the net gain for each one of the five graphing skills in each stage. Next, we focus on the second stage experimental group students regarding the expression of chemistry understanding levels through graphing skills. We then examine an example from the second stage experimental group students regarding graphing skills by academic levels. Finally, we compare high and low performers of the experimental group students (from second and third stage combined) to their control counterparts in two skills: graphing and chemical understanding–retention. These results are sorted and analyzed by academic level.

Each student (and some of the teachers) participated in only one of the three stages. The Mixed Procedure technique (General Linear Model—GLM) was used throughout to analyze the data of the experimental group for all three stages of the experiment.

Graphing Skills Net Gain

Table 7 shows that the net gain of the CCL experimental students' graphing skills as a whole improved significantly in each one of the three stages. High results of the effect size, which is a standardized mean difference, indicate a worthwhile educational effect (Rennie, 1998), which is also replicable in the Israeli high school honors population.

Net Gain for Each One of the Five Graphing Skills

To gain deeper understanding of these results, we analyzed the data according to each one of the five graphing skill categories: data processing, graph construction, description and interpretation, comparison, and drawing conclusion. Pre–post comparisons of these five graphing skill categories in the first, second, and third stages are presented in Figure 8a, b, and c, respectively.

The net gain scores of all three stages show that on average the graphing skills scores in the posttest were about twice as much as the scores in the pretest.

Table 7
Experimental group students' net gain scores in graphing skills

Research stage	*N*	Net Gain	S E	*t* Value	Effect Size
1st	196	37.6	3.0	13.6*	0.9*
2nd	235	27.4	1.9	14.8*	0.9*
3rd	364	38.0	1.8	20.1*	1.1*

*$p < 0.0001$.

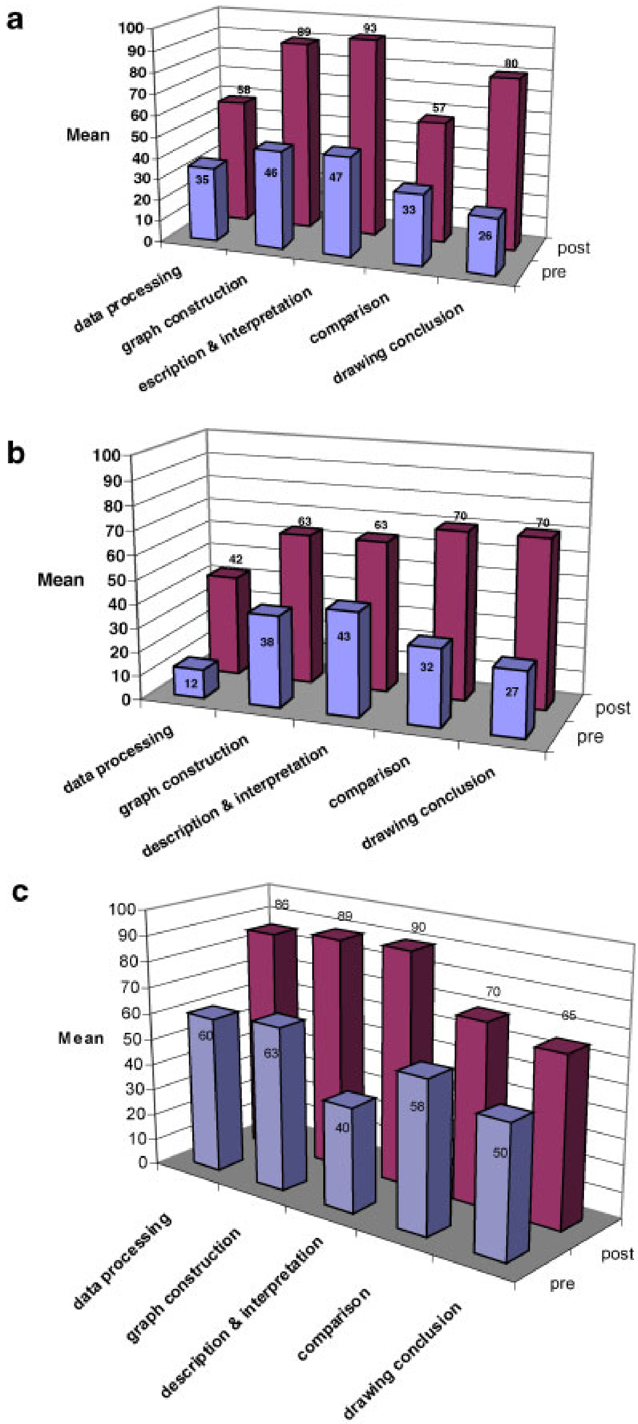


Figure 8. (a) Experimental group pre- and posttest average scores of the five graphing skills—first stage. (b) Experimental group pre- and posttest average scores of the five graphing skills—second stage. (c) Experimental group pre- and posttest average scores of the five graphing skills—third stage.

Table 8
Frequency of using chemistry understanding levels in graph constructing and reasoning in the pretest and posttest by second stage experimental group

	Frequencies of the number of chemistry understanding levels (%)			
Questionnaire	None	One	Two	Three
Precase-based	28	6	46	20
Postcase-based	3	2	41	54

Table 9
Students' net gain in graphing skill—experimental group sorted by academic level, second stage

Academic Level	*N*	Net gain	SE	*df*	*F* Value	Effect Size
High	50	21.1	3.8	227	30.2*	0.6*
Intermediate	133	26.5	3.4	368	59.1*	0.4*
Low	52	35.5	4.1	237	76.0*	1.4*

*$p < 0.0001$.

Expression of Chemistry Understanding Levels through Graphing Skills

As described earlier, type B assignment called for prediction of curve shapes based on the information provided in the case study and the student's previous chemical understanding. To investigate students' understanding of chemical phenomena, especially in type B assignments, and explore how they construct and explain graphs, we tested in both the pretest and the posttest the usage of the four levels of chemistry understanding—symbolic, macroscopic, microscopic, and process.

As presented in Table 4, constructing the graph required three chemistry understanding levels: symbol, macro, and micro. Table 8 presents the distribution of chemical understanding level combinations in the responses of experimental students in the second stage to the graph constructing and reasoning question.

As Table 8 shows, in the pretest, 28% of the students did not use any chemistry understanding level in their graph explanation and only 20% combined the three levels (symbol, macro, and micro). In the posttest, however, 54% of the students combined the three levels in their responses, an almost threefold increase. Only few students (5%) in the posttest used less than two chemistry understanding levels, compared with 34% in the pretest. These specific results are for the second stage. Similar results were also obtained for the first and third stages.

The Effect of Academic Level on Graphing Skills

To analyze the effect of academic level on graphing skills, we divided the experimental student population using Duncan's Multiple Range Test into three academic levels—low, intermediate, and high—based on their total pretest scores. The total score of the pretest questionnaire was calculated based on the average scores of all the thinking skills, including question posing, chemical understanding–retention, inquiry, graphing, modeling, and transfer skills.

Table 9 presents students' change in graphing skills sorted by academic level. We would like to emphasize that the low academic level students, described in this study, are relatively "low performers'' because they are science-oriented students who elected to study chemistry at an honors level.

Comparison between the Experimental and Control Group Students by Academic Levels

We compared the experimental group students from second and third stage combined with their control counterparts. The comparison, which was done in two phases, was based on two skills: graphing and chemical understanding–retention. In the first phase we compared all the students in the experimental group to those in the control group. In the second phase, the comparison between the experimental and control groups was based on academic level: we compared the low and high academic level students in the experimental group separately to their respective peers in the control group.

Using the General Linear Model Procedure for comparing average net gain scores of the experimental group ($N = 599$) with that of the control group ($N = 62$), we found that the experimental students demonstrated better graphing skills ($t = 7.76$, $p < 0.0001$ for the second stage and $t = 4.82$, $p < 0.0001$ for the third stage). No statistical differences were found with respect to chemical understanding–retention. Regression lines of the experimental and control groups using students' pretest and posttest scores in graphing skills indicated positive relationship between the pretest and posttest scores for both the experimental and the control groups. For both research groups (experimental and control), a high score in the pretest questionnaire may predict a high score in the posttest one, however, being in the experimental group predicts an even higher score in the posttest.

As described in the Population section, most of the control group students studied in inquiry/industry-oriented laboratory with emphasis on reading and interpreting science articles, while the rest of the control group students studied in a traditional setting without routine laboratories activities. The inquiry/industry-oriented control group was denoted C-I and the traditional group, C-T. We performed a statistical comparison between the experimental and control groups for high academic and low academic level students, separately. The high academic level students studied in the inquiry/industry-oriented approach only. The low academic level of the control was a mix of both C-I and C-T. The first step in the analysis was to compare the pretest scores of the high academic level experimental students to the pretest scores of their peers in the control group. We found no significant differences for each of the stages (second and third). We then compared the pretest scores of the low academic level experimental students to the pretest scores of their peers in the control group and again found no significant differences for each of the stages (second and third).

Because the results in the second and third stages were similar, we combined the two stages. Figures 9 and 10 present pretest and posttest mean scores in graphing skills and retention, respectively, sorted by research group and academic level for these stages.

High academic level control group students did not improve their graphing skills during their 12th grade chemistry course. The highest improvement in graphing skills was among low performers in the experimental group (labeled ''exper. Low''), who improved from 25 to 68, as shown on the right-hand side of Figure 9. Both high and low performers of the experimental group gained significantly higher graphing skills' net gain scores in comparison to their control group peers.

Having obtained these positive results, we went on to examine whether a similar effect of the CCL learning approach exists in students' chemical understanding–retention skill. Figure 10 presents the pretest and posttest mean scores in chemical understanding–retention for the experimental and control groups sorted by academic level.

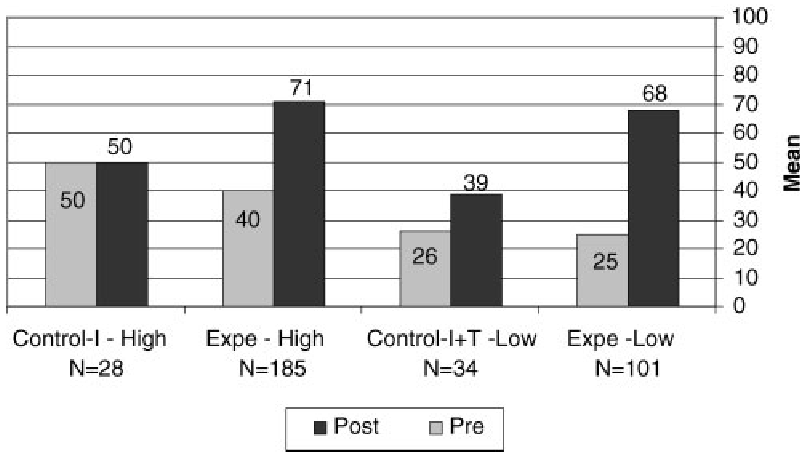


Figure 9. Pre- and posttest graphing skills mean scores of experimental versus control groups—second and third stages combined.

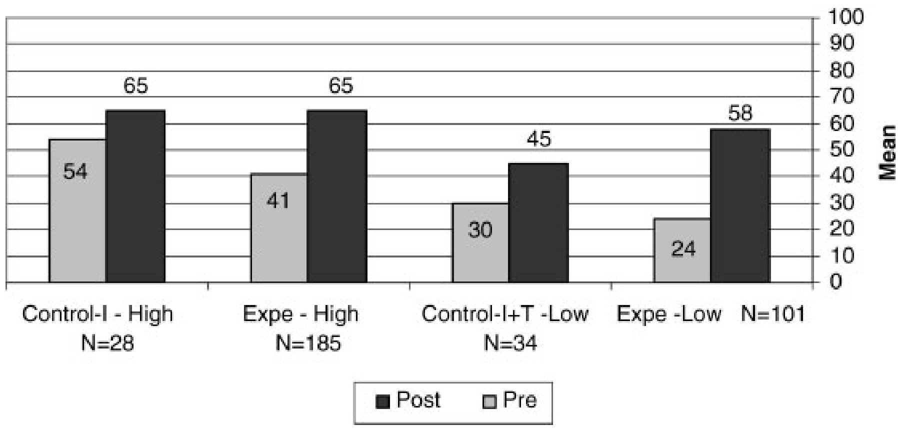


Figure 10. Pre- and postmean scores in chemical understanding–retention. Experimental versus control groups—second and third stages.

Examining the chemical understanding–retention skill no statistical differences were found between experimental and control students. Although, not significant, small differences were found between the experimental and control low academic level groups.

Results of the Reflective Questionnaire

We used a reflective questionnaire at the end of the learning process to gather qualitative data in one of the experimental (CCL) classes ($N = 25$). The purpose of the two questions we analyzed from that questionnaire was to investigate the characteristics of the visualization aspects in the CCL environment, as expressed by students' reflection on the learning processes. At the first phase of the analysis process, we extracted all the expressions that were related to the visualization aspects of the learning environment and the contribution of the CLL environment to students' learning. We found 101 relevant expressions regarding visualization and textual representations.

Table 10
The CCL contribution aspects—Content analysis of student responses

Category	Subcategory	Frequency $N_{items} = 101$	Examples
Visual and textual components	Graph representations	32%	'The experiment and the graph (like acid-base titration) represented the process and the microscopic aspects in a visual way.'
	Experiments and graphs relationships	26%	'By looking at the graph I could see how the experiment progress'
	Text representations	18%	'My favorite case studies were ones that were interesting and relevant to my life.'
Expanding knowledge and understanding		24%	'Working in the CCL environment helped me to think about a chemical process through the four chemistry understanding levels: macro, micro, symbol and process.'

Content analysis of students' responses to these questions revealed two main categories regarding the contribution of the CCL environment. Table 10 presents each category, frequency of expressions and examples for students' responses.

To understand students' perceptions regarding the role of graph representations in the CCL environment, we divided all the graph-related expressions into three subcategories. As presented in Table 11, students value the importance of visualization tools as a crucial component in their comprehension processes. The most valued visualization tool was graph representation. Students see the graph as a possible bridge between the concrete level of understanding (the visible parts of the experiment) and the abstract level (microscopic aspects of the chemical phenomena). One of the students' responses, which strengthen this statement, follows: "I learned to connect the graph

Table 11
Content analysis of students' responses related to the contribution of graphs to their chemical understanding

Category	Subcategory	Frequency[a] $N_{items} = 101$	Examples
Graph representations	Graphing as a visual tool for comprehension processes	17%	'Through the graph I could see and understand when the reaction started and when it finished'
	Future contribution	11%	'I learned new skills that I will use in the future, at the university: Graph analyzing, inquiry skill and working in a group.'
	Graphing as a transferable skill	4%	'I helped my friend, who studies social studies, in graph analyzing. I used techniques that we learned in chemistry.' 'I'm using knowledge and skills that I learned in the CCL program, in biology. Especially in graphing assignments.'

[a]The number of items related to the contribution of graphs to students' chemical understanding was 33.

data to the processes that occurred in the experiment. That way, I combined information that I could see (in the macro level) with information that I couldn't see, but still happened in the experiment (the micro level)."

Discussion

The purpose of our research was to investigate the effect of the CCL environment on the acquisition of both chemical understanding and graphing skills. The unique CCL environment, which integrates case studies and inquiry-based laboratory experiments, has proved to be an effective combination to enhance these two skills. The research focused on the extent of contribution of the CCL environment—visual representation via graphs, "hands-on" laboratory activities, and texts—to students' ability to bidirectionally transfer between the textual representations in the case studies and the visual representations in the computer-generated graphs. Research in MBL environment revealed that visualizations can make significant contributions to graphing skills (Adams and Shrum, 1990; Brasell, 1987; Svec, 1999). Students who used MBL materials improved learning and retention compared with students who were taught in a traditional lecture (Sokoloff & Thornton, 1997; Thornton & Sokoloff, 1990). Reviewing the performance of chemistry students in several studies, Kozma and Russell (2005) suggested a list of skills that might contribute to the development of representational competence in chemistry, including the abilities to (1) use representations for describing chemical phenomena, (2) generate or select an appropriate representation, (3) verbally analyze features of the representation, (4) make connections and relations between different representations, and (5) use the representation as evidence to support claims and make predictions about observable phenomena. The CCL assignments include key features that go hand in hand with the above recommendations of Kozma and Russell (2005). Our CCL environment motivates students to visualize results using graph representations and to draw graphs and draw conclusions from their manipulations. The graphical assignments in the CCL environment functioned as part of an embedded assessment of students' abilities to process, describe and interpret data, compare between graphs, and draw conclusions. Students' responses to these assignments reflected their comprehension of chemical phenomena and the relationships between the variables under investigation. Our research has shown that experimental students significantly improved their graphing skills scores in the postcase-based questionnaire compared with the precase-based questionnaire. Because the CCL environment employed mainly two interventional tools including MBL technology and case studies, the improvement might be attributed not just to the use of real-time graphing, but also to the incorporation of case studies into the CCL curriculum. Students' experience in the case-based computerized laboratory led to a significant improvement in their graphing skills and chemical understanding–retention. Examining each one of the five subcategories—data processing, graph construction, description and interpretation, comparison, and drawing conclusion—we found that the experimental students improved their graphing skills in all five subcategories.The positive results of the experimental students, repeated for each one of the three research years (first, second, and third stages). This consistent result further validates the positive effect of the CCL environment on students' learning outcomes, in particular on the low performers. This replication indicates that our research findings are consistent and persistent. Statistical analyses of the results in general and effect size calculations in particular provide a quantitative estimate of practical or educational value (Rennie, 1998). These outcomes point out the educational importance of integrating real-time graphing with case studies implemented in inquiry-based chemistry laboratory activities. In the first stage, the improvement in graph comparison was relatively low, because students related mainly to the differences between graphs and ignored the similarities.

Consequently, in the second stage we instructed the teachers to emphasize the importance of the similar aspects in the comparison procedure. We also added a specific instruction to find similarities and differences between two graphs in the case-based questionnaire. This resulted in an impressive improvement in the comparison skill in the second and third stage.An impressive improvement was obtained in drawing conclusions. This could indicate that the benefits students gained from their ability to use the CCL equipment for generating graphs in real time, might enabled freeing intellectual resources to engage in higher order thinking skills. This assumption lies upon Nakhleh et al. (2002), who stated that computer-interfaced instruments produce a visual display, typically a graph, that can shift the emphasis in an experiment from data collection to data analysis and interpretation. Such a shift requires students to become more proficient in interpreting the symbol system of the visual display in terms of what it means for the physical system they are studying.

For graph constructing and reasoning, we found a significant increase in the number and quality of chemistry understanding levels students invoked in the posttest questionnaire with respect to the pretest questionnaire. The graph construction requirement in assignment type B called for prediction of curve shapes based on the information provided in the case study and the student's previous chemical understanding. Our findings are in line with Freidler and McFarlane (1997), who found a positive effect of MBL on students' ability to sketch predictive curves based on a textual description of events. Several studies have explored students' understandings of data and measurement, and the way they reason from data when carrying out a practical science inquiry task (Kanari & Millar, 2004; Koslowski, 1996; Kuhn, Amsel, & O'Loughlin, 1988). These studies indicated that students usually do not consider the possibility that their predicted theory or explanation might be false, or that alternative theories might exist. Students tend to treat their ideas about relationships between variables as working hypotheses. Our research results might emphasize the important role of graph representations in comprehension processes during inquiry experiments. Visual representations of data allow an accessible confrontation between predicted theory and correct theory, which is based on evidence. The graph is a visual artifact, which fosters strong links between experimental data and high quality explanations or theory. One of the CCL students' responses is cited below to support this conclusion: "When I saw the graph I realized that my first hypothesis was wrong. I tried to understand why the experiments' results worked out like that and I wrote the conclusion."

The improvement in students' graphing skills was observed at all three academic levels, with the low performers demonstrating the highest improvement and the high academic level students demonstrating a smaller yet impressive gain. We should bear in mind that even these low academic level students are only relatively low performers because they are science-oriented students who elected to study chemistry at an honors level. Our results suggest that these low performers, who need more scaffolding that the CCL method provides, gained the most from this learning environment. Being more mathematically adept, high academic level students are capable of coping with graph-related problems regardless of the learning environment. Still, experimental high academic level students had better gains than their control counterparts, indicating that even for high academic level students the CCL environment had a positive effect on understanding graphical representations.

One research limitation is that the comparison between the experimental and control groups is not always statistically complete due to population nonhomogeneity, small size, and differences in the motivations between the experimental and control groups. Yet, the following findings are worth discussing due to their practical educational value.

Comparing between experimental and control students' chemical understanding–retention, we found a difference (albeit not significant) only between low level academic students of these two research groups. We assume that the difficulties of the relatively low level academic control students in carrying out this task were due to the intervention of the near transfer factor on the retention assignment. The following citation from one of the CCL students' responses supports this near transfer intervention assumption: "Today, I can relate chemical topics that we learned to relevant phenomena or issues from our daily life—geyser, water treatments—things that I had not considered to be chemical processes before." Students who had to apply chemical understanding in a new learning situation presented by a new case study, to which they were exposed for the first time, had difficulties transferring the knowledge across domains. This finding has led us to investigate the effect of the CCL environment on the development of near and far transfer skills. We present the outcomes of this research in an upcoming paper (Sasson and Dori, submitted).

The contribution of the CCL learning environment to students' retention was most noticeable for the experimental low performers, probably due to the combination of visual and textual representations, which helped this population the most in increasing the retention. Three studies of Kozhevnikov, Hegarty, and Mayer (2002) have shown that distinction between low-spatial visualizers and high-spatial ones is due to differences in visual versus spatial imagery. In contrast to visualizers with low spatial ability, spatial types generate mostly schematic images and interpret graphs as abstract representations. Based on these findings, we assume that some of the students' difficulties in studying chemistry are due to the fact that they lack the ability to operate with and link between internal (symbolic, graph-based) visual representations and external (physical, observable) phenomena. Wu and Shah (2004) suggested several design principles to overcome these difficulties, such as providing multiple representations and descriptions; presenting the dynamic and interactive nature of the chemistry phenomena; and promoting the transformation between different representations. A similar approach was applied also by Ardac & Akaygun (2004), who investigated the effects of using a multimedia instructional unit that integrates the macroscopic, symbolic, and microscopic aspects of chemical phenomena on students' ability to represent matter at the molecular level. The researchers suggested that the long-term positive effects of the multimedia-based environment could be improved by including instruction that requires students to transfer between different representations of the same phenomena. The CCL environment applies most of Wu and Shah's (2004) and Ardac and Akaygun's (2004) recommendations. This environment, together with the appropriate learning unit, created a rich visualization setting and affected students' understanding and graphing skills by fostering meaningful learning. Our findings are in agreement with those of Kozma and colleagues (2000), who recommended that students be exposed to learning environments that support a variety of representations and investigation styles, in the spirit of the nature of research that chemists carry out.One might claim that the improvements we found in students' thinking skills are simply a result of their maturation and experience gained during the course. However, students' reflections analysis indicated that the inquiry process they had to undergo while engaging in the computerized laboratory activities was instrumental in expanding their knowledge and deepening their chemical understanding. Although only few of the experimental students responded to the reflection questionnaire, we revealed students' awareness and recognition of the positive effect that the visual aspects in the CCL had on their chemical understanding. Students mentioned the importance of applying chemical knowledge in science experiments and the benefits of the real-time graph representations to their learning processes. In addition, most of the students found graphing to be an important and transferable skill, which they will use in the future at the university. Students indicated the interest and challenge to which they were exposed during the case-based computerized experiments. In particular, they noted that the graph built in real time has a challenging factor that improved their understanding of the chemical aspects of the experiment. Our statistical analysis as well as students' reflection on their learning processes strengthen other researchers recommendations for using real-world (also referred to as ill-structured) problems or assignments as a tool for developing the necessary knowledge and skills of our future citizens (Fortus et al., 2004). The positive findings of our study might strengthen the results of Kramarski (2004), who investigated graph interpretation and construction with metacognitive instruction. The CCL teachers encouraged their students to compare a variety of graphs (derived from their own experiments or provided in the learning unit) with a specific focus on similarities and differences. This emphasis is quite similar to the comprehension and the connection stages in the metacognitive study of Kramarski (2004).

Based on literature review, Nakhleh et al. (2002), who discussed implications of integrating laboratory activities into science teaching, recommended emphasizing the real-world connections of the science content of proposed experiments and conducting pre/postlaboratory oral discussions. It is during these discussions that students can make the most meaningful connections between the phenomena they observe and measure in the laboratory and the concepts they study in class. They emphasized the importance of allowing students to ask the ‘‘what-if’’ questions that help them explore the boundaries of the topic. In the CCL unit, each laboratory session includes pre/postlaboratory activities aimed at developing higher order thinking skills and inquiry. We claim that these CCL learning environment components contribute to improving graphing and retention skills fond in this study. Besides the strong points discussed below, this study has the following three limitations: (1) the laboratory is a complex environment with interactions among students, between students and the activity, students and the equipment, and students and laboratory instructors. These interactions can be viewed as occurring within the broader framework of the cognitive, affective, and psychomotor domains (Nakhleh et al., 2002). The study does not differentiate between the effects of the four relevant CCL components—case-based learning, computerized-based learning, interactions among students, and real-time graphing. The results do not indicate what percentage of the improvement can be attributed to the visualization aspects and what could be explained through other factors of the learning environment. Rather, the results indicate the combined aggregate effect of the various CCL components and their contribution to graphing and chemical understanding skills. (2) For the experimental group students only, the postcase-based questionnaire served as one component of the advanced (five units) Israeli matriculation examination—the national assessment in chemistry. This might have motivated these experimental students to invest more effort in responding correctly to their questionnaire in comparison to their control peers. (3) The number of control classes was small compared with the number of the experimental classes. A larger control population would have helped us to further validate the significance of the results obtained. Beside these three limitations, the research features the following strong points. (a) We have developed and implemented a new method for analyzing the content of students' responses to graphing skills' assignments in chemistry. (b) Using this method, we not only analyzed the process students have to go through, as suggested by Lunetta and Tamir (1979), but also integrated into the analysis the researchers' suggestions with our approach of analysis according to the four chemistry understanding levels (Dori & Hameiri, 2003; Dori et al., 2003). (c) By showing that low performers respond well to the case-based computerized environment, we provide the science education community with concrete examples of how to enhance and assess students' graphing skills. (d) We have shown that when teachers get appropriate training and on-going support, they are able to integrate textual and graphical representations and contribute to the learning and assessment processes of their students in the science classrooms. This finding further strengthens another study that focused on the CCL teachers (Dori et al., 2006). (e) This is a large-scale longitudinal study in real classroom setting. This type of study is difficult to design and perform, and therefore rarely described in the research literature. (f) The most significant contribution of this study is the establishment of the educational

Table 12
Rubric for assessing students' graph description and interpretation skill

Chemistry level	From symbol to macroscopic level	From symbol to microscopic level*	From symbol to process level
Score			
0	Irrelevant reference to macro level or correct description of the changes in ethyl ethanoate concentration in time only at one region in the graph	Wrong or irrelevant reference to micro level	Wrong or irrelevant reference to process level
1	Partial reference to macro level: Correct description of the changes in ethyl ethanoate concentration in time at two regions in the graph	Reference to one aspect of the micro level: Reproductively collisions between molecules	Partial reference to process level: Correct interpretation to one or two regions in the graph
2	Correct description of the changes in ethyl ethanoate concentration in time at all 3 regions in the graph: No change in ethyl ethanoate concentration at region 1, a decrease at region 2 and new stabilization at region 3		Correct interpretation of the process progress at all three regions in the graph: Pre-reaction in region 1, a decrease in the reactants concentration during the reaction in region 2 and chemical equilibrium at region 3

*The transfer from symbol to microscopic level required invoking only one aspect, so the maximum score for this criterion was 1.

value of integrating the case-based method with graph representations into chemical education in particular and science education in general. This graphics–text combination enhances profound chemical understanding. The structure of knowledge or the mental models learners and experts use is made explicit or concrete via "visible thinking" (Jacobson, 2004), which, in our work, is combined with "stories to educate"—the case studies (Dori & Herscovitz, 2005; Herreid, 1997). The combination of the graphical–visual and textual–verbal aspects might stimulate the two complementary sides of the human brain. Our findings regarding the positive effect of this graphics–text mix support the educational effort of combining the case-based method with computerized laboratories for enhancing students' chemistry understanding and graphing skills, and for developing their ability to bidirectionally transfer between textual and visual representations.

Appendix 1

In assignment type A, students were asked to describe and interpret graphs; to compare between them; and to draw conclusions. The following is an example of the assessment criteria used while we assessed the description and interpretation skill. Students were asked to describe and explain marked regions on a given graph (see Figure 3). Excellent response for this assignment was identified (by five chemistry educational experts) as one, which contains transferring information from graph representation (the symbol level) to three chemistry understanding levels (textual representations): the macroscopic, the microscopic and the process levels.

References

Abd-El-Khalick, F., Boujaoude, S., Duschl, R., Lederman, N.G., Mamluk-Naaman, R., Hofstein, A., Niaz, M., Treagust, D., & Tuan, H. (2004). Inquiry in science education: International perspectives. Science Education, 88, 397–419.

Adams, D. D., & Shrum, J.W. (1990). The effects of microcomputer based laboratory exercises on the acquisition of line graph construction and interpretation skills by high school biology students. Journal of Research in Science Teaching, 27, 777–787.

Ainsworth, S. & VanLabeke, N. (2004). Multiple forms of dynamic representation. Learning and Instruction, 14, 241–255.

Ardac, D. & Akaygun, S. (2004). Effectiveness of multimedia-based instruction that emphasizes molecular representations on students' understanding of chemical change. Journal of Research in Science Teaching, 41, 317–337.

Ausubel, D.P., Novak, J.D., & Hanesian, H. (1978). Educational psychology—A cognitive view. New York: Holt, Rinehart and Winston, Inc.

Barnea, N., & Dori, Y.J. (1999). High-School Chemistry Students' Performance and Gender Differences in a Computerized Molecular Modeling Learning Environment. Journal of Science Education and Technology, 8, 257–271.

Barnea, N. (2000). Teaching and learning about chemistry and modeling with computer managed modeling system. In: J. K. Gilbert, & C. J. Boutler (Eds.), Exploring models in science education. (pp. 307–323). Dordrecht: Kluwer Academic Publishing.

Barnea, N. (2002). Updating high-school chemistry syllabus: the process of change. 17th International Conference on Chemical Education (17th ICCE). Beijing, China.

Barnea, N. & Dori, Y.J. (1996). Computerized molecular modeling as a tool to improve chemistry teaching. Journal of Chemical Information and Computer 36, 629–636.

Beichner, R.J. (1994). Testing student interpretation of kinematics graphs. American Journal of Physics, 62, 750–762.

Beichner, R.J. (1996). The impact of video motion analysis on kinematics graph interpretation skills. American Journal of Physics, 64, 1272–1277.

Brasell, H. (1987). The effect of real time laboratory graphing on learning graphic representation of distance and velocity. Journal of Research in Science Teaching, 24, 385–395.

Bybee, R. (2000). Teaching science as inquiry. In: J. Minstrell, & E. van Zee (Eds.), Inquiring into inquiry learning and teaching in science. (pp. 20–46). Washington, DC: American Association for the Advancement of Science.

Challen, P.R. & Brazdil, L.C. (1996). Case studies as basis for discussing method teaching in introductory chemistry courses. The Chemical Educator 1, 5.

Denzin, N.K. & Lincoln, Y.S. (2000). Handbook of qualitative research. London: SAGE Publications Ltd.

Detterman, D.K. (1993). The case for the prosecution: Transfer as an epiphenomenon. In: D. K. Detterman, & R. J. Sternberg (Eds.), Transfer on trial: Intelligence, cognition and instruction. (pp. 1–24). Norwood, NJ: Ablex.

Dori, Y.J. (2003). From nationwide standardized testing to school-based alternative embedded assessment in Israel: Students' performance in the "Matriculation 2000" Project. Journal of Research in Science Teaching, 40, 34–52.

Dori, Y.J., Barak, M., & Adir, N. (2003). A Web-based chemistry course as a means to foster freshmen learning. Journal of Chemical Education, 80, 1084–1092.

Dori, Y.J., Barak, M., Herscovitz, O., & Carmi, M. (2006). Preparing pre- and in-service teachers to teach high school science with technology. In: C. Vrasidas, & G. V. Glass (Eds.), Preparing teachers to teach with technology, 2nd Volume of the book series: Current perspectives on applied information technologies. (pp. 303–321). Greenwich, CT: Information Age Publishing.

Dori, Y.J. & Belcher, J.W. (2005a). How does technology-enabled active learning affect students' understanding of scientific concepts? The Journal of the Learning Sciences, 14, 243–279.

Dori, Y.J. & Belcher, J.W. (2005b). In: J. K. Gilbert (Ed.), Visualization in Science Education. (pp. 187–216). Dordrecht: The Netherlands: Springer

Dori, Y.J. & Hameiri, M. (2003). Multidimensional analysis system for quantitative chemistry problems—Symbol, macro, micro and process aspects. Journal of Research in Science Teaching, 40, 278–302.

Dori, Y.J. & Herscovitz, O. (1999). Question—Posing capability as an alternative evaluation method: Analysis of an environmental case study. Journal of Research in Science Teaching, 36, 430–441.

Dori, Y.J. & Herscovitz, O. (2005). Case-based long-term professional development of science teachers. International Journal of Science Education, 27, 1413–1446.

Dori, Y.J. Sasson, I., Kaberman, Z., & Herscovitz, O. (2004). Integrating case-based computerized laboratories into high school chemistry. The Chemical Educator, 9, 4–8.

Dori, Y.J., Tal, R.T., & Tsaushu, M. (2003). Teaching biotechnology through case studies—Can we improve higher order thinking skills of non-science majors? Science Education, 87, 767–793.

Fortus, D., Dershimer, R.C., Krajcik, J., Marx, R.W., & Mamlok-Naaman, R. (2004). Design-based science and student learning. Journal of Research in Science Teaching, 41, 1081–1110.

Freidler, Y. & McFarlane, A. (1997). Data logging with portable computers: A study of the impact on graphing skills in secondary pupils. The Journal of Computers in Mathematics and Science Teaching, 16, 527–550.

Gabel, D.L. & Bunce, D.M. (1994). Research on problem solving: Chemistry. In: D. L. Gabel (Ed.), Handbook of research on science teaching and learning. (pp. 301–326). New York: Macmillan Publishing Company.

Gobert, J.D. (2000). A typology of causal models for plate tectonics: Inferential power and barriers to understanding. International Journal of Science Education 22, 937–977.

Heller, P., Keith, R., & Anderson, S. (1992). Teaching problem solving through cooperative grouping. Part 1: Group versus individual problem solving. American Journal of Physics, 60, 627–636.

Heller, P., & Hollabaugh, M. (1992). Teaching problem solving through cooperative grouping. Part 2: Designing problems and structuring groups. American Journal of Physics, 60, 637–644.

Herreid, F. (1994). Case studies in science—A novel method of science education. Journal of College Science Teaching, 23, 221–229.

Herreid, F. (1997). What is a case? Bringing to science education the established tool of law and medicine. Journal of College Science Teaching, 27, 92–95.

Hofstein, A., & Lunetta, V.N. (1982). The Role of the Laboratory in Science Teaching: Neglected Aspects of Research. Review of Educational Research, 52, 201–217.

Hofstein, A. & Lunetta, V.N. (2003). The laboratory in science education: Foundations for the twenty-first century. Science Education, 88, 28–54.

Hofstein, A., & Lunetta, V.N. (2004). The laboratory in science education: Foundations for the twenty-first century. Science Education, 88, 28–54.

Hofstein, A., Shore, R., & Kipnis, M. (2004). Providing High School Chemistry Students with Opportunities to Develop Learning Skills in an Inquiry-Type Laboratory: A Case Study. Research Report .International Journal of Science Education, 26, 47-62.

Hofstein, A. & Walberg, H.J. (1995). Instructional strategies. In: B. J. Fraser, & H. J. Walberg (Eds.), Improving science education. (pp. 1–20). Chicago: National Society for the Study of Education.

Jacobson, M.J. (2004). Cognitive visualizations and the design of learning technologies. International Journal of Learning Technology, 1, 40–62.

Johnston, R.B. & Onwuegbuzie, A.J. (2004). Mixed methods research: A research paradigm whose time has come. Educational Researcher, 33, 14–26.

Johnstone, A.H. (1991). Why is science difficult to learn? Things are seldom what they seem. Journal of Computer Assisted Learning, 7, 75–83.

Jones, L. & Atkins, P. (2000). Chemistry: Molecules, matter and change. (4th ed) New York: W.H. Freeman.

Kanari, Z. & Millar, R. (2004). Reasoning from data: How students collect and interpret data in science education. Journal of Research in Science Teaching, 41, 748–769.

Kobballa, T.R., & Tippins, D.J. (Eds.). (2000). Cases in middle and secondary science education: The promise and dilemmas. Upper Saddle River, NJ: Prentice-Hall, Pearson Education.

Koslowski, B. (1996). Theory and evidence: The development of scientific reasoning. Cambridge, MA: MIT Press.

Kown, O.N. (2002). The effect of calculator-based ranger activities on students' graphing ability. School Science and Mathematics, 102, 57–67.

Kozhevnikov, M., Hegarty, M., & Mayer, R.E. (2002). Revising the visualizer-verbalizer dimension: Evidence for two types of visualizers. Cognition and Instruction 20, 47–77.

Kozma, R., Chin, E., Russel, J., & Marx, N. (2000). The roles of representations and tools in the chemistry laboratory and their implications for chemistry learning. The Journal of Learning Sciences, 9, 105–143.

Kozma, R. & Russell, J. (2005). Student becoming chemist: Developing representational competence. In: J. K. Gilbert (Ed.), Visualization in science education. (pp. 121–146). Dordrecht, The Netherlands: Springer.

Kozma, R.B. & Russel, J. (1997). Multimedia and understanding: Expert and novice responses to different representations of chemical phenomena. Journal of Research in Science Teaching, 34, 949–968.

Kramarski, B. (2004). Making sense of graphs: Does metacognitive instruction make a difference on students' mathematical conceptions and alternative conceptions? Learning and Instruction, 14, 593–619.

Kuhn, D., Amsel, E., & O'Loughlin, M. (1988). The development of scientific thinking skills. London: Academic Press.

Larkin, J.H. (1983). The role of problem representation in physics. In: D. Gentner, & A. L. Stevens (Eds.), Mental models. (pp. 75–98). London: Erlbaum.

Lazarowitz R. & Tamir P. (1994). Research on using laboratory instruction in science, in D. L. Gabel. (Ed.) Handbook of research on science teaching and learning (pp. 94-130), New-York: Macmillan.

Lohman, M.C. (2002). Cultivating problem-solving skills through problem-based approaches to professional development. Human Resource Development Quarterly, 13, 243–261.

Lunetta, V.N. (1998). The school science laboratory: Historical perspectives and context for contemporary teaching. In: B. Fraser, & K. Tobin (Eds.), International handbook of science education. (pp. 249–262). Dordrecht, The Netherlands: Kluwer Academic.

Lunetta, V. & Tamir, P. (1979). Matching lab activities with teaching goals. The Science Teacher, 46, 22–24.

Mathewson, J.H. (1999). Visual–spatial thinking: An aspects of science overlooked by educators. Science Education, 83, 33–54.

Mayer, R.E. (2002a). Cognitive theory and the design of multimedia instruction: An example of the two-way street between cognition and instruction. In: D. F. Halpern, & M. D. Hakel (Eds.), Applying the science of learning to university teaching and beyond. (pp. 55–72). San Francisco, CA: Jossey-Bass.

Mayer, R.E. (2002b). Invited reaction: Cultivating problem-solving skills through problem-based approaches to professional development. Human Resource Development Quarterly, 13, 263–269.

McDermott, L.C., Rosenquist, M.L., & van Zee, E.H. (1987). Student difficulties in connecting graphs and physics: Examples from kinematics. American Journal of Physics, 55, 503–513.

McKenzie, D.L. & Padilla, M.J. (1986). The construction and validation of the Test of Graphing in Science (TOGS). Journal of Research in Science Teaching, 23, 571–579.

Mintzes, J. J. Wandersee, & Novak, J. D. (Eds.), (2005). Teaching science for understanding: A human constructivist view. Amsterdam, The Netherlands: Elsevier Science.

Munneke, L., Van Amelsvoort, M., & Andriessen, J. (2003). The role of diagrams in collaborative argumentation-based learning. International Journal of Educational Research, 39, 113–131.

Nakhleh, M.B. & Krajcik, J.S. (1994). Influence of levels of information as presented by different technologies on students' understanding of acid, base and pH concepts. Journal of Research in Science Teaching, 31, 1077–1096.

Nakhleh, M.B., Polles, J., & Malina, E. (2002). Learning chemistry in laboratory environment. In: J. K. Gilbert, O. D. Jong, R. Justi, D. F. Treagust, & J. H. Van Driel (Eds.), Chemical education: Towards research-based practice. (pp. 69–94). The Netherlands: Klwer Academic Publishers.

National Research Council. (1996). National science education standards. Washington, DC: National Academy Press.

Padilla, M.J., McKenzie, D.L., & Shaw, E.L. (1986). An examination of line graphing ability of students in grades seven through twelve. School Science and Mathematics, 86, 20–26.

Redish, E.F. (2003). Teaching physics with the physics suite. Chap. 8: Recitation and laboratory-based methods Available online at http://www2.physics.umd.edu/~redish/Book/08.pdf

Redish, E.F., Saul, J.M., & Steinberg, R.N. (1997). On the effectiveness of active-engagement microcomputer-based laboratories. American Journal of Physics, 65, 45–54.

Rennie, L.J. (1998). Improving the interpretation and reporting of quantitative research. Journal of Research in Science Teaching, 35, 237–248.

Resnick, L. (1987). Education and learning to think. Washington, D.C.: National Academy Press.

Roth, W.M., & Mcginn, M.K. (1998). Toward a Theory of Representing as Social Practice. Review of Educational Research, 68, 35–59.

Roth, W.M., Bowen, G.M., & Mcginn, M.K. (1999). Differences in graph-related practices between high school biology textbooks and scientific ecology journals. Journal of Research in Science Teaching, 36, 977–1019.

Russell, D.W., Lucas, K.B., & McRobbie, C.J. (2004). Role of the microcomputer-based laboratory display in supporting the construction of new understanding in thermal physics. Journal of Research in Science Education, 41, 165–185.

Russell, J. & Kozma, R. (2005). Visualizations in chemical education. In: J. K. Gilbert (Ed.), Visualization in science education. (pp. 121–146). Dordrecht, The Netherlands: Springer.

Sassi, E., Monroy, G., & Testa, I. (2005). Teacher training about real-time approaches: Research-based guidelines and training materials. Science Education, 89, 28–37.

Scheker, H.P. (1998). Integration of experimenting and modeling by advanced educational technology: Examples from nuclear physics. In: B. J. Fraser, & K. J. Tobin (Eds.), International handbook of science education. (pp. 383–398). Dordrecht, The Netherlands: Kluwer Academic.

Sokoloff, D.R. & Thornton, R.K. (1997). Using interactive lecture demonstrations to create an active learning environment. The Physics Teacher, 35, 340–347.

Suthers, D.D. (2001). Towards a systematic study of representational guidance for collaborative learning discourse. Journal of Universal Computer Science, 7, 254–277.

Svec, M. (1999). Improving graphing interpretation skills and understanding of motion using microcomputer based laboratories. Electronic Journal of Science Education, Vol. 3 Available at http://unr.edu/homepage/crowther/ejse/ejsev3n4.html

Sykes, G., & Bird, T. (1992). Teacher Education and the Case Idea. Review of Research in Education, 18, 457–521.

Tal, R. & Hochberg, N. (2003). Assessing higher order thinking of students' participating in the "WISE" project in Israel. Studies in Education Evaluation, 29, 69–89.

Thornton, R.K. & Sokoloff, D.R. (1990). Learning motion concepts using real-time microcomputer-based laboratory tools. American Journal of Physics, 58, 858–866.

Tobin, K. (1990). Research on science laboratory activities: In pursuit of better questions and answers to improve learning. School Science and Mathematics, 90, 403–418.

Tobin, K., Kahle, J. B., & Fraser, B. J. (Eds.). (1990). Windows into science classes: Problems associated with higher level cognitive learning. London: Falmer Press.

Toth, E.E., Suthers, D.D., & Lesgold, A.M. (2002). "Mapping to know": The effects of and reflective assessment on scientific inquiry. Science Education, 86, 264–286.

Treagust, D.F., Chittleborough, G., & Mamiala, T.L. (2003). The role of submicroscopic and symbolic representations in chemical explanations. International Journal of Science Education, 25, 1353–1368.

Wassermann, S. (1994). Introduction to case method teaching. New York: Teachers College Press.

Woolnough, J. (2000). How do student learn to apply their mathematical knowledge to interpret graphs in physics? Research in Science Education, 30, 259–267.

Wu, H. & Shah, P. (2004). Exploring visio-spatial thinking in chemistry learning. Science Education, 88, 465–492.

Zohar, A. & Dori, Y.J. (2003). Higher order thinking skills and low achieving students—Are they mutually exclusive? The Journal of the Learning Sciences 12, 145–182.

Zoller, U. (1993). Are lectures and learning compatible? Maybe for LOCS, unlikely for HOCS. Journal of Chemical Education, 70, 195–197.

Zoller, U. & Tsaparlis, G. (1997). Higher and lower-order cognitive skills: The case of chemistry. Research in Science Education, 27, 117–130.