The representational levels: Influences and contributions to research in chemical education

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ABSTRACT

Chemistry is considered a difficult subject to study since it comprises microscopic, macroscopic, and symbolic components. This paper provides a comprehensive review of the literature on the representational levels (macroscopic, microscopic, and symbolic) that involve models of thinking in chemistry, and it summarizes what is currently known and provides guidance for further research. This work reports the outcomes of theoretical and empirical studies about the representative levels in chemistry, science, and teacher education. The outcomes present a major concern around the difficulties and abilities of high school and undergraduate students in understanding chemistry in all the representational levels. Nevertheless, few studies were found about the teaching of educational programs, which shows that scientific studies on this topic are still lacking.

Keywords: Chemistry Education; Representational Levels; Visualization.

INTRODUCTION

Chemistry is conceived by many people as a difficult subject, since it is composed of abstract concepts and topics. The complex and abstract nature of chemistry makes learning and teaching difficult for students and teachers (Johnstone, 1991; 1993; Nakhleh, 1992; Gabel, 1998; Treagust & Chittleborough, 2001). Sabelli and Livshits (1995) pointed out that, unlike other scientific subjects, when we see chemical reactions (cooking, moving cars, sunburning, healing), we do not see the chemistry we are taught, and therefore we do not see chemistry at all.

The formation of most chemical concepts and explanations of chemical phenomena rely on understanding the microscopic world that is connected with the phenomenological world, both of which are communicated with symbols. Thus, conceptual understanding in chemistry includes the ability to represent and translate chemical problems using macroscopic (observable), microscopic (particulate), and symbolic forms of representation (Gabel & Bunce, 1994).

Because of the complex nature of chemistry, Johnstone (1991, 1993 & 2000) proposed a model of thinking in chemistry that consists of three modes, addressed as levels of thought: the macroscopic, the sub-microscopic, and the symbolic. This multilevel way of thinking can
be represented by the corners of a triangle (Figure 1) where the sub-micro and symbolic modes are at the base of the triangle, and the macro mode at the apex.

![Triangle Diagram]

**Figure 1.** The three representational levels in chemistry (Johnstone, 1991).

According to Johnstone (1991), the macroscopic level is concrete and corresponds to observable chemical objects that may or may not be part of students’ everyday experiences, but students can observe chemical phenomena by experiments. The sub-micro is also real but is abstract; it forms the particulate level, which can be used to describe what is observed at the macroscopic level as the movement of electrons, molecules, particles, or atoms. The symbolic level represents chemical and macroscopic phenomena by the use of chemical equations, mathematical equations, graphs, reaction mechanisms, analogies, and model kits. A minimum level of modeling ability or representational competence is required to use these symbols to learn and understand chemistry. Thus, the study of chemistry is based on the theory of the particulate nature of matter, the sub-microscopic level of matter. But most things encountered in the world, and on which we form many of our concepts, are macro in nature. That is, we see the macroscopic and use models to represent the sub-microscopic and symbolic levels. According to this aspect of the chemistry study, Johnstone (2000) asserts:

> On the macro level, chemistry is what you do in the laboratory or in the kitchen (...). This is the experiential situation to which we are accustomed in most aspects of life. But chemistry, to be more fully understood, has to move to the sub-micro situation where the behavior of substances is interpreted in terms of the unseen and recorded in some representational language. This is at once the strength of our subject as an intellectual pursuit, and the weakness of our subject when we try to teach it, or more importantly, when beginners (students) try to learn it (p.11).

Gabel (1999) says that chemical phenomena, which are studied at the macroscopic level, can also be studied at the sub-microscopic level, but are generally described at this level to solve complicated problems. The same occurs at the symbolic level. However, students are apparently able to understand complex ideas when asked to express the relationships between all the representational levels (Jansoon, Coll & Somsook, 2009).

According to Johnstone (2000), a good understanding of chemistry requires the ability to integrate these levels. However, acquiring this ability is a big challenge for the teaching of chemistry. Students often have trouble connecting the different representational levels, making the threefold manner of representing chemistry the main obstacle to their learning (Johnstone, 1991; Treagust, Chittleborough & Mamiala, 2003). In this respect, the utilization of visual tools for teaching chemistry is required to promote visualization capacities and understanding of representations.

The use of pictures, concrete models, photos, graphics, diagrams, computational programs, and other kind of visualizations tools has increased strongly in the last years in
science education. Studies have tried to prove that the use of these tools for chemistry learning can improve students’ representational capacity and understanding of chemical phenomena by illustrating ideas that words cannot describe. Nevertheless, visual tools can’t replace the teacher’s role. Teachers are responsible for introducing activities that use visual tools, and thus, their practice will also determine students’ ability to perceive, understand, and shift among the visual representations. Therefore, investigations into the role of teachers and the characteristics of their practice, as well as works that shows the importance of teachers’ training, are also significant to understanding aspects of chemistry education and the teacher’s part in chemistry learning in all the representational levels.

Sirhan (2007) emphasizes that chemistry has to be taught in a simple way. The key lies in seeing chemistry from the point of view of the student to avoid confusion and misunderstandings. According to the author, teachers have to know what the learners already know and how they came to acquire the knowledge, presenting material in a way that is consistent with students’ learning and linking concepts so the learner can make a coherent whole of key ideas.

Students and professionals face difficulties learning and teaching chemistry, and studies on this topic are necessary. This study aims to review and discuss theoretically the studies on the macroscopic, microscopic, and symbolic representative levels and their contributions to chemistry education.

METHODOLOGY

A literature review was carried out in this article aiming to convey to the reader knowledge and ideas that have been established on the representational levels in chemistry education. A database search identified articles related to representational levels in chemistry education published up to 2011. After that, those articles related to representational levels in chemistry issues and teacher education were selected. The keywords used for selection were chemistry representation, representative level, visualization, teacher education program, visual abilities, and science education. The articles selected were from 10 peer-reviewed science-education journals, as shown in Table 1.

The articles were selected by their content and relevance to the study. The performed steps of the literature review were done according to Taylor (2010):

- Organizing the literature selection and review by relating it directly to the research focus;
- Synthesizing results into a summary of what is and is not known;
- Identifying areas of controversy in the literature;
- Raising questions that need further research.

Once the articles were identified and collected, we conducted a qualitative analysis identifying the objectives and primary research outcomes for each paper. This process was conducted with the purpose of organizing the papers under subheadings. For example, the works that have exposed a theoretical work or a review of visualization or the representative levels were placed under the subheading “Theoretical approach to visualization and the representational levels.” Articles emphasizing instruction with or without the use of computer or multimedia tools, but linking with the instructions of teachers, were located under the subheading “Influence of different instructions on student learning.” Papers that put emphasis on developing an assessment of multimedia tools and its effects on learning were placed under the subheading “Multimedia tools that lead students to understand chemistry in all the levels.” Papers located under the subheading “Students’ abilities and difficulties in shifting among the representational levels” focused on the abilities of students in understanding
chemistry completely and shifting among the levels, with some instruction assistance or not. Only one paper in this review fit under the subheading “Teacher training to work among the representational levels.”

These categories are somewhat flexible because many papers have multiple outcomes. In these cases, papers were placed in the most suitable category. Some articles were put in more than one category, as appropriate for their outcomes.

### Table 1. Journal search results

<table>
<thead>
<tr>
<th>Journal</th>
<th>Number of studies selected</th>
</tr>
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<tbody>
<tr>
<td>Chemical Education: Research and Practice in Europe</td>
<td>2</td>
</tr>
<tr>
<td>Chemistry Education: Research and Practice</td>
<td>3</td>
</tr>
<tr>
<td>International Journal of Environmental &amp; Science Education</td>
<td>1</td>
</tr>
<tr>
<td>International Journal of Science Education</td>
<td>5</td>
</tr>
<tr>
<td>Journal of Chemical Education</td>
<td>3</td>
</tr>
<tr>
<td>Journal of Chemical Educator</td>
<td>1</td>
</tr>
<tr>
<td>Journal of Research in Science Teaching</td>
<td>4</td>
</tr>
<tr>
<td>Journal of Science Educational and Technology</td>
<td>1</td>
</tr>
<tr>
<td>Science Education</td>
<td>4</td>
</tr>
<tr>
<td>University Chemistry Education</td>
<td>1</td>
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<tr>
<td>Science Education International</td>
<td>1</td>
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<td><strong>Total</strong></td>
<td><strong>26</strong></td>
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### FINDINGS

A major concern of teachers and researchers in chemistry education is the difficulties and abilities of high school and undergraduate students in understanding chemistry at all representational levels. Thus, many studies present research about methodologies and tools, such as computer programs, that can help these students obtain a complete learning of chemistry. Nevertheless, these tools cannot replace the teacher’s role. Thus, studies are also conducted to analyze the influence of teacher interventions in student learning. The works found in the literature review were placed under the subheadings (Table 2) “Theoretical approach to visualization and the representational levels,” “Students’ abilities and difficulties in shifting among the representational levels,” “Influence of different instructions in student learning,” “Multimedia tools that lead students to understand chemistry in all the levels,” and “Teacher training to work among the representational levels.” Each category with the synthesis of the articles is detailed below.

### Table 2. Summary of studies related to five different categories.

<table>
<thead>
<tr>
<th>Theoretical approach to visualization and the representational levels</th>
<th>Cook (2006)</th>
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<tbody>
<tr>
<td></td>
<td>Wu and Shah (2004)</td>
</tr>
<tr>
<td>Students’ abilities and difficulties in shifting among the representational levels</td>
<td>Bodner and Domin (2000)</td>
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<tr>
<td></td>
<td>Chandrasegaran, Treagust, and Mocerino (2007)</td>
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<td></td>
<td>Ferk et al. (2003)</td>
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<td></td>
<td>Grosslight et al. (1991)</td>
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<td></td>
<td>Hinton and Nakhleh (1999)</td>
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<td></td>
<td>Jaber and BouJaoude (2011)</td>
</tr>
<tr>
<td></td>
<td>Rappoport and Ashkenazi (2008)</td>
</tr>
<tr>
<td></td>
<td>Chittleborough and Treagust (2007)</td>
</tr>
</tbody>
</table>
Table 2. Continued..

| Influence of different instructions on student learning | Ardac and Akaygun (2005)  
Barnea and Dori (2000)  
Treagust, Chittleborough, and Mamiala (2003)  
Wu (2003)  
Cook (2011)  
Dori and Sasson (2008) |
|-----------------------------------------------|
| Multimedia tools that lead students to understand chemistry in all the levels | Ardac and Akaygun (2004)  
Barnea and Dori (1999)  
Tasker and Dalton (2006)  
Wu, Krajcik, and Soloway (2001)  
Russell et al. (1997) |
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<tr>
<td>Teacher training to work among the representational levels</td>
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</table>

DISCUSSION

Theoretical approach to visualization and the representational levels

Theoretical works are important to show the advance of theory and the many views on the topic. Some articles found in the research describe theoretical approaches to visualization and the representational levels. The papers emphasize the characteristics of chemistry education: the difficulties of learning chemistry and how the use of representations can help students understand chemistry on the macroscopic, submicroscopic, and symbolic levels.

Two studies reviewed here (Johnstone, 1993; 2000) show a part of Johnstone’s work and how it has increased over the years. Johnstone focused on the difficulties presented by students when learning chemistry. Johnstone’s triangle was the starting point in many studies about the representational levels in chemistry learning.

In order to draw a personal view on the development of chemistry teaching and the forces that have affected its growth, Johnstone (1993) discussed the problems and difficulties related to chemistry teaching in recent years. According to the author, chemistry has three basic components: macrochemistry, sub-microchemistry, and representational chemistry. Much of the old chemistry and actual chemistry teaching concerns only the macro and representational corners of the triangle, so the triangle’s interior is like a black hole for most people. Going into the psychology, Johnstone asserts that to expect learners to come readily into the chemical triangle and be able to switch rapidly around it to link the levels (corners) is to ask for overloading the working memory. Chemistry is an intellectual endeavor that must be designed carefully by teachers to be learned more effectively by students.

Johnstone (2000) explores the possibilities for the curriculum, the gradual development of concepts, the function of laboratory work, and the place of quantitative ideas. Chemistry is a difficult subject for students, and its difficulty may lie in the intrinsic nature of the subject; the psychology of forming most chemical concepts is quite different from that of the normal world. Johnstone highlights that we are trying to share our beautiful subject with young people in an apparently logical way and, at the same time, conflicting with what psychology knows about the way we learn. Therefore, the author emphasizes the necessity of harmonizing a logical approach and a psychological approach in the teaching of chemistry, which can be achieved by using information processing and the chemistry triangle.

Besides the works of Johnstone, Cook (2006) made another theoretical approach to the representational levels. The article presents instructional design considerations, provides empirical evidence, and integrates theoretical concepts related to cognitive loads. According to the author, learners have a limited working memory, and instructional representations should be designed with the goal of reducing unnecessary cognitive load. In this context,
individual differences have to be considered, since they are critical in determining the impact that visual representation will have on learners’ cognitive structures and processes. Presentations with visual representations are widely used for displaying learning materials, but not all of these presentations necessarily lead to better learning results. Thus, Cook asserts that multiple representations of information using the same modality, or multiple representations of information in visual and verbal modes, must be physically and/or temporally integrated so students may extract information out of all the representations, leading to a more complete understanding.

Wu and Shah (2004) have also done a literature review on correlational studies of spatial abilities and chemistry learning, students’ conceptual errors and difficulties in understand visual representations, and visualization tools that have been designed to help overcome these limitations. They concluded that visuospatial abilities and more general reasoning skills are relevant to chemistry learning. Some of these students’ conceptual errors in chemistry are due to difficulties in operating on the internal and external visuospatial representations. Furthermore, some visualization tools have been effective in helping students overcome the kinds of conceptual errors that may arise from difficulties in using visuospatial representations. Based on the review, the authors suggested five design principles: (1) provide multiple representations and descriptions, (2) make linked referential connections visible, (3) present the dynamic and interactive nature of chemistry, (4) promote the transformation between 2D and 3D, and (5) reduce cognitive load by making information explicit and integrating information for students. These principles could guide educators and designers to develop chemistry-learning tools that help students understand chemistry concepts and practice their representational skills through supporting their visuospatial thinking.

The articles presented in this section show a concern about the overload of working memory. While Johnstone (1993) emphasized that relation between the corners of the triangle can overload the working memory, Wu and Shah (2004) and Cook (2006) highlight that the development of visual abilities and the use of representation can reduce cognitive loads in working memory. On the other hand, the authors also show the necessity of developing a chemistry course that links the three levels. Johnstone’s work (2000) doesn’t discuss psychological questions about memory but says that the teaching of chemistry has to be planned to harmonize a logical approach and a psychological approach. Thus, the works in this section emphasize the necessity of psychological and practical issues in the teaching/learning of chemistry.

**Students’ abilities and difficulties in shifting among the representational levels**

Inappropriate connections between representational levels are common for students, mainly at the macro and sub-micro levels. They tend to attribute macro properties to sub-micro particles, such as ice molecules being colder than molecules of liquid water. Research that emphasizes students’ difficulties and possible solutions is desirable for helping teachers to work chemistry thinking into their instruction. Although chemists and chemical educators are able to operate across the levels quickly and easily, students face many difficulties in operating at all the representational levels.

Rappoport and Ashkenazi (2008) observed this fact when they used a think-aloud interview protocol to study the way students use and connect the representational levels when solving conceptual problems. The research was applied to faculty members and undergraduate chemistry students. After the inquiries, the researchers observed that, while the faculty members explained the problems by integrating the three representational levels, most of the students formed no meaningful connection between the levels and used just the macroscopic and symbolic representation to solve problems, with preference given to the symbolic level. Furthermore, a significant difference was noted in the way they related the representations:
the faculty members were able to deduct the macro and symbolic levels from the microscopic level, while the students tried to deduct the properties of the sub-micro level by the symbolic level. In conclusion, they found that the explanation for this would be the difference in cognitive development between the populations, which allows university students to operate more freely on symbolic terms. It might be that the situations dealt with in university do not lend themselves to representations based on personal experience.

Hinton and Nakhleh (1999) examined the mental representations of chemical reactions used by six students who achieved above-average grades in a college freshman chemistry class at a large Midwestern university. The study revealed that the participants made at least some use of each of the three representations, but some of the students were able to make associations with only macroscopic and symbolic levels. Thus, the researchers reported that chemical phenomena are generally understandable at the macroscopic level and can be interpreted at the symbolic level by undergraduate students. However, it seems students are often unable to connect correctly either of these levels to the sub-microscopic level.

Jaber and BouJaoude (2011) characterized tenth-grade students’ conceptual profiles regarding their understanding of chemical reactions in terms of macro, micro, symbolic levels, and the relations among them at the end of the teaching sequence. They reported that, without appropriate instruction, students usually fail to produce meaningful links across the levels, use only macroscopic and symbolic representations, and confound the microscopic level with the macroscopic level in terms of constructs and language. In their work, they introduced an instruction characterized by macro-micro-symbolic teaching that focuses on the interplay between the levels, integrates various representations, and engages students in an epistemic discourse about the nature of knowing in chemistry. Findings indicated that macro-micro-symbolic teaching enhanced students’ conceptual understanding and relational learning of chemical reactions. Thus, they concluded that chemistry instruction in the three levels should become a habit of teaching chemistry, reflected in lesson planning, classroom interaction, and assessment.

Bondner and Domin (2000) used a combination of techniques, including field notes collected in operating classrooms, informal interviews with students in a tutorial environment, and formal structured interviews to study problem-solving in chemistry. The research was applied to groups ranging from freshmen enrolled in general chemistry to sixth-year graduate students in a variety of content domains, including general, organic, inorganic, and physical chemistry. The data obtained were consistent with the notion that the ability to switch between representations or representation systems plays an important role in determining success or failure in chemistry problem-solving. They found that one of the characteristic differences between successful and unsuccessful problem solvers is the number and kinds of representations they bring to the problem. Therefore, according to the authors, encouraging students to use different representations when solving a problem might therefore be a simple way of helping them.

Grosslight et al. (1991) studied seventh- and eleventh-grade honors students’ conceptions of models and their use in science. They found that students in both groups have conceptions of models that are basically consistent with a naive realist epistemology. Students are more likely to think of models as physical copies of reality that embody different spatiotemporal perspectives than as constructed representations that may embody different theoretical perspectives. However, as students’ ideas become more sophisticated, they increasingly include the fact that models are designed for particular purposes, especially to help communication. The authors suggest that students need more experience using models as intellectual tools, more experience in models that provide contrasting conceptual views of phenomena, and more discussions of the roles of models in the service of scientific inquiry,
since, according to them, modeling ability is the ability to traverse the three levels of chemical representation of matter.

Chandrasegaran, Tregust, and Mocerino (2007) developed a fifteen-item, two-tier multiple-choice diagnostic instrument to evaluate secondary students’ ability to describe and explain seven types of chemical reactions using macroscopic, submicroscopic, and symbolic representations. The instrument was administered to sixty-five ninth-year students after nine months of instruction to evaluate their use of multiple levels of representation. Findings showed that, despite the emphasis on multiple levels of representation during instruction, 14 conceptions were identified that indicated confusion between macroscopic and submicroscopic representations, a tendency to extrapolate bulk macroscopic properties of substances to the submicroscopic level, and limited understanding of the symbolic representational system. On the positive side, analysis of students’ responses from the diagnostic test indicated, in several instances, students’ ability to use multiple levels of representation to describe and explain the chemical reactions. The authors conclude that the administration of this test to evaluate students’ understandings about the use of multiple levels of representation could provide useful information to teachers in planning classroom instruction.

Ferk et al. (2003) studied the meanings attached by students to the different kinds of molecular-structure representations used in chemistry teaching. The accuracy of students’ appreciation of 3D molecular structure on the basis of different kinds of representations was studied on primary, secondary, and university students. A computerized Chemical Visualization Test was developed and applied; it consisted of tasks in which the correct perception of different representations of molecular structure and the students’ ability to manipulate these mental images in three dimensions were evaluated. The research indicates that students’ appreciation of three-dimensional molecular structures differs according to the kind of representation used. To all students the concrete representations seemed to be more useful than abstract representations. However, secondary-school students and university students achieved the best results when using photographs of 3D molecular models or computer-generated models, while primary-school students were better when using concrete 3D models.

Cook, Wiebe and Carter (2008) investigated how high school students ($n=54$) with different levels of prior knowledge transitioned between the macroscopic and molecular representations of the selected cell transport graphics. The research examined how students with high and low levels of prior knowledge interpreted meaning from these graphics with both macroscopic and molecular representations. The researchers were concerned with how frequently these students transitioned from molecular to molecular features, macroscopic to macroscopic features, and macroscopic to molecular features. The findings indicated the role of multiple representations was very different for low- and high-prior-knowledge learners. Low-prior-knowledge students distributed more of their visual attention on macroscopic features, and in turn interpreted the graphics in a very literal way. Their interview responses indicated few instances of using the multiple representations in their interpretation of the graphics. On the other hand, high-prior-knowledge learners were able to connect the information in the representations to their existing schema. From the sequential analysis and interview responses, these learners were more successful in linking the macroscopic and molecular representations to interpret the underlying themes of the graphics. From these results, the authors concluded that low-prior-knowledge learners need more guidance when they view and interpret graphics with macroscopic and molecular representations.

Jansson, Coll and Somsook (2009) investigated and evaluated 414 first-year Thai undergraduate students’ understanding of dilution and related concepts by assessing their mental models and how they were able to make connections between the macroscopic and...
submicroscopic levels. In the work, they probed students’ understanding by using the interview-for-events approach, employing open-ended questions, and analyzing student descriptions and drawings. The research findings suggest that the students’ mental models of many aspects of dilution chemistry were generally in accord with the scientific conceptualization that is to say, they did not show many alternative conceptions. The more-able students seemed to understand the role and relationships of representations at all three levels using Johnstone’s (1991) framework. In particular, they understood the role of macroscopic and sub-microscopic levels of representation and were able to integrate into the other level. In contrast less-able students usually presented their work mostly at the symbolic level followed by the sub-microscopic and macroscopic levels, which were typically not related to the symbolic level. Hence, as might be expected, students’ mental models for dilution varied, with more-able students possessing more complete, relational mental models than their less-able peers. In the opinion of the authors, this focus on the symbolic level may be related to the mode of science instruction in Thailand.

Chittleborough and Treagust (2007) examined the modeling abilities of three first-year, non-major chemistry students to understand chemical concepts according to Johnstone’s three levels of chemical representations of matter. When chemical models are correctly used, they form links between the symbolic representations and the macroscopic and sub-microscopic levels. The study demonstrates that each of the students’ modeling abilities with chemical representations improved with instruction and practice. Furthermore, students who used models and different levels of representation were able to develop higher-order thinking processes of the chemistry they were learning. This is because they were able to use models for testing, predicting, and evaluating their ideas; develop mental pictures of the submicroscopic level of matter; transfer ideas of different levels of representation; create symbolic representations of observed reactions; and appreciate the target of representation or analogue.

The papers presented in this section show that students in various levels of education have more ability to understand and represent chemical content in macroscopic and symbolic levels. Most students had difficulties in understanding chemical content at the microscopic level, and when they tried to represent this level, many put macroscopic characteristics in microscopic representations. The different papers introduce the importance of teaching tools that support students in producing representations and mental models in all the representational levels. Jaber and BouJaoude (2011) emphasize the importance of introducing an instruction characterized by macro-micro-symbolic teaching that focuses on the interplay between the levels. Many authors also emphasize the necessity of encouraging students to produce models in all the representational levels.

Influence of different instructions on student learning

Based on the difficulties presented by students, teachers try to differentiate their instruction with the aim of helping students. But the instruction is not always efficient for all students. Teachers can use some strategies to integrate instructions with methodologies that provide favorable conditions for students to develop chemical concepts and learn at the three levels of representation. Instructions can combine with computerized and dynamic visual instructions (Ardac & Akaygun, 2005); provide opportunities for students to produce mental models using computerized molecular modeling (Barnea & Dori, 2000); employ the notion of intertextuality to conceptualize chemical representations by connecting them to real-life experience (Wu, 2003); and produce meaning by using representations in all the levels (Treagust, Chittleborough & Mamiala, 2003).

Some instructions make use of technological resources to provide a complete understanding of chemistry. Ardac and Akaygun (2005) examine the effectiveness of visually
enhanced instruction that emphasizes molecular representations, using visual displays to reflect multilevel thought in chemistry. Fifty-two eighth graders (age range 14–15 years) participated in one of the three instructional conditions (dynamic-individual, dynamic-whole class, and static-whole class) designed to improve molecular understanding of chemical change. The study questions the relative effectiveness of the specified instructional conditions in supporting student progress towards the acceptable particulate models. The results of the study provide a number of implications for instructional practices that are designed to promote conceptual understanding at a molecular level. For such tasks that include the visual display of submicroscopic particles, dynamic visuals would be a better alternative than static visuals, since dynamic visuals enable the display of collective particle motion and convey a complete mental image of changes in matter. Thus, the study highlights that students could have a greater understanding of chemistry between all the representational levels if the suitable instructions were used.

Dori and Sansson (2008) investigated the effect of the case-based, computerized-laboratory (CCL) environment on the acquisition of both chemical understanding and graphing skills of high school honors students via bidirectional visual and textual representations. 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. Students were exposed to visual representations, which included hands-on experiments, real-time graph construction and interpretation, and textual representations of case studies. They found that students in the CCL learning environment significantly improved their graphing skills and chemical understanding retention in the post-evaluation with respect to the pre-questionnaires. The findings emphasize the educational value of combining two related instructions: the case-based method of computerized laboratories, for enhancing students’ chemistry understanding and graphing skills, and the development of their ability to bidirectional transfer between textual and visual representations.

Barnea and Dori (2000) investigated how chemistry teachers and high school students who enrolled in a special program perceive the nature and functions of models and representation. Two groups of high school chemistry students (experimental and control) were submitted to different kinds of instruction. The teachers of the experimental group participated in training and developed a computer molecular-modeling (CMM) learning environment via implementing a constructivist approach, whereas the control group teachers taught the topic in the traditional way. The findings indicated a significant difference between the experimental and control groups of the high school students. Experimental-group students scored higher than those of the control group in the model perception questionnaire applied to them. Students’ results indicated the effectiveness of the treatment of students’ conceptualizing the meanings of models, especially in the domain of chemistry.

Treagust, Chittleborough, and Mamiala (2003) examined the use of submicroscopic and symbolic representations in chemical explanations and verified how they provide meaning. The major interest of the research was the development of students’ levels of understanding, conceived as instrumental (knowing how) and relational (knowing why) understanding, as a result of regular Grade 11 chemistry lessons using analogical, anthropomorphic, relational, problem-based, and model-based explanations. The data indicated that effective learning at a relational level of understanding to require simultaneous use of submicroscopic and symbolic representations of chemical explanations.

Wu (2003) investigated how class members interactionally construct meanings of chemical representations by connecting them to real-life experiences, and how the teachers’ content knowledge shapes their ways of co-constructing intertextual links with students. Multiple sources of data were collected over seven weeks with the participation of 25
eleventh graders, an experienced teacher, and a student teacher. The teachers applied several discursive strategies to scaffold students, building meaningful links based on their prior knowledge and experiences. During this cycle of activity, students worked with one or two other classmates, and each small group conducted an investigation of a known toxin from a list provided by their teachers. The students’ activities showed that they could understand conceptual information on the three levels of chemistry and revealed that the students’ chemistry thinking could move among phenomena, representations, and concepts.

We cannot think about instruction without taking into account the teacher’s performance in class—that is, how the teacher used visualization and the representative levels to make students understand chemical content. Cook (2011) investigated how seven high school science teachers used visual representations in their teaching. A case study approach was used in the research. The findings suggest that science teachers take into account multiple considerations when selecting and using graphics in the classroom, including course content, type of visual, realism, learning styles, prior knowledge, and ability level. Among the science courses evaluated, chemistry’s visual representations were more abstract in nature. Besides this fact, many of the representations teachers used to teach chemistry were at the molecular level; rarely was their macroscopic counterpart shown. The remainder of the representations used in the course was symbolic—presenting formulas, equations, or structures. The outcomes showed that learner characteristics seemed to be the most influential in the teacher’s use of visualizations.

**Multimedia tools that lead students to understand chemistry in all the levels**

In order to solve the problems associated with the difficulties faced by students in understanding and move between the triplet representational levels, teachers have been using methodologies and tools to help students’ learning. As an example, multimedia tools are used to help students understand and move between the triplet representational levels.

Computational programs, stereo-diagrams, dynamic pictures, animations, and simulations have proved to be useful in improving spatial-ability skills. An advantage in using multimedia to learn chemistry is the multiple symbol systems they have that enhances learning. Studies have shown that the combined use of text and animated graphics makes the information more memorable (Ardac & Akaygun, 2004). Other studies have shown that multimedia tools can improve the teaching and learning of chemistry by developing spatial ability, model perception, and chemistry understanding (Barnea & Dori, 1999). This section shows the efficiency of multimedia tools and how some tools can improve the learning of chemistry by using the representational levels.

Ardac and Akaygun (2004) studied the capabilities of computerized environments to enable simultaneous display of molecular representations that correspond to observations at the macroscopic level and to provide an enhanced visual presentation of chemical phenomena at three levels. The study questioned whether the multimedia instructional unit emphasizing the molecular level of representation would improve chemical phenomena conceptualization at the molecular level. The results showed a significantly higher performance by students who received multimedia instruction, and the relative ease with which they could use particulate representations supported the favorable effects of the treatment. Molecular representations were observed to become more refined as the students progressed along the instructional sequence. Furthermore, the results of interview data suggest that the changes observed during the multimedia-based instruction were more than instantaneous and were likely to last over longer periods of time. Fifteen months after the treatment, students who participated in multimedia-based instruction could maintain a relatively high performance level, as evidenced by the more frequent use of particulate representations with less macroscopic interference.
Barnea and Dori (1999) developed a computerized molecular-modeling (CMM) learning environment via implementing a discovery approach in high school chemistry. The CMM contributes to the development of visualization skills via vivid animation of three-dimensional representations. They investigated the effects of molecular-modeling use on students’ spatial ability and their understanding of new concepts related to geometric and symbolic representations and perception of the model concept. The study looked at an urban high school in Israel and involved five heterogeneous classes of fifteen-year-old tenth graders who studied chemistry for the first year. Three experimental classes worked with the molecular-modeling software, and two control classes studied the subject in the traditional way. The results demonstrated that the experimental group scored higher than the control group in some of the spatial-ability tests, in the model-perception questionnaire, and in chemistry understanding. This may be attributed to better understanding of chemical bonding and improved three-dimensional perceptions of molecular structure gained from the CMM experience of students in the experimental group.

Tasker and Dalton (2006) discussed and disclosed the utilization of animations to visualize the molecular world by the use of the constructivist VisChem Learning Design. Motivated by frustration with the lack of resources in the early 1990s depicting Johnstone’s sub-micro level, the VisChem project was founded to produce a suite of molecular animations depicting the structures of substances and selected chemical and physical changes. The animations were produced as useful models at this level and paid careful attention to the often-competing demands of scientific accuracy. The VisChem Learning Design can be used for any chemistry topic that requires a scientifically acceptable mental model of the molecular world. Resources were developed to link these animations to the macro and symbolic levels, which the authors discuss. The work in the VisChem project indicated that animations and simulations can effectively communicate many key features about the molecular level, and these ideas can link the laboratory level to the symbolic level. However, we have also shown that new misconceptions can be generated.

Based on research that emphasizes the difficulties of students in learning symbolic and molecular representations of chemistry, Wu, Krajcic, and Soloway (2001) studied the influence of a computer-based visualizing tool, eChem, on the students’ understanding of chemical representation. This tool allows students to build molecular models and view multiple representations simultaneously. The use of eChem was integrated into a six-week unit called the Toxin Project. Multiple sources of data were collected with the participation in 71 eleventh graders at a small public high school over a six-week period. The analysis of video recordings revealed that several features of eChem helped students construct models and translate representations. Students who were highly engaged in discussions while using eChem made referential linkages between visual and conceptual aspects of representations. This in turn may have deepened their understanding of chemical representations and concepts. The research suggests that computerized models can serve as a vehicle for students to generate mental images.

Russel et al. (1997) studied a prototype multimedia program developed to facilitate student-learning in the classroom. Multimedia and Mental Models in Chemistry (4M:CHEM) utilizes a computer split-screen design to show simultaneous videos of real experiments, molecular-level animations, real-time graphs of macroscopic properties or structural diagrams, and chemical equations. These synchronized views enable teachers and students to engage in discussions about connections between macroscopic, microscopic, and symbolic representations. In order to study the advantages of 4M:CHEM in chemistry learning, an initial assessment was conducted in two lecture sections for two one-hour presentations. It showed an increase in students’ understanding of characteristics of systems at equilibrium and a marked decrease in misconceptions of chemical equilibrium.
Teacher training to work among the representational levels

Besides the use of visualization, multimedia tools, and other methodologies to improve students’ understanding of chemistry between all representational levels, the teacher’s role is very important to students’ success. In their practice, teachers constantly move between multiple representation modes, each time using the one that is most appropriate for the situation, but for students the integration of the representations is not highlighted. In order to adopt a teaching method that enables students to understand and move between the representational levels, chemistry teachers need to be trained for planning lessons and implementing instruction accordingly.

Therefore, some works cited in other sections emphasize the need of teacher preparation to work at the representative levels. This idea agrees with Jaber and BouJaoude (2011) when they say that teacher-preparation programs ought to be designed to promote teachers’ pedagogical content knowledge in this aspect. Also, according to Hinton and Nakleh (1999), in order to develop students’ facility in using multiple representations, teachers have to help students become explicitly aware of these representations and provide classroom opportunities for students to use them. They should also develop assessments designed to reveal students’ macroscopic, microscopic, and symbolic ideas.

Although we know the importance of the teacher’s role in the students’ full appreciation of chemical content, there is still a lack of scientific studies related to teacher training to help students understand chemistry completely and move between all levels. Of all the papers mentioned here, only one conducts research focusing on teachers’ training programs.

Barnea and Dori (2000) investigated how chemistry teachers and students perceive the nature and functions of models. According to the authors, teachers’ perceptions are important; if teachers do not have the necessary understanding of the nature and role of models in the development of a discipline, they probably will not be able to incorporate them properly in their teaching. The research was done in two steps. In the first step, 34 pre- and in-service teachers attended a 14-hour workshop on models, and their model perception was investigated with the model questionnaire. During the training, teachers learned the different meanings of models and experienced various types of models. After this step, some teachers applied what they learned in school, using molecular modeling software for an experimental group, while teaching the subject to the control group in the traditional way. The results of the study indicated that, overall, the in-service training program on models put emphasis on many aspects of the trainees’ model perception. The training made teachers realize the role of models, and their initial perception of models was expanded. The most significant outcome of the training is reflected in the school implementation, where a noticeable difference between experimental and control groups was found.

Understanding chemistry on the macroscopic, microscopic, and symbolic levels is necessary for the development of many skills in students: the capacity for abstraction, logical reasoning, and the understanding of natural phenomena and themselves in the world. The researches show the importance of discussing this topic and for researchers to help teachers improve their class work.

For high school students, shifting among the three levels is not an easy task. Some students are more able to do this, but most cannot understand the content in all levels and shift mainly between the macro and symbolic levels. To help these students, teachers have to improve and vary their instructions and aim to achieve understanding in every student. Multimedia tools can help teachers in this task, but the knowledge and ability of teachers to help their students cannot be replaced by technology. Teachers have to be trained to feel prepared for the task of teaching in the three levels.
The studies reviewed for this work show that a lot of research has aimed to improve learning and teaching in the three levels. The outcomes obtained have shown that this topic has raised the interest in many science education researchers. However, there is still a predominance of works about students’ difficulties and the methodologies to improve their visual capacities to understand chemistry between all representational levels, since it is a real necessity in chemistry education.

However, a gap can be observed in studies that focus on teachers’ training to use the representational levels in their classes, making students understand chemistry completely. This results show the need to direct research to the topic of visualization, highlighting the importance of teachers’ training in the learning of chemistry between all representational levels.

CONCLUSION and IMPLICATIONS

Students’ acquisition of knowledge without a clear understanding, or the generation of misconceptions, may be attributed to the confusion caused by having to deal simultaneously with the macroscopic, submicroscopic, and symbolic worlds of chemistry. If students understand the role of each level of chemical representation, they can often see how to transfer knowledge from one level to another. Thus, when learners develop relational understanding, they acquire ways to move easily and skillfully within the macro-micro-symbolic triangle, meaningfully linking the various chemical concepts.

This work has presented some general characteristics about visualization and the representative levels in chemistry education topics. The works reviewed here have shown that students face a lot of difficulties in operating at all representational levels; they are able to understand a chemical phenomenon more at the macroscopic and symbolic level, but the microscopic level is difficult to understand without proper explanation and visual methodologies. It was also reported that without appropriate instruction, students usually fail to produce meaningful links across the levels. The use of models and multimedia tools in chemistry classes has helped increase the students’ performance on all representational levels, but researchers emphasize that the teacher’s role is still very important for the students’ success. Nevertheless, there is still a lack of scientific studies related to teacher training to help students understand chemistry at all levels. Most studies focused on the students and not the teacher training. But there is no sense to focus only on students or on resources and materials considering the complexity of this process. Thus, future research showing the role of teachers in chemistry learning at all representational levels is essential, and teachers must support students in activities involving different levels of representation and transitions between these levels. The focus in the majority of these studies is on cognitive approaches, but there is not enough focus on sociocultural approaches.

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