Exploring Visuospatial Thinking in Chemistry Learning

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ABSTRACT: In this article, we examine the role of visuospatial cognition in chemistry learning. We review three related kinds of literature: correlational studies of spatial abilities and chemistry learning, students' conceptual errors and difficulties understanding visual representations, and visualization tools that have been designed to help overcome these limitations. On the basis of our review, we conclude that visuospatial abilities and more general reasoning skills are relevant to chemistry learning, some of students' conceptual errors in chemistry are due to difficulties in operating on the internal and external visuospatial representations, and some visualization tools have been effective in helping students overcome the kinds of conceptual errors that may arise through difficulties in using visuospatial representations. To help students understand chemistry concepts and develop representational skills through supporting their visuospatial thinking, we suggest five principles for designing chemistry visualization tools: (1) providing multiple representations and descriptions, (2) making linked referential connections visible, (3) presenting the dynamic and interactive nature of chemistry, (4) promoting the transformation between 2D and 3D, and (5) reducing cognitive load by making information explicit and integrating information for students. *Sci Ed* **88:**465–492, 2004; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/sce.10126

INTRODUCTION

Chemistry is a visual science. Kekulé, for example, credited the discovery of the benzene ring to a daydream, in which he visualized a group of atoms moving like a snake and grabbing its own tail (Benfey, 1958; Rothenberg, 1995). Beyond this and other anecdotes, visualization plays a major role in chemists' daily practices. To investigate natural phenomena through ideas of molecules, atoms, and subatomic particles, and the relationships amongst them, chemists have developed a variety of representations, such as molecular models, chemical structures, formulas, equations, and symbols (Hoffmann & Laszlo, 1991). These "master images" (Mathewson, 1999) have become the basis for knowledge extension within the professional community of chemists. A typical example of visual reasoning in a laboratory task is outlining a multiple-step synthesis of an organic compound (Figure 1).

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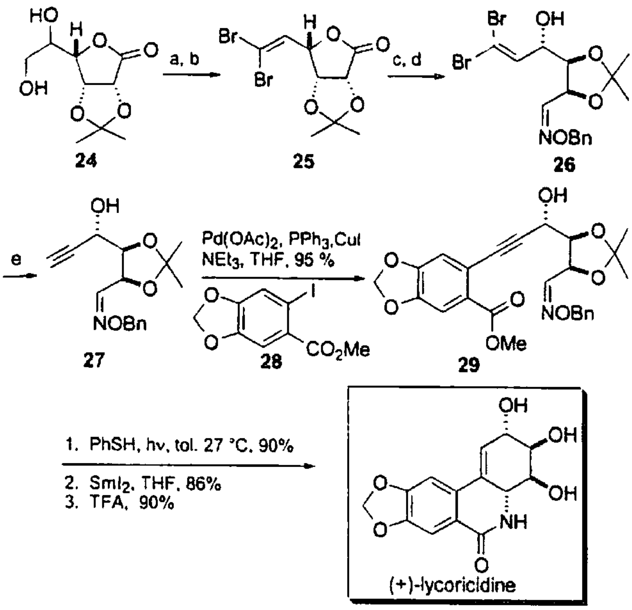

[a] Key: (a) $NaIO_4$, CH_2Cl_2. (b) CBr_4, PPh_3, NEt_3, 80% over two steps. (c) L-Selectride, Et_2O, −78 °C. (d) HCl·H_2NOBn, pyridine, 90% over two steps. (e) ^{n}BuLi, Et_2O, −90 °C, 93%.

Figure 1. A synthesis scheme from an article by Keck, Wager, and Rodriquez (1999). Reprinted with permission from Journal of the American Chemical Society, 121(22), 5179. Copyright 1999 American Chemical Society.

To visualize the synthesis process, chemists always sketch structures of reactants and products, and draw symbols, arrows, and equations to describe chemical processes (Kozma et al., 2000). These chemical representations spatially present the imagery of particles and their geometrical shape in two dimensions and compose a spatial language (Balaban, 1999; Habraken, 1996; Nye, 1993). They present information that may not be easily understood otherwise (Larkin & Simon, 1987) and allow chemists to think visually and convey information efficiently through a form of visual display.

Visualizations have also been used for communicating concepts to students of chemistry. Secondary school and college chemistry curricula and textbooks use a variety of visual representations to introduce fundamental chemical concepts (Noh & Scharmann, 1997). Figure 2 shows an example of using visual representations to explain isomerism in chemistry. To identify geometric isomers, which have the same chemical formula but different structures and properties, students are required to translate a chemical formula into its molecular structure(s), visualize the possible three-dimensional (3D) configurations, and compare these configurations. Therefore, being able to comprehend and mentally manipulate chemical representations is critical for students to understand the content and conduct advanced scientific research.

Chemistry teachers and educational researchers have recognized the importance of visualization in chemistry learning. However, a number of questions remain about the role of visual thinking in chemistry. First, to what degree do individual differences in visuospatial abilities predict learning in chemistry? Second, to what extent do conceptual errors in chemistry arise from difficulties in comprehending, translating, and transforming internal and external visual representations? And third, to what extent can visualization tools, ranging from physical models to computer-based multimedia software, help support visuospatial thinking in chemistry learning? In this review, we systematically examine current studies to

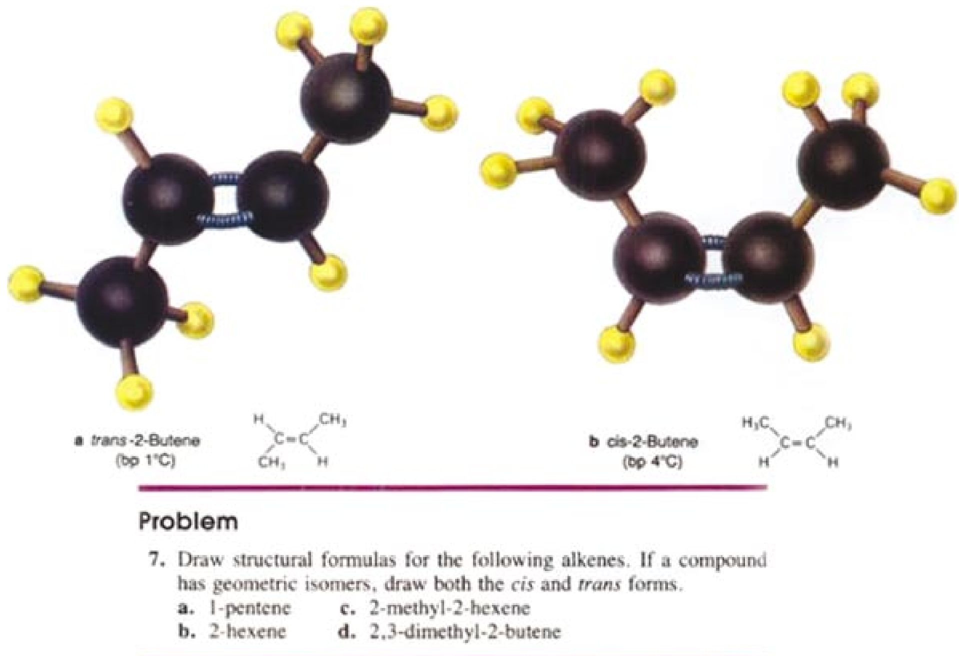

Figure 2. Representations of geometric isomers and a relevant problem in a chemistry textbook for high school students. From *Addison-Wesley Chemistry* by Antony C. Wilbraham, Dennis D. Staley, and Michael S. Matta © 1987 by Addison-Wesley Publishing Company, Inc. Published by Pearson Education, Inc., publishing as Pearson Prentice Hall. Used by permission.

answer these three questions in three separate sections. In our general discussion, we consider the implications of the answers to these questions for the design of new visualization tools for chemistry learning and suggest possibilities for guiding further research efforts.

The studies included in this review are based on searches using ERIC (Educational Resources Information Center) database that contains articles from 1966 to the present and PsychInfo, an electronic database of American Psychological Association, which contains papers from 1987 to the present. When choosing key words, we used the word "chemistry" and all the following terms one by one: representation, misconception, alternative conception, alternative framework, diagrams, visualization, spatial ability, visual ability, inscription, technology, and model, and obtained over 200 citations. Of these, we chose to analyze only those that were empirical studies published in research journals and relevant to the three questions. We then read the reference sections of each of these papers to identify prior research that addressed similar questions. We continued to do so till we were satisfied we had collected all of the studies involving visual representations, visuospatial abilities, students' alternative conceptions, and visualization tools in chemistry learning. This left us with 135 studies.

Before we outline the research on visual thinking in chemistry education, it would be helpful to establish what kinds of visual representation are used in chemistry. Chemical representations such as molecular structures and atomic models are partially schematized and partially iconic diagrams that depict abstract concepts and apply conventions to illustrate both the components and their organization (Hegarty, Carpenter, & Just, 1991). The relationship between visual displays and chemical concepts is neither arbitrary, as is the relation between words and concepts, nor a first-order isomorphism, as is the relation between pictures and their referents (Winn, 1991). Thus, in the continuum of different forms of written information, chemical representations are typically more abstract than pictorial diagrams, but still represent information in an analogical, nonarbitrary fashion. For example, Figure 2 illustrates a partially schematic diagram of two butene molecules in which individual atoms and chemical bonds are schematized to look like balls and sticks. At the same time key concepts are represented such as the number of bonds that a hydrogen atom has and the geometrical shape of a butene molecule. Using these representations to perform tasks requires a series of cognitive operations in spatial domain, such as recognizing the graphic conventions, manipulating spatial information provided by a molecular structure, and mentally tracking the constraints based on concepts. Thus, it is likely that learning chemistry involves students' visuospatial abilities that support students to perform certain cognitive operations spatially.

TO WHAT DEGREE DO INDIVIDUAL DIFFERENCES IN VISUOSPATIAL ABILITIES PREDICT LEARNING IN CHEMISTRY?

Interested in whether spatial abilities affect students' chemistry learning achievement, a series of studies emphasize the role of visuospatial thinking by investigating the correlations between spatial abilities and chemistry learning. The studies we will review included spatial abilities as one of the cognitive factors that may be relevant to the mastery of chemistry concepts. Other cognitive factors that have been considered by correlational research on chemistry learning included formal reasoning skills (Abraham & Westbrook, 1994; Chandran, Treagust, & Tobin, 1987; Haidar & Abraham, 1991; Keig & Rubba, 1993; Niaz, 1987, 1988, 1989; Niaz & Robinson, 1992; Staver & Halsted, 1985), proportional reasoning skills (Anamuah-Mensah, Erickson, & Gaskell, 1987), field dependence/independence (Niaz & Lawson, 1985), and memory capacity (Niaz, 1988, 1989; Niaz & Lawson, 1985; Niaz & Robinson, 1992). To narrow the scope of this article and focus on the visual aspect of chemistry learning, we review key findings of the correlational studies regarding chemistry learning and spatial abilities.

Because psychometric tests of spatial abilities vary in the underlying skills they might be measuring (Miyake et al., 2001), we first briefly discuss what spatial ability tasks measure, and their possible role in chemistry problem solving. Indeed, factor analytic studies have identified five or more separate factors representing different kinds of spatial abilities (Carroll, 1993), and most of the studies outlined below focused on three spatial ability factors: spatial visualization, closure flexibility, and spatial relations.

Spatial visualization involves tests that "reflect processes of apprehending, encoding, and mentally manipulating spatial forms" (Carroll, 1993, p. 309) and require performance of a complex sequence of mental manipulations. An example of such a test is the Purdue Visualization of Rotation test (see example in Figure 3), a commonly used measurement of spatial visualization in chemistry education (Bodner & McMillen, 1986; Carter, LaRussa, & Bodner, 1987; Yang, Greenbowe, & Andre, 1999). In this test, participants view two rotated versions of one 3D figure, infer the type of transformation between them, and make the same transformation with a new 3D figure (Figure 3). Mental manipulation of spatial representations such as those on spatial visualization tests are required in chemistry problem solving. For example, to determine whether dibromomethane (CH_2Br_2) is a polar molecule (a common high school chemistry task), students typically draw or are shown a schematized two-dimensional (2D) structural formula (Figures 4a and 4c). However, the two diagrams could lead to different conclusions unless students mentally or physically create a 3D model of the molecule as in Figures 4b and 4d. These 3D models indicate that dibromomethane is polar because the two polar bonds between carbon and bromine do not lie along the same axis in 3D space as shown in Figure 4c. Even if students had a 3D model available, they

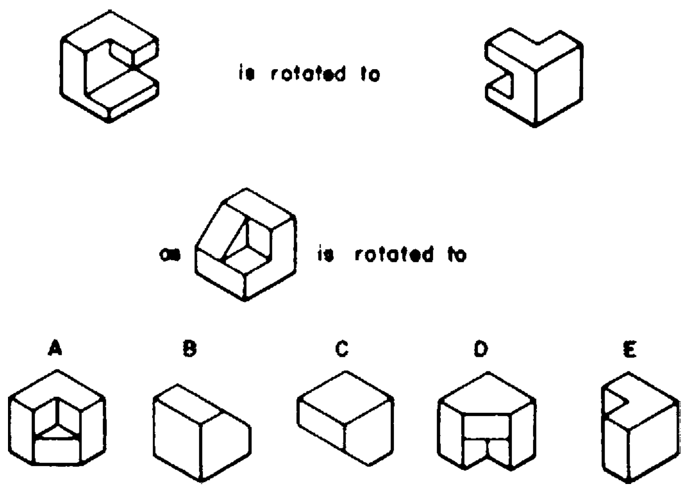

Figure 3. One item from the Purdue Visualization of Rotations Test.

may have to mentally rotate it in order to judge the bond angles. As this example indicates, making a simple judgment about polarity involves constructing a 3D mental model of a 2D depiction and possibly mentally rotating it.

Another factor, closure flexibility, is concerned with the speed of apprehending and identifying a visual pattern, often in the presence of distracting stimuli. It requires students to internally maintain a given pattern and counteract the distracting stimuli. Closure flexibility is measured by tasks such as the Find-a-Shape-Puzzle in which people must find simple figures embedded in more complex ones (see example in Figure 5). This factor is also considered related to chemistry problem solving (Bodner & McMillen, 1986; Carter, LaRussa, & Bodner, 1987). The synthesis scheme shown in Figure 1 is an example. When considering what chemical reagents are needed to produce compound **25** by using compound **24** as a reactant, chemists first identify visual similarities and differences between the two complex molecular structures. In this case, the structural differences are the disappearance of the two hydroxyl (—OH) groups in compound **24** and the formation of a double bond attached to two bromine atoms in compound **25**. Based on this information, the chemist would decide that bromine is necessary in the reagents for the reaction. Reading an IR (infrared), UV (ultraviolet), or NMR (nuclear magnetic resonance) spectrum to decide the structure of a

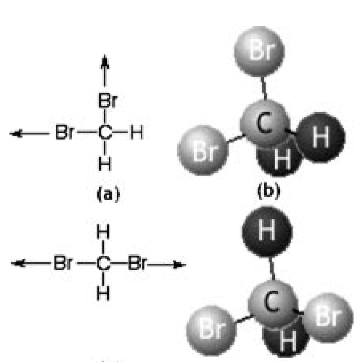

Figure 4. 2D and 3D representations of CH_2Br_2.

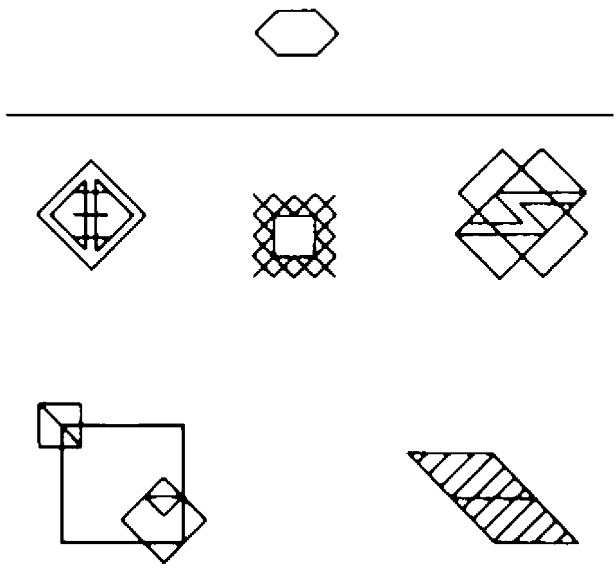

Figure 5. One item from the Find-a-Shape-Puzzle test.

molecule is another task that requires the apprehension and identification of a visual pattern in the presence of distracting stimuli. Thus, closure flexibility skills are frequently used in chemists' daily practices.

A third factor is spatial relations and one of the examples is card rotation test (Barnea & Dori, 1996) in which participants must judge which of the figures are the same as the target figure. This factor is similar to spatial visualization in that spatial relations also require mental transformations, but differ in that they involve simpler manipulations (usually within a single step) of 2D objects and tend to emphasize speed (Carroll, 1993). Chemistry problems related to the identification of isomers require this kind of spatial reasoning. For instance, to identify whether structures (a) and (b) in Figure 6 represent geometric isomers, students have to mentally rotate the single bond between the two carbon atoms. Because the structures are superimposable after rotation, they are not isomers but represent the same structure.

The Existence of a Positive Correlation Between Spatial Ability and Learning Achievement

The examples of spatial ability tests and chemistry tasks described above illustrate how visuospatial thinking may be involved in doing chemistry. In this section, we provide correlational evidence that visuospatial abilities are an important component of students' learning in chemistry.

(a) (b)

Figure 6. Two structural formulas of C_3H_7Cl.

In a general study of spatial abilities and problem-solving skills, Bodner and McMillen (1986) measured students' chemistry learning achievement in problems with and without obvious spatial components, such as identifying crystal structures and solving stoichiometry problems. They found that total scores on the spatial visualization and closure flexibility tests were significantly correlated with performance on all chemistry subtests. That is, visuospatial skills partially explained students' performances on the apparently spatial type of chemistry problems as well as the nonspatial chemistry problems.

To further investigate the relationship between spatial abilities and students' performances on problem solving, Bodner and his colleagues (Carter, LaRussa, & Bodner, 1987) designed a study to examine whether spatial abilities influenced students' abilities to solve various types of chemistry problems differently. They found that students with high spatial ability appeared to have higher scores on problems that required problem-solving skills rather than rote memory or the simple algorithms such as crystal structure and stoichiometry. Correlations were stronger for verbally complex questions that required multiple steps of calculations and restructuring relevant information of the problem (Carter, LaRussa, & Bodner, 1987). Similarly, Staver and Jacks (1988) showed that students' visuospatial abilities significantly influenced their performance on balancing chemical equations.

On the other hand, research showed that direct training or practice on visuospatial tasks could improve chemistry achievement. In Small and Morton (1983), students who received training on visualization skills had significantly higher scores on questions that required the use of 3D models in a retention test. Tuckey, Selvaratnam, and Bradley (1991) developed an instruction program to improve students' visual thinking and found that by practicing several kinds of spatial reasoning that are frequently used in chemistry, students' performances on chemistry tests were significantly better after the intervention.

These findings raise at least two questions: What are the possible explanations of this correlation? How could visuospatial abilities and training be correlated to students' performances on both explicitly spatial problems (e.g., crystal structure) and nonspatial problems (e.g., stoichiometry)?

Possible Explanations for the Correlation Between Spatial Ability and Learning Achievement

The results of Bodner's studies are surprising in that, although there is an expectation that explicitly visuospatial chemistry problems may require visuospatial abilities, it is not clear why visuospatial skills are relevant for nonspatial problems. Bodner and McMillen (1986) argued that the stoichiometry problems required visuospatial thinking because solving them needed multiple steps of calculations to approach the answer. When formulating these multiple steps and examining whether these steps were feasible, students might manipulate the relevant information and restructure the problem in the spatial domain so the Rotations test (Figure 3) could be an indicator of cognitive restructuring ability. By using factor analysis, Staver and Jacks (1988) found that three variables, e.g., reasoning, rotation, and disembedding abilities, could be collapsed to create a new variable that might be an indicator of students' restructuring ability. In a sense, Staver and Jacks (1988) supported Bodner and McMillen's claim about cognitive restructuring; however, they did not provide direct evidence to answer the questions of whether and how students restructure a problem in the spatial domain when solving chemistry problems.

Another possible explanation for the correlation might be similar to the one provided by Pattison and Grieve (1984) in their study of the role of spatial thinking in mathematics. They found that spatial abilities were correlated with both performances on spatial and nonspatial mathematical problems (e.g., geometry and algebra). Their explanation for this relationship was that although some domains like algebra appear to be nonspatial compared to geometry, they may involve spatial thinking, such as mentally manipulating numbers and estimating quantities. Indeed, recent neuroimaging data suggest that tasks such as the estimation of numerical data activate similar brain areas as spatial tasks (D'Esposito et al., 1998). Similarly, when students complete chemical equations, their attempts to search for correct equations might involve mentally decomposing and combining reactants and products in a chemical equation. In addition, a comprehensive use of visual representations in both spatial and nonspatial questions may require students to perform their spatial thinking skills in order to answer the questions (Bodner & Domin, 1996). The importance of comprehending and manipulating these visual representations will be analyzed in a later section.

A third explanation is provided by Pribyl and Bodner (1987) who examined the underlying basis for the correlation between students' visuospatial abilities and their problem-solving skills. They indicated that high spatial ability students tended to draw preliminary figures even though the drawings were not required by questions, whereas low spatial ability students drew fewer figures and were more likely to have incorrect drawings with nonsymmetric and inappropriate structures. The figures drawn by the high spatial ability students seemed to help them to solve problems successfully. According to Larkin and Simon's argument (1987) of why diagrams have the potential for conveying information efficiently, creating preliminary figures helped high spatial ability students spatially organize and represent the conceptual information provided by a problem (see also Johnson-Laird, 1998; Oestermeier & Hesse, 2000). These figures, which were problem representations (Chi & Feltovich, 1981), allowed students to make problem-solving inferences explicitly and search for information easily. This representing process in the spatial domain existed for solving problems like completing a reaction or outlining a multiple-step synthesis. Thus, even when problems do not explicitly include a spatial component, students with good spatial skills may use their strength in visuospatial thinking to solve chemistry problems. Again, this is similar to the mathematics domain, in which high spatial students were more likely to create diagrams of problems that were not necessarily framed as spatial problems (Fennema & Tartre, 1985).

A fourth explanation is that the significant correlation between spatial ability and chemistry problem-solving skills is based on a more general cognitive factor, such as general reasoning skills or intelligence rather than on visuospatial thinking. Indeed, general reasoning skills play a role in predicting performance on complex spatial tests (Miyake et al., 2001). Although there seems to be no study that has systematically examined the possible joint or separable roles of general cognitive skills and visuospatial abilities on chemistry achievement, two correlational studies have shown that general cognitive skills do play an important role in chemistry achievement. Baker and Talley (1972) showed that college freshman and sophomore students' academic performance partially explained their chemistry achievement and visualization skills, but they found no correlation between visualization skills and chemistry achievement. In addition, high students' ability to translate between different kinds of representations in chemistry (Keig & Rubba, 1993) and college students' performance on biochemistry (Schoenfeld-Tacher, Jones, & Persichitte, 2001) did not correlate with their spatial abilities, but their reasoning skills and prior knowledge.

There are a number of possible reasons why these studies did not find a correlation between visuospatial skills and chemistry achievement that other studies have found. First, the tasks used to assess students' learning performance seem to influence the significance of the correlation. The content test used in Schoenfeld-Tacher, Jones, and Persichitte (2001) consisted of 14 multiple-choice items and measured students' knowledge of material presented in a multimedia scenario which might not be the problems that required mental operations in the spatial domain. In Keig and Rubba (1993), only 19% of students were able to come up with an appropriate ball-and-stick model to complete the formula-to-model translation.

Analysis of interview protocols indicated that the most common errors made by students were caused by a lack of content knowledge instead of an inability to manipulate information spatially. Thus, a floor effect seems to exist when the tasks require a certain level of content knowledge. When students have relatively lower content knowledge than is required by tasks, their prior knowledge is a more influential factor in their learning performance than their spatial abilities. Second, two of the studies that showed no correlation between spatial abilities and chemistry learning achievement had relatively small sample size. There were 42 high school students participating in Keig and Rubba (1993) and 52 college students in Baker and Talley (1972). Third, although the studies demonstrated a possibility that other general cognitive factors might play a more significant role in chemistry learning than visuospatial skills, the zero-order correlational analysis does not allow us to identify the possibly separable roles of visuospatial skills and more general cognitive skills on chemistry achievement.

Discussion of Correlational Studies

The correlational studies outlined in this section demonstrate that many problem-solving tasks in chemistry involve visuospatial thinking, but a number of questions remain. First, what accounts for the correlation between visuospatial thinking in solving nonspatial chemistry problems? Although explanations of the correlation were proposed, more empirical data are needed to justify some of the hypothesized explanations, such as solving stoichiometry problems requiring the manipulation of the problem information in the spatial domain.

Second, does the correlation exist in students' early years of learning chemistry? Substantial chemistry instruction begins in high school; yet, not much information regarding students' visuospatial thinking and chemistry learning at the precollege level is provided by the correlational studies, as only few of them had high school students as participants. More studies conducted with participants at the secondary school level are needed. They will extend our understandings about whether there is the correlation between visuospatial skills and learning achievement at students' early years of learning chemistry, whether chemistry learning experiences have a positive impact on visuospatial abilities, and what level of visuospatial thinking is required for students who have relatively low content knowledge.

Finally, as we mentioned previously, it is possible that the significant correlation between spatial ability and chemistry problem-solving skills is based on a general cognitive factor, but no studies have systematically separated the role of visuospatial abilities and general cognitive factors. Therefore, before visuospatial thinking is examined as an influential factor of chemistry problem solving, the role of some general factors, such as general intelligence and academic ability, in problem solving needs to be clarified.

In addition to clarifying the role of individual difference in spatial ability on chemistry achievement, it is important to understand exactly what aspects of chemistry tasks involve visuospatial thinking. As we take a close look at both spatial and nonspatial chemistry problems, one common characteristic of them is a comprehensive use of visual and symbolic representations, such as chemical structures, formulas, and equations. When students solve a chemistry problem, they may visualize or translate representations into another form that allows them to make inferences efficiently (Bodner & Domin, 1996). Thus, forming an internal visual representation, comprehending a visual representation, and transforming representations, all of which likely require substantial visuospatial thinking skills, may be a critical component of chemistry problem solving. In the next section, we outline research on the comprehension and translation of visual representations that provides insights into how visuospatial thinking interacts with chemistry learning.

TO WHAT EXTENT DO CONCEPTUAL ERRORS IN CHEMISTRY ARISE FROM DIFFICULTIES IN COMPREHENDING, TRANSLATING, AND TRANSFORMING VISUAL REPRESENTATIONS?

Because the focus of this review article is visuospatial thinking in chemistry, this section is not a comprehensive review of students' alternative conceptions in chemistry (see Gabel, 1998; Garnett, Garnett, & Hackling, 1995; Krajcik, 1991). Research on students' conceptions about matter (Andersson, 1990; Stavy, 1991; Taber, 1998), substances (Solomonidou & Stavridou, 2000), particles (Johnson, 1998), stoichiometry (Huddle & Pillay, 1996; Tingle & Good, 1990), and chemical equilibrium (Hackling & Garnett, 1984; Wilson, 1994) will not be discussed in detail. Rather, our review will center on students' difficulties comprehending, interpreting, translating, and transforming visual representations in chemistry.

Difficulties in Comprehending and Interpreting Representations

Much research on alternative conceptions about chemical representations has been done in the context of a research tradition that focuses on developmental changes in students' conceptual understandings of different conceptions (e.g., Ben-Zvi, Eylon, & Silberstein, 1987; Krajcik, 1991; Nakhleh, 1992). This research has identified three major alternative conceptions that arise from difficulties comprehending and interpreting representations: (1) representing chemical concepts at the macroscopic level rather than the microscopic or symbolic level; (2) comprehending visual representations at the macroscopic level and by surface features; and (3) interpreting chemical reactions as a static process.

Chemical representations can be categorized into three levels: the macroscopic, microscopic, and symbolic levels (Gabel, 1998; Gabel, Samuel, & Hunn, 1987; Johnstone, 1982, 1993). Chemical representations at the macroscopic level refer to pictures or diagrams that represent observable phenomena.[1] Microscopic representations of chemistry refer to models or other visual displays that depict the arrangement and movement of particles. Representations at the symbolic level include symbols, numbers, and signs used to represent atoms, molecules, compounds, and chemical processes, such as chemical symbols, formulas, and structures.

Although symbolic and microscopic representations are frequently used in chemistry textbooks, applying ideas of particles and constructing microscopic representations to make explanations of observations are very difficult for many secondary school students (Brosnan & Reynolds, 2001; Griffiths & Preston, 1992; Renstroem, Andersson, & Marton, 1990). They usually represent chemical concepts or phenomena at the macroscopic level rather than microscopic or symbolic levels. In Krajcik (1989), 17 ninth graders were interviewed and asked to draw and describe how the air in a flask would appear if they could see it through a very powerful magnifying glass. Only three of them drew air composed of tiny particles, while others held a continuous view of matter and represented the air by wavy lines or a vapor model.

A second alternative conception, comprehending visual representations at the macroscopic level and by their surface features, is demonstrated by secondary school students as well as college students when they are asked to interpret microscopic and symbolic representations (Garnett, Garnett, & Hackling, 1995; Kozma & Russell, 1997; Krajcik, 1991). Ben-Zvi, Eylon, and Silberstein (1988) explored the levels of descriptions generated by high school students when they were asked to interpret the meanings of two symbolic

[1]As may be noticed, throughout the article "chemical representations" refer to the molecular and symbolic ones unless with further explanations.

representations: $H_2O(l)$ and $Cl_2(g)$. Although most of the students in the study were able to generate some macroscopic descriptions of water, e.g., its properties, the microscopic representations they used to explain the phenomena were not appropriate. Some students viewed $Cl_2(g)$ as a representation of one particle instead of a collection of multiple molecules, because they did not recognize that (g) represents chlorine molecules in a gas state and means a large amount of Cl_2 molecules. By literally interpreting the chemical formula of water molecules $H_2O(l)$, some students believed that a water molecule contains a unit of hydrogen gas, H_2. These students confused atoms with molecules, so they held a conception that a water molecule consists of another molecule, H_2. Ben-Zvi et al. also showed that many students, even after receiving substantial chemistry instruction, thought that formulas were merely abbreviations for names rather than a way to represent the composition or a structure.

Finally, students had difficulties interpreting chemical equations (Krajcik, 1991). They interpreted an equation, such as $C(s) + O_2(g) \rightarrow CO_2(g)$, as a composition of letters, numbers, and lines instead of a process of bond formation and breaking. The technique of balancing chemical equations made students picture chemical equations as mathematical puzzles (Ben-Zvi, Eylon, & Silberstein, 1987), and they could even work algorithms without having a conceptual understanding of the phenomena (Nakhleh, 1993; Yarroch, 1985). Thus, while chemists view a chemical reaction represented by an equation as an interactive and dynamics process, students can only construct a static model of it.

Difficulties in Translating and Transforming Representations

In addition to the difficulties comprehending representations, many students are not capable of providing equivalent representations for a given representation (Kozma & Russell, 1997) because of a lack of content knowledge (Keig & Rubba, 1993) or a lack of visuospatial thinking skill (e.g., Tuckey, Selvaratnam, & Bradley, 1991).

High school students are frequently unable to make translations among formula, electron configuration, and ball-and-stick models (Furio et al., 2000; Keig & Rubba, 1993). Students had difficulties determining molecular structures when empirical formulas were given (Furio et al., 2000), and their performances on the translation of representations were not correlated to their visuospatial ability but their conceptual understanding about the representations. Hence, Keig and Rubba argued that translation between representations is an information processing task that requires knowledge of the underlying concept. The conceptual knowledge allows students to interpret the information provided by the initial representation and infer the details to construct the target representation (Lesh, Post, & Behr, 1987).

Another type of translation is between 2D and 3D representations (Rozzelle & Rosenfeld, 1985; Srinivasan & Olson, 1989). On the basis of a hypothesis that a logical process to transform or mentally manipulate 3D representations was through a step-by-step approach, Tuckey, Selvaratnam, and Bradley (1991) argued that students' difficulties were caused by either not using a stepwise approach or unable to finish one or more steps. Tuckey et al. decomposed the process of rotation and reflection of 3D structures into a series of cognitive components and developed test items to test each of the cognitive components. The results showed that many students were not able to make use of the depth cues and had difficult identifying the axes and planes. Tuckey et al. then designed a remedial instruction program to improve students' visual thinking and found that by focusing on these elementary steps students performed significantly better after the intervention.

Seddon, Shubbar, and their colleages (Seddon & Eniaiyeju, 1986; Seddon, Eniaiyeju, & Chia, 1985; Seddon & Shubber, 1985; Shubbar, 1990) examined how the four depth cues (i.e., the foreshortening of lines, the relative sizes of different parts of the structure, the representations of angles, and the extent to which different parts of the diagram overlap) of 2D molecular structures influenced students' mental rotation of them. They found that students needed to respond correctly to all four depth cues in order to visualize the effects of performing rotations. To address students' learning difficulties, they designed different instructional programs such as using slides with explicit instruction to improve their ability to visualize 3D representations (Seddon, Eniaiyeju, & Chia, 1985).

Discussion

Students' conceptual errors and difficulties suggest that chemical representations are conceptual constructs (Hoffmann & Laszlo, 1991) that convey conceptual knowledge as well as visual diagrams that require domain-general visuospatial skills to comprehend. Similar to the graph comprehension model developed by Carpenter and Shah (1998), visualizing chemical representations requires the cognitive linkages between conceptual components that involve substantial content knowledge of underlying concepts, and visual components that involve encoding and interpreting the symbols and conventions (Wu, Krajcik, & Soloway, 2001). Because conceptual and visual components could be linked (Paivio, 1986), students' conceptual understanding might be enhanced by comparing visual features of multiple representations. For example, students' conception of viewing H_2 as hydrogen gas in water molecules might be changed if students are given opportunities to see other types of representations of water and hydrogen gas, such as ball-and-stick models and structural formulas (see Figure 7). Structural formulas, which represent spatial relationships among atoms, could help students visualize that at the atomic level, their alternative conception is partially correct because the number of hydrogen atoms in water and hydrogen gas are the same. At the molecular level, however, hydrogen atoms within individual water and hydrogen molecules form totally different types of chemical bonds (i.e., H—O and H—H in Figure 7), that make water and hydrogen gas have different physical and chemical properties. Thus, visual representations indeed facilitate students to understand concepts and by using multiple visual representations, students could achieve a deeper understanding of phenomena and concepts (Ainsworth, 1999; Kozma et al., 1996).

DISCUSSION AND INTERIM SUMMARY

The correlational studies reviewed previously indicate a possible correlation between students' visuospatial abilities and their performance on chemistry. Students with lower visuospatial abilities

1. are unable to perform as well as their peers with higher visuospatial abilities on solving both spatial and nonspatial chemistry problems (Bodner & McMillen, 1986; Carter, LaRussa, & Bodner, 1987);
2. have difficulties reorganizing or transforming the information provided by questions into a visual representation, such as drawing preliminary figures (Pribyl & Bodner, 1987).

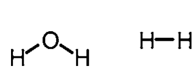

Figure 7. Structural formulas of water and hydrogen molecules.

This suggests that as using visual representations is common practice in chemistry and conceptual knowledge of chemistry is embedded in various types of molecular and symbolic representations, low spatial ability students are disadvantaged.

Additionally, students at the secondary school level have difficulties comprehending and translating molecular and symbolic representations. Most of them are unable to

3. represent chemical concepts at the microscopic or symbolic levels (Ben-Zvi, Eylon, & Silberstein, 1988; Krajcik, 1989);
4. comprehend symbolic and molecular representations conceptually (Ben-Zvi, Eylon, & Silberstein, 1988; Kozma & Russell, 1997);
5. visualize the interactive and dynamic nature of chemical process by viewing symbols and equations (Ben-Zvi, Eylon, & Silberstein, 1987; Krajcik, 1991);
6. make translations between chemical formula, electron configuration, and ball-and-stick model (Keig & Rubba, 1993);
7. identify the depth cues of 2D models (Seddon, Eniaiyeju, & Chia, 1985);
8. form 3D mental images by visualizing 2D structures (Tuckey, Selvaratnam, & Bradley, 1991).

Because of the dual nature of chemical representations (i.e., visual and conceptual), in addition to a focus on students' conceptual understandings, this article suggests incorporating a visuospatial thinking approach in chemistry instruction. In the previous sections, we reviewed empirical foundations of this approach. First, visuospatial thinking is involved in both spatial and nonspatial problem-solving processes in chemistry. High spatial ability students tend to perform better in chemistry tasks because they are able to mentally manipulate information in the spatial domain or represent complex information visually. Thus, there is a need for teachers and students to realize how to think visually and reason with visual displays, especially with those visual and symbolic representations in chemistry.

Second, this approach emphasizes a close interaction between visual representations and relevant concepts. Visual representations indeed could be used to scaffold students' learning of concepts, because most of them include visual features that correspond to conceptual entities. Chemistry instruction should indicate the close connections between visual features and conceptual entities and include multiple representations as coreferents of a specific concept.

A third focus of this approach is representational skills, including abilities to use representations to generate explanations, fluently translate one representation into another, and make connections between representations and concepts (Kozma & Russell, 1997). As Kozma (2000) stated, "the use and understanding of a range of representations is not only a significant part of what chemists do—in a profound sense it is chemistry" (p. 15). Namely, reasoning with representations is the basis of chemistry inquiry as well as epistemological thinking of chemistry. In the following section, we analyze studies of instructional tools to illustrate how these tools are beneficial for learning chemistry by taking a visuospatial thinking approach.

TO WHAT EXTENT CAN VISUALIZATION TOOLS, RANGING FROM PHYSICAL MODELS TO COMPUTER-BASED MULTIMEDIA SOFTWARE, HELP SUPPORT VISUOSPATIAL THINKING IN CHEMISTRY LEARNING?

Given the importance for visuospatial thinking in chemistry, visual aids and learning tools have garnered much research attention in recent years. These tools have unique capabilities that enable students to visualize imperceptible chemical entities (e.g., molecules and atoms) that may not be accessible by traditional instructional methods (Beckwith & Nelson, 1998; Hurwitz & Abegg, 1999; Kozma, 1991; Smith & Stovall, 1996). To present how visualization tools address specific learning difficulties, this section is organized by types of tools, including concrete models, animation and simulation, and computer-based visualization tools.

Concrete Models: Visualizing 3D Configurations of Molecules

As previously discussed, students with lower visuospatial abilities have difficulty mentally manipulating molecular models and chemistry learning experience might improve students' visuospatial abilities. Manipulating 3D concrete models could be one of these learning experiences (Gilbert & Osborne, 1980; Ingham & Gilbert, 1991). Hyman (1982) indicated that using molecular models either as demonstrations or for manipulation was equally beneficial for students' visuospatial ability. It seems that the learning experience students need is to "see" atoms and molecules and that physical interactions with concrete models may not be necessary for improving visuospatial abilities.

However, to help students solve chemistry problems and represent chemical concepts at the microscopic or symbolic levels, experience in manipulating models seems crucial. Perceptual experience including viewing and manipulating with concrete models of molecules, atoms, and bonds helps students construct a more concrete understanding between concepts and representations (Friedel, Gabel, & Samuel, 1990). Students who manipulated models performed significantly better on solving chemistry problems than those who merely saw the demonstrations on a general chemistry achievement test (Gabel & Sherwood, 1980). Harrison and Treagust (1996, 1998, 2000) also suggested that when students were encouraged to use multiple particle models, their understanding of abstract concepts, e.g., bonding and the structure of an atom, was enhanced. One possible explanation for these findings is that students do not always learn what the teachers intend from demonstrations (Roth, 1997) because they have no opportunity to make predictions and explanations that requires them to connect visual features of representations to relevant concepts (Globert & Clement, 1999).

Hence, while watching the demonstrations of concrete models done by teachers could improve students' abilities to visualize molecules, manipulating these models could help students understand the underlying concepts of visual representations. When concrete models are used in science classrooms, teachers should encourage students to focus on the visualization process (e.g., rotating a model to view it from different angles) and assist them to make cognitive connections between molecular representations and concepts (e.g., deciding the relationship between an atom and its number of bonds).

Animation: Visualizing the Dynamic Nature of Chemical Processes

Students usually hold a static model of chemical reactions and represent chemical concepts at the macroscopic level. Williamson and Abraham (1995) attributed these difficulties to students' incomplete or inappropriate mental models. Viewing dynamic and three-dimensional animations created by technological tools could be a way to change and improve students' incomplete mental models. Thus, Williamson and Abraham (1995) designed animations that allowed students to view a chemical process in a dynamic matter and that illustrated how to use microscopic and symbolic representations to describe and explain a chemical process, such as dissolving salt in water. They found that students who used animations either as a supplement in the whole class lecture or as an assigned activity performed better than students who were only lectured without viewing any animation in applying concepts of molecules and atoms for explanations and descriptions.

Similarly, Kozma et al. (1996), Sanger, Brecheisen, and Hynek (2001), and Sanger and Greenbowe (2000) showed that compared to students who were not given animations to learn chemical concepts, those who viewed animations did significantly better on questions dealing with the dynamic nature of chemical reactions. Like Kekulé's daydream, mentally animating chemical particles is one of visuospatial abilities that could help students understand and apply chemical concepts. As many students are unable to construct a dynamic mental model of chemical processes by merely reading texts or viewing 2D diagrams (Kozma et al., 1996), visual assistance is necessary to enhance students' ability to conduct mental animation.

Computer-Based Visualization Tools

With rapid development of technology, more and more computer-based visualizing tools have been developed such as *4M:Chem* (Kozma et al., 1996), *Cache* (Crouch, Holden, & Samet, 1996), *Chemsense* (Schank & Kozma, 2002), *CMM* (Barnea & Dori, 1996), and *eChem* (Wu, Krajcik, & Soloway, 2001). These tools can be generally categorized into three types: model construction tools, multimedia learning tools, and learning environments.

Construction Tools: Visualizing and Promoting Translations Among Representations

Similar to concrete models, model construction tools address students' difficulties in visualizing 3D molecular structures. With more technological capabilities, such as multiple linked representations, computer-based construction tools externalize the visual or conceptual relationships between chemical representations and help students make translations among various types of representations.

For instance, *eChem* (Wu, Krajcik, & Soloway, 2001) provided features that allowed students to manipulate 3D molecular models and visualize the connections between molecular models at the microscopic level (e.g., molecular structures) and their collective behaviors at the macroscopic level (e.g., chemical and physical properties). Wu et al. showed that after using *eChem* for 6 weeks, a majority of high school students were able to transform 2D structures into 3D models and used molecular structures to explain properties of chemical compounds. Additionally, the analysis of interviews suggested that using *eChem* enabled students to reason with chemical representations either mentally or on a computer screen. A similar tool, *CMM* (Computerized Molecular Modeling), allowed students to visualize possible 3D configurations and compute the bond energy and angle of chemical compounds. Barnea and Dori (1999) showed that using *CMM* improved spatial visualization abilities and students' performance on questions that required students to translate from symbols to the 3D structures.

When using a model construction tool, students have opportunities to construct 3D models, transform a 2D structure on paper into a 3D model on a computer screen, and visualize the rotation of 3D models. These operations of 3D models are very similar to the tasks that spatial ability tests ask students to accomplish. Students might internalize these visualization experiences that in turn enable them to manipulate structures mentally and improve their visuospatial thinking skills as shown in Barnea and Dori (1999). Additionally, since the construction tools externalize the visualization processes, using them might lower the cognitive demand for students with low spatial ability.

When both concrete models and computer-based construction tools allow students to create 3D models and manipulate them, which one is more effective for learning chemistry? Having students learn organic structures from either one of the following visualizations:

(1) 2D textbook representations, (2) 3D computer models, (3) 3D ball-and-stick models, and (4) combination of the computer molecular models and the ball-and-stick models, Copolo and Hounshell (1995) found no significant difference between the means of posttest by groups. Yet, based on their performances on two retention tests, the two groups using computer models retained the material longer than the other two groups. Thus, Copolo and Hounshell concluded that both physical and computational models could offer benefits as an effective tool for teaching molecular structures and isomers and suggested that manually manipulating concrete models might distract students from focusing on the image of molecules, while using computer models allowed students to concentrate on the molecular representations.

Multimedia Tools: Visualizing the Dynamic and Interactive Nature of Chemistry

Multimedia tools address at least two of students' alternative conceptions: (1) comprehending visual representations at the macroscopic level and by surface features, and (2) interpreting chemical reactions as a static process. This type of tools integrates multiple symbol systems (Salomon, 1979), such as texts, videos, graphs, and animations, to demonstrate chemical reactions at the microscopic and symbolic levels.

The multimedia tool developed by Kozma and his colleagues (Kozma et al., 1996; Kozma & Russell, 1997), *MultiMedia and Mental Models* (*4M:Chem*), helped students recognize relationships among chemical entities and comprehend representations by the underlying concepts instead of the surface features. For example, to present a chemical equilibrium process, $2NO_2(g)$ (brown) $\leftrightarrow$ $N_2O_4(g)$ (colorless), *4M:Chem* included a video segment showing the change of color within an enclosed tube under different temperatures; an equation with chemical formulas and symbols; an animation showing the interaction and movement of molecules at the microscopic level; and a graph showing how the concentrations of two gases changed over time. These four representations were shown simultaneously and linked to each other. To make sense of these representations, students were encouraged to identify the referential links among the representations and engaged in discussions about concepts (Kozma, 2000).

Additionally, this multimedia tools promoted students to construct a dynamic model of chemical processes when students' understanding of a phenomenon was shaped by the unique characteristics of a symbol system (Kozma, 2000; Salomon, 1979). In their study of *Seeing through Chemistry* (Dershimer & Rasmussen, 1990), Jones and Berger (1995) showed that video and animation were helpful for students to experience certain characteristics of light, energy, and molecules that may not be visible otherwise. Students tend to construct a dynamic model rather than a static one when using this multimedia tool, because compared to text, video and animation do better in conveying the information of movements and interactions.

Integrated Learning Environment

To provide students with opportunities to practice various representational skills (e.g., translating and interpreting chemical representations) and help students represent chemical concepts at the microscopic level, the third type of tools integrate features of construction and multimedia tools and create a learning environment in which students create models and animations. *Chemsense* (Schank & Kozma, 2002), including a molecular drawing tool, notepad, spreadsheet, a graphing tool, and an animation creating tool, was such a tool that allowed students to construct models, collect data, make graphs, and create animations.

Schank and Kozma (2002) found that through creating animations and models on *Chemsense*, students seemed more focused on the dynamic process of a chemical reaction and demonstrated significantly better performance on representing scientific phenomena at the microscopic level.

The discussion above provides several innovative solutions to the difficulties students have. Specifically, they address the importance of visualizing the interactive and dynamic nature of chemical process, represent chemical concepts at molecular and symbolic levels, and externalize the process of translating a given representation into another. However, they do not completely address the difficulties students have with visualizing concepts in chemistry. Furthermore, few of these visualization tools are designed based on more general cognitive principles regarding multimedia and display design. Thus, in the next section, we propose several principles for designing visualization tools for chemistry instruction.

GENERAL DISCUSSION: PRINCIPLES FOR DESIGNING VISUALIZATION TOOLS

In the previous sections, we reviewed the literature on correlational studies of spatial abilities and chemistry learning, students' conceptual errors and difficulties understanding visual representations, and visualization tools that have been designed to help overcome these limitations. We can conclude that visuospatial abilities and more general reasoning skills are relevant to chemistry learning. Some of 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 through difficulties in using visuospatial representations.

On the basis of our review, we suggest several principles for designing tools[2] that help students understand concepts and develop representational skills through supporting their visuospatial thinking. To identify these guidelines, we began with the conceptual errors identified in the second section of our review paper. We then used the correlational data from the first section of our review paper to consider what aspects of spatial thinking may need to be supported by visualization tools and to identify how students with different visuospatial abilities may or may not benefit from different kinds of visualization tools. Finally, we bolstered our claims by presenting, whenever possible, evidence from previous examples of visualization tools that demonstrate the efficacy of these guidelines. In this general discussion, we also consider general guidelines for designing multimedia tools (Baumgartner & Bell, 2002; Dijkstra, 1997; Stern, 2000) and consider what they mean in the context of chemistry education (e.g., Mayer, 2001).

Table 1 summarizes students' learning difficulties, types of learning tools, and principles that would help researchers and designers to develop chemistry learning tools. These principles include (1) providing multiple representations and descriptions, (2) making linked referential connections visible, (3) presenting the dynamic and interactive nature of chemistry, (4) promoting the transformation between 2D and 3D, and (5) reducing cognitive load by making information explicit and integrating information for students.

Providing Multiple Representations and Descriptions

A major difficulty identified in the section on conceptual errors is that students have difficulty representing chemical concepts at the microscopic and symbolic levels, comprehending representations conceptually, and making translations between different representations.

[2] This paper is not intended to be a comprehensive review of the multimedia design principles. Instead, we selectively choose some important principles relevant for the chemistry instruction context.

TABLE 1
The Learning Difficulties, Learning Tools, and Principles for Designing Tools

	Design Principle				
	(1) Providing Multiple Representations and Descriptions	(2) Making Linked Referential Connections Visible	(3) Presenting the Dynamic and Interactive Nature of Chemistry	(4) Promoting the Transformation Between 2D and 3D	(5) Reducing Cognitive Load by Making Information Explicit and Integrating Information for Students
Learning difficulties	Representing chemical concepts at the microscopic or symbolic levels. Comprehending symbolic and molecular representations conceptually. Making translations between chemical formula, electron configuration, and ball-and-stick model.	Comprehending symbolic and molecular representations conceptually. Making translations between chemical formula, electron configuration, and ball-and-stick model.	Visualizing the interactive and dynamic nature of chemical process by viewing symbols and equations.	Identifying the depth cues of 2D models. Forming 3D mental images by visualizing 2D structures.	Reorganizing or transforming the information provided by questions into a visual representation, such as drawing preliminary figures.
Examples	*Chemsense* *4M:Chem*	*CMM* *eChem*	Animations *4M:Chem*	*eChem*	*CMM* *eChem* Concrete model
Additional features and considerations	Presenting text and representations contiguously in a structured way. Including a reflective feature to encourage self-explanation.	Providing prompts to scaffold the construction of referential connections. Providing a workspace to group representations and make annotations.	Carefully considering the accuracy of the content, the complexity of visual representations, and students' visualization capacities.	Showing 2D and 3D views of the same molecule. Allowing students to superimpose one view on top of another.	Allowing students to integrate and manipulate multiple views such as superimposing one view on top of another.

Thus, we argue that one major characteristic of chemistry visualization tools should be providing multiple representations and descriptions of the same information. This general principle holds true for most multimedia tools (Ainsworth, 1999; Ainsworth, Bibby, & Wood, 1997) because multiple representations enable students to visualize the connections between representations and relevant concepts, and provide students with opportunities to actively choose a representation suitable for different stages of understanding (Narayanan & Hegarty, 1998). Given students' difficulty translating between representations and the fact that different chemical representations emphasize different aspects of chemical concepts and correspond to different chemical entities, this principle is likely to be particularly important for chemistry (Bowen, 1990; Harrison & Treagust, 1996, 2000). *4M:Chem* (Kozma et al., 1996), *eChem* (Wu, Krajcik, & Soloway, 2001), and *CHEM-Flips* (*Chemistry: Flexible Learning in the Periodic System*) (Mishra & Spiro, 1998) are examples that apply this principle.

Additionally, providing multiple representations might help students who differ in visuospatial abilities understand specific concepts. Some representational systems might be too cognitively demanding (Chandler & Sweller, 1992; Dechsri, Heikkinen, & Jones, 1997). Viewing animations presented by multimedia may be beneficial only to students who have the visuospatial skills to interpret them (Yang, Greenbowe, & Andre, 1999). By contrast, manipulating 3D molecular structures created by concrete models or computer-based tools might require less cognitive resources in the spatial domain. These model construction tools do not require students to mentally keep track of changes of configurations; rather, they illustrate a molecular model from different angles and allow students to visualize spatial relationships among atoms and to make predictions and explanations with models. Hence, this type of learning tools might help low spatial ability students more, when high spatial ability students are already able to create 3D images mentally by viewing 2D representations on paper.

To enhance students' representational skills, providing verbal descriptions or explanations of the visual representations might be useful because compared to chemists, students are less able to use chemical terminology to describe and interpret representations verbally (Kozma & Russell, 1997). To apply this principle, learning tools could include either a feature that presents text and representations contiguously (Mayer, 1997; Mayer & Anderson, 1992) in a structured way or a reflective feature to encourage self-explanation (Chi et al., 1994; Davis, 1995) when students view multiple representations and make comparisons among them.

Making Linked Referential Connections Visible

Providing multiple representations may not be enough for students to develop in-depth understandings about chemistry concepts. When visual representations are accompanied by text or other types of representations, students may not be able to make referential connections among them or even though they do, they may create incorrect connections (Narayanan & Hegarty, 1998) or make links between representations based on surface features, such as colors and types of symbol system, rather than underlying concepts (Kozma & Russell, 1997). This may be a special problem for students with low visuospatial abilities, because research has suggested that this process is particularly demanding of cognitive resources (van Bruggen, Kirschner, & Jochems, 2002). Thus, a second principle that helps students overcome their difficulties comprehending and translating between representations is to make linked referential connections among representations visible so that students could construct appropriate conceptual connections among multiple representations.

One way to help students visualize the connections is to allow a representation to be changed by manipulating its connected representation or description. On *4M:Chem*, as the partial pressure of NO_2 (brown) on the graph went up, the animation showed more and more brown particles. This linked-representation feature would allow students to build a conceptual connection as well as visualize how to transform one representation into another. This in turn could enhance students' representational skills such as making translations among representations. In addition, if the referential connection is established between text and visual representation, students may be able to construct a representation based on a description and vice versa.

Some features employed in science learning technologies might help facilitate the construction of referential connections among multiple representations. Reflective prompts (Davis & Linn, 2000), including questions and hints that encourage students to monitor their learning process, may engage them in thoughtful discussions about representations and concepts. A workspace that allows students to group representations, make annotations, and write up explanations (Loh et al., 2001) might also encourage students to categorize different representations and verbally explain the conceptual connections among representations.

Presenting the Dynamic and Interactive Nature of Chemistry

A third learning difficulty identified by our review is the difficulty visualizing the movement of particles and develop a dynamic model of chemical processes. A considerable amount of research has showed that animations are useful for students to visualize the dynamic and interactive nature of chemistry (e.g., Kozma et al., 1996; Lavioe, 1995; Williamson & Abraham, 1995; Yang, Greenbowe, & Andre, 1999). The dynamic mental models (mental animation in Hegarty, 1992) developed via viewing animation could help students learn advanced chemical concepts and enhance their visuospatial thinking. But it should be noted that in some situations there is virtually no benefit of animation over a series of static diagrams (Tversky, Morrison, & Betrancourt, 2002). If static diagrams are well designed such as the sequence of panels used in Michas and Berry (2001), contain approximately equivalent information as animations, and allow users to appropriately interact with the information presented, then animation does not appear to be beneficial. However, as Shah and Freedman (in press) argue, "given current technology and the difficulty of designing appropriate static controls, it might actually be easier to create an animation that by definition contains all the changes than to design static diagrams." In practice, animations may be still better than static diagrams for presenting change over time. Other types of media that share similar media attributes, such as simulation and video, might also allow students to develop dynamic mental models (Hegarty, 1992).

Although multimedia learning, such as video and animations, seems beneficial, it requires cognitive resources to construct mental images and the learning effect is constrained by students' spatial ability (Mayer, 1997, 2001). For example, some students had difficulty coordinating text with animation simultaneously in Rodrigues, Smith, and Ainley (2001). Mayer (2001) indicated that students with low spatial ability learn better when animation and narration are presented in a coordinated way. But even though they learn better in well-designed instructional environment, compared to those with high spatial ability, students with low spatial ability must devote more cognitive resources in order to build connections between animation and narration (Mayer, 2001).

Additionally, visualization tools should represent the content accurately. The colors, the movements, and the numbers of particles represented in animation and simulation should be carefully designed. Otherwise students may develop or strengthen their alternative conceptions by using multimedia tools, such as viewing color as one of the characteristics of atoms (Ben-Zvi, Eylon, & Silberstein, 1986). Hence, educators and designers need to consider the accuracy of the content, the complexity of visual representations, and students' visualization capacities all together when developing a tool, so that the tool could promote students to change their alternative conceptions and meet the needs of students with different levels of spatial abilities.

Promoting the Transformation Between 2D and 3D

A fourth difficulty discussed in our review is that some students are not able to form 3D mental images by visualizing 2D structures because in some situations, the 2D images presented do not provide depth cues, such as the two structural formulas in Figure 6. Therefore, the fourth design principle for designing visualization tools is to provide features that facilitate the identification of depth cues and the transformation between 2D and 3D.

In the study of *eChem*, Wu, Krajcik, and Soloway (2001) described the process of how students learned to visualize a 2D structural formula and a 3D ball-and-stick model as representations of the same molecule. To decode the information of bond angles and geometry of molecules that were not represented by 2D structures, some students rotated a 3D model into a specific angle that vanished depth cues and had a 3D model looking similar to a linear 2D structural formula on paper. These students appeared to have better performances on items that required mental transformations between 2D and 3D models in the posttest and interviews. It seems that students need to recognize the visual similarities and differences between 2D and 3D models through rotating and comparing these representations. Thus, a visualization tool should allow students to manipulate and interact with 3D models and support them to compare the differences and similarities between 2D and 3D representations. Two features on *eChem*, allowing students to rotate a 3D model and providing multiple views of the same molecular model from different angles, are examples that apply this principle. Other features that might help students identify isomers by viewing 2D and 3D models include showing 2D and 3D views of the same molecule simultaneously and allowing students to superimpose one view on top of another.

Reducing Cognitive Load by Making Information Explicit and Integrated

The section of visuospatial abilities and chemistry suggests that one of the reasons visuospatial abilities play such an important role in chemistry is that people need the ability to actively maintain and manipulate visual representations in many chemistry contexts. This skill is highly demanding of working memory resources for spatial information (Shah & Miyake, 1996). At the same time, many visuospatial learning tools are highly demanding of cognitive resources. Unfortunately, visualizations benefit those learners who have high spatial abilities more than those who have low visuospatial abilities (e.g., Gyselinck et al., 2002). Factors that reduce cognitive load are fundamental to help those students who need the most help.

To reduce load on cognitive resources, several approaches to multimedia learning propose "contiguity" principle (Mayer, 1997; Mayer & Anderson, 1992; see also Sweller, van Merrienboer, & Paas, 1998). According to this principle (Mayer, 1997), multimedia is most beneficial when visual and verbal information are presented contiguously rather than separately. The coordinated presentations of explanations in both verbal and visual formats promote students to actively select relevant information from presentations, organize the new information, integrate the information into a coherent mental model, and build systematic connections between the verbal and visual representations. This principle might be especially important in the context of chemistry learning because of the high spatial demands on chemistry tasks that are indicated by the correlational studies discussed above. As the use of multimedia tools increases, students with low spatial ability may be disadvantaged in learning chemistry, especially if the multimedia tools are poorly designed and thus add additional burden to their visuospatial processing resources (Gyselinck, Cornoldi, Dubois, De Beni, & Ehrlich, 2002).

On the other hand, when visualizations are designed to overcome students' difficulties in integrating information and thus reducing the demands on visuospatial processing resources, then these visualizations benefit low spatial ability students more than high spatial ability students. In Vekiri (2001), for example, low spatial students were benefited in making weather forecasts when they were given weather maps that could be placed on top of each other so that they could integrate relevant information together, whereas high spatial students were not benefited by this tool.

Together, these studies suggest that when visualization tools require a great deal of cognitive resources to mentally keep track of visuospatial information, these tools are likely to only benefit those students who have strong visuospatial skills. When tools are specifically designed to reduce cognitive load, they support learning for low spatial students.

CONCLUSION

In this article, we reviewed the literature on correlational studies of spatial abilities and chemistry learning, students' conceptual errors and difficulties understanding visual representations, and visualization tools that have been designed to help overcome these limitations. We can conclude that visuospatial abilities and more general reasoning skills are relevant to chemistry learning. Some of 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 through difficulties in using visuospatial representations. On the basis of our review, five design principles are suggested: (1) providing multiple representations and descriptions, (2) making linked referential connections visible, (3) presenting the dynamic and interactive nature of chemistry, (4) promoting the transformation between 2D and 3D, and (5) reducing 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.

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