IDENTIFYING STUDENTS' MISCONCEPTIONS IN WRITING BALANCED EQUATIONS FOR DISSOLVING IONIC COMPOUNDS IN WATER AND USING MULTIPLE-CHOICE QUESTIONS AT THE SYMBOLIC AND PARTICULATE LEVELS TO CONFRONT THESE MISCONCEPTIONS

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I dedicate this research to my mother and father. I love you both.

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ABSTRACT

Students who harbor misconceptions often find chemistry difficult to understand. To improve teaching about the dissolving process, first semester introductory chemistry students were asked to complete a free-response questionnaire on writing balanced equations for dissolving ionic compounds in water. To corroborate errors and misconceptions identified from students' generated balanced equations, another sample of students participated in semi-structured interviews where they were asked to explain their thought processes involved in writing the balanced equations for the dissolving ionic compounds dissolving in water. Misconceptions of the dissolving process were identified and described in detail. The most popular misconception was that water chemically reacts with an ionic compound through double displacement to form a metal oxide and an acid. The second popular misconception was that an ionic compound dissolves as neutral atoms or molecules. The third popular misconception was that students confused subscripts and coefficients.

Another sample of introductory chemistry students were assessed on the dissolving process using the three popular misconceptions as three of the four choices in multiple-choice questions at the symbolic- and particulate-level. The symbolic-level questions involved symbolic balanced equations and the particulate-level questions involved dynamic animations or static pictures of the same four choices. Students' responses to these questions were discussed in terms of four variables— Answer (the correct answer and three misconceptions), Representation (symbolic or particulate questions), Visualization (static or animated pictures), and Representation Order (symbolic questions before or after the particulate questions).

The same test instrument was used on the same student sample to assess how two types of subscripts affected students understanding of dissolving ionic compounds in water. Two of the ionic compounds had monatomic subscripts ($MgCl_2$, Ag_2SO_4) and two did not (NaBr, KNO_3). Two had polyatomic subscripts (KNO_3, K_2SO_4) and two did not (NaBr, $MgCl_2$). Students' responses to these questions were also discussed in terms of four variables— Answer (the four choices), Representation (symbolic or particulate questions), Monatomic subscripts, and Polyatomic subscripts. The subscript misconception was more popular for symbolic questions compared to particulate questions, and the correct answer was less popular for particulate and symbolic questions when the question contained a monatomic subscript.

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CHAPTER ONE

GENERAL INTRODUCTION

Dissertation organization

This dissertation consists of seven chapters including this chapter. The second chapter is a review of the chemical education literature regarding students' understanding of the dissolving process. The third chapter contains the research results on students' understanding of dissolving ionic compounds in water based on student-generated balanced equations. The third chapter contains the research results on students' understanding of the dissolving process based on visualization type, question order, and question representation. The fifth chapter contains the research results on students understanding of the dissolving process based on question, representation, monatomic and polyatomic subscripts. The sixth chapter contains the chemical research results on synthesis and characterization of functionalized mesoporous carbon acid catalyst for biodiesel production. The seventh chapter contains the conclusions of the three chemical education research studies. With the exception of the format required by the respective journals, all four studies were submitted for publication in the format presented in this dissertation.

Summary of research

This dissertation consists of three chemical education research studies and one chemical research study. The first study focused on identifying students' misconceptions in writing balanced equations for dissolving ionic compounds in water. An initial sample of 105 college students were asked to complete a free-response questionnaire on writing balanced equations for four dissolving ionic compounds in water. These written responses were analyzed for common students' errors and misconceptions. To corroborate errors and misconceptions identified from the written balanced equations, another sample of 37 college students participated in semi-structured interviews where they were asked to write balanced equations for the same four ionic compounds dissolving in water and explain their thought processes. This study provided a list of common student misconceptions, and concluded by discussing the possible sources of these misconceptions and suggesting instructional interventions that will help dispel some of these misconceptions.

The second study assessed 98 college students' understanding of the dissolving process using several multiple-choice questions at the symbolic- and particulate- level containing the correct response and three popular misconceptions identified in the first study as distractors in multiple-choice questions posed at the symbolic- and particulate-levels. Symbolic-level questions included symbolic balanced equations of ionic compounds dissolved in water as the four choices, and the particulate-level questions involved dynamic animations or static pictures for the same four choices. Each of the 98 students randomly assigned to one of four groups were asked to answer eight multiple-choice questions (a symbolic- and particulate-level question for four ionic compounds).

Students' responses to these questions were statistically analyzed and discussed in terms of the significant associations among students' answers, the question representation (symbolic or particulate), visualization type (static or animated), and the order the symbolic and particulate questions were presented to students (symbolic questions before or after animation).

The third study used the same test instrument and student sample to assess how the two types of subscripts affected students' understanding of dissolving ionic compounds in water. Two of the ionic compounds had monatomic subscripts ($MgCl_2$, Ag_2SO_4) and two did not (NaBr, KNO_3). Two had polyatomic subscripts (KNO_3, K_2SO_4) and two did not (NaBr, $MgCl_2$). Students' responses to these questions were statistically analyzed and discussed in terms of significant associations between students' answers, the question representation (symbolic or particulate), monatomic subscript, and polyatomic subscript.

The chemical study focused on the synthesis and characterization of functionalized mesoporous carbon acid catalyst for biodiesel synthesis. The highly ordered mesoporous carbon (MPC-127) was prepared by one-pot synthesis approach using pluronic F-127 (a block co-polymer of polyethylene oxide and polypropylene oxide), phloroglucinol, and formaldehyde. The mesoporous carbon was then functionalized with sulfonic acid groups and characterized by Brunauer-Emmet-Teller (BET) method and scanning electron microscope. Its catalytic activity was tested on the transesterification reaction involved in the conversion of vegetable oil to ethylesters.

CHAPTER TWO

REVIEW OF LITERATURE CONCERNING STUDENTS' UNDERSTANDING OF THE DISSOLVING PROCESS

Major studies on students' misconceptions in chemistry

In 1983, Osborne and Cosgrove (1983) explored 43 high school students' (ages eight to seventeen years) conceptions of the boiling process. The results of the study showed that one group of students viewed the bubbles formed in boiling water to consist of air pockets, another group of students thought the bubbles consisted of oxygen and hydrogen gas, and the remaining group viewed the bubbles as consisting of steam. Based on these results, Osborne and Cosgrove (1983) concluded that children often differ from scientists in their ideas about chemical phenomena. This study, however, limited its scope to students' observations and explanations of the changes of state of water, but others have looked at whether students' performance differs when asked to solve chemistry problems posed in quantitative versus conceptual forms.

Nurrenbern and Pickering (1987) examined 205 chemistry college students' abilities to solve quantitative and conceptual gas law problems. The results showed that 65% of these students correctly solved the traditional gas law problems while only 35% correctly solved the corresponding particulate (atomic-level) conceptual problems. The researchers concluded that students who use algorithms to successfully solve quantitative problems, may not understand the underlying chemical concepts at the molecular level. The findings of Osborne and Cosgrove (1983) and Nurrenbern and Pickering (1987) indicated that students often find chemistry concepts difficult to understand. For this reason, chemical education researchers must identify these difficulties so that appropriate instructional strategies may be designed to address these difficulties. Carefully designed instructional activities will not only allow students to develop conceptual understanding consistent with the scientific consensus, but will also grant them the opportunity to apply their understanding in various ways to find solutions to existing problems.

How are misconceptions developed?

The constructivists' theory of learning posits that learning is a constructive process by which active learners interact with the physical and social world to construct meaning for themselves (Doll, 1992). Another way of saying this is that since knowledge cannot be directly transferred from the mind of an instructor to that of a learner, students must actively construct their own knowledge by integrating new ideas into their existing knowledge base (Bodner, 1986). Because students constantly interact with the physical and social environment, students in any field of study often carry along their experiences and inadequate interpretation of the physical and social world into the classroom. These interpretations often develop from the students' sensory input, their cultural background, peers, mass media and classroom instruction (Duit and Treagust, 1995). When these experiences and interpretations differ from those widely accepted in the discipline, they are referred as *misconceptions* (Bodner, 1986).

The term misconception is defined as "student conceptual and propositional knowledge that is inconsistent with or different from the commonly accepted scientific consensus and is unable to adequately explain observable scientific phenomenon"

(Sanger and Greenbowe, 1997, pp. 378). Many misconceptions that students hold about chemical phenomena are resistant to instruction. One reason for this resistance is that students often apply their real-world notions and experiences in explaining the phenomenon. As a result these misconceptions are entrenched and while they may appear coherent to the student, they are often inadequate in explaining chemical phenomena (Driver and Easley, 1978). Sometimes in the chemistry classroom, when students are taught new concepts that do not make sense to them, they revert to their own incomplete or inferior notions (Treagust *et al.* 1996).

Another reason why many students find chemistry difficult to understand is the multiple-levels of representation used in chemistry instruction (Johnstone, 1993; Gilbert and Treagust, 2009; Talanquer, 2011). These levels are the macroscopic, particulate and symbolic representations. When we use our five senses to perceive chemical phenomena that include color changes, precipitation and heat, it is referred as the macroscopic representation. Beyond a certain macroscopic level, however, our senses become inadequate at perceiving chemical phenomena. These phenomena include the interactions of atoms, ions, electrons, and molecules and that level is referred as the particulate representation. To express and describe the properties of the macroscopic and the particulate levels, chemists often use symbolic representations that include chemical symbols, chemical equations, and animations, graphed and tabulated data etc. The ability of chemists or students to interpret and transform from one representation to another is referred as the *representational competence* (Kozma and Russell, 1997). When students are taught chemistry using the three levels, instructors seamlessly move from one level of representation to another while novice students often view the movement in confusion and can develop misconceptions during the instruction. Several researchers have reported students' difficulties in moving from the macroscopic to the particulate level (Osborne and Cosgrove, 1983; Andersson, 1986; Ben-Zvi, 1986; Gabel, 1993; Kelly and Jones, 2008) and from the symbolic to the particulate level (Yarroch, 1985; Nurrenbern and Pickering, 1987; Sawey, 1990; Pickering, 1990; Nakhleh, 1993; Sanger, 2005; Nyackwaya *et al.* 2011).

Empirical studies of students' misconceptions about dissolving

Ebenezer and Erickson (1996) explored nine female and four male conceptions about the solubility of three chemical systems— sugar/water, salt/water, and water/alcohol/paint thinner at the macroscopic and particulate levels. The researchers asked these students to explain the chemical and physical processes occurring in the solvent systems. The results of the study showed that students held different conceptions about the solubility of the three systems. These conceptions were categorized into the following six groups:

Physical transformation from solid to liquid. Many students believed that dissolving is a process of a solid changing form into a liquid, and incorrectly described this process as "melting." Of these students, two conceptions were identified: a continuous view of the "liquid state" and a particle view of the "liquid state." Students who held a continuous view believed that sugar or salt melts in water to form a liquid. One student believed that hot water makes solid sugar soft and turns it into syrup. The student also added that when candy is sucked in the mouth, it melts.

On the other hand, students who held a particle view used the concept of atoms, molecules, and particles to describe the dissolving process of sugar or salt in water. One student described her understanding using molecular motion, stating that the molecules in sugar moved when sugar was added to water, causing the sugar to become liquid.
Yet, this same student believed that heat melted the salt when water was added. It appears she was confused in her understanding of the kinetic molecular theory and the relationship between heat and dissolving. Although heat was not applied in this case, she still believed that an increase in temperature would speed the dissolving of salt in water (a correct conception).

Chemical transformation of solute. Some students believed that when sugar was added to water, it reacted to form a new substance. Of these students, two conceptions were identified: Attachment or attraction between components and the solute occupying air spaces in water.

One student who held the view of molecular attachment used sugar and tea as an example, and describing the dissolving process as *mixing, dissolving, and combining* when sugar was added to hot water. When this student was asked to draw how she saw sugar and tea in solution, She drew two circles (one big and one small) to explain how the tea and sugar form molecular attachments in solution. It was, however, unclear which of the two circles in her drawing represented sugar or tea. When she was asked to apply her understanding to the sugar and water system, she stated that heat melts sugar and it combines with water to form a new substance. This new substance she referred as sugar-water, with the sugar in the liquid state. For this student, sugar chemically reacted with water, regardless of whether the original substance was recovered from the liquid state or not. Students who held the view of solute occupying air spaces in water believed that water contains small air pockets. These small air pockets allowed sugar molecules to fill in those spaces. These students also believed that water in itself was a solution because hydrogen and oxygen reacted to form it.

Density of solute. Students who held this view believed that the difference in density was the reason for the immiscibility among different liquids. One student explained that when paint thinner was added to a mixture of water/alcohol, it floated on the mixture because the solute floats or sinks depending on its weight.

Amount of space available in solution. Some students held the view that a solute dissolves only if the solvent contains enough space for the solute to occupy. One student believed that paint thinner was unable to dissolve in the water/alcohol system because it was unable to break the strong attraction between molecules of water and alcohol to create space. She further indicated that the strong attraction between water and alcohol caused the two solvents to mix well and the weak attraction caused the two solvents to separate.

Size of solute particles. One of the students believed that before a solute can dissolve, it must first be broken into microscopic pieces. This student stated that the paint thinner failed to dissolve in the water/alcohol system because the paint thinner-layer was not broken into tiny pieces.

Properties of solute. Some students believed that before salt can dissolve in a solvent, the salt must be pure, inert, and chemically stable. One student who saw salt settled at the bottom of salt and water mixture stated that it settled at the bottom because the salt was pure, and like gold, it was inert and chemically stable.

Although Ebenezer and Erickson (1996) used a small sample of students to identify students' inaccurate conceptions about the dissolving process, it was unknown if these misconceptions could be generalized to other student populations.

In 2001, Ebenezer (2001) conducted two studies examining another cohort of fifteen 11th graders' conceptions about the process of dissolving. The first study asked students to dissolve sugar in water then generate their own particulate diagrams to describe what they thought was happening to the sugar. The results showed six of these students believed that sugar transformed from the solid state to the liquid state when it dissolves in water. Four believed that sugar reacted with water, and three believed that sugar occupied empty spaces between the water molecules. These results were consistent with the previous study (Ebenezer and Erickson 1996). In the second study, Ebenezer (2001) used a hypermedia environment, a computer program that showed an animation of sugar dissolving in water, to see whether students would revise their understanding of the dissolving process. The results showed that four of the fifteen students revised their initial views of the dissolving process. Three students not only retained their views that sugar reacted with water, but they also insisted that their views were consistent with what they had seen in the animation. Only one of these students, however, was able to draw particulate models close enough to that of the chemists. Based on these results, Ebenezer (2001) concluded that students had difficulty in understanding the chemical features involved in ion formation, the polar nature of water molecule, and the hydration processes depicted in the hypermedia environment. In other words students found the chemical processes and features depicted in the hypermedia difficult to understand.

Kelly and Jones (2007) used two animations depicting different chemical features to test college chemistry students' understanding of sodium chloride dissolving in water. The first part of this study asked students to draw molecular diagrams to illustrate their initial conceptions of salt and water before mixing, during, and after mixing. In these initial molecular drawings, 15 students represented sodium chloride as neutral molecules and eight drew water molecules as linear. Five students showed sodium chloride molecules interacting with water, and two of these students showed sodium chloride molecules forming bonds with water molecules. The notion of sodium chloride forming bonds with water was consistent with previous studies (Ebenezer and Erickson, 1996; Ebenezer, 2001). In the second part of this study, Kelly and Jones (2007) asked the students to view two different animations to see whether they would revise their understanding of the dissolving process of sodium chloride dissolving in water. One animation depicted the ions vibrating in the solid lattice; the other depicted sodium chloride lattice structure, the charges on the ions, and water molecules surrounding the hydrated ions. After all 18 students saw the animations, ten of these students corrected errors in their before-mixing drawings; however, six of these ten students still had errors in their diagrams. Similarly, all the students corrected errors in their during- and after-mixing drawings, however 12 of these diagrams still contained errors. Although the animations affected students understanding of the dissolving process, it was unclear why most students still committed errors in their revised drawings.

In a subsequent study, Kelly and Jones (2008) examined how college general chemistry students transferred their understanding from viewing particulate animations of sodium chloride dissolved in water to explain the precipitation reaction of aqueous sodium chloride and silver nitrate in a video demonstration one week later. Although all 18 students corrected errors in their initial molecular drawings and showed fewer misconceptions after seeing the molecular animations of sodium chloride dissolving in water in the first study (Kelly and Jones, 2007), none showed the spheres of hydration around the sodium chloride and silver nitrate ions in their molecular drawings in this study. Six students showed sodium chloride as molecular pairs, and three students showed sodium chloride pairs with water molecules. Four students incorrectly applied ideas from the previous animation in their molecular drawings. Kelly and Jones (2008) concluded that students generally had trouble transferring their improved conceptions from the molecular animation used in the previous week's study to the precipitation reaction. This difficulty after one week leads researchers to wonder how students will perform six months to a year after their instruction on solubility.

Kabapinar *et al.* (2004) used five paper-and-pencil diagnostic questions involving a particle model based on the Kinetic Molecular Theory to test 23 secondary school students' understanding about solubility. The results showed that 87% of the control group and 92% of the treatment group failed to use the particle model to explain their ideas in the pretest. Seventy four percent of students in the control group and 48% in the treatment group used the term "melt" when they meant "dissolve". However, after students in the treatment group were introduced to the particle model, 96% of these students and 9% of students from the control group referred to the model in their explanations. After 6 months, however, 87% of students in the treatment group and 26% of the control group still applied the particle model in their explanations. After the delayed posttest, 52% of the control group and 30% of the treatment group used the term "melt" instead of "dissolve". Kabapinar *et al.* (2004) concluded that the particle model helped some students see the difference between melting and dissolving. Many students also retained the particulate ideas after six months, meaning that students could apply these ideas to more complex topics in chemistry. The two groups, however, were similar in their abilities in identifying solution mixtures and to predict the result of simple quantitative problems. It was also unclear why the number of students who confused dissolving with melting increased after six months.

Tien *et al.* (2007) used the Model-Observe-Reflect-Explain (MORE) approach to evaluate students' understanding of the dissolving process of sodium chloride and sugar in water. The MORE approach allows students to predict, reflect, and write their initial ideas about dissolving before conducting experiments to support or refute these ideas. Of the 84 college students who were tested with the MORE approach, only 15% indicated correct initial molecular models of how both sodium chloride and sugar dissolves in water. About one-third (35%) drew correct molecular models of only aqueous sodium chloride and 32% drew correct molecular models of only aqueous sugar. Several misconceptions were identified from these drawings. Some of these include the notion that salt exists in solution as "NaCl molecules," that salt breaks up as neutral atoms, that sugar molecules dissociate into atoms or ions, that salt and sugar form chemical bonds with water, and that salt and sugar reacts by metathesis with water. However, after students dissolved both sodium chloride and sugar in water, most of them revised their initial ideas to align with the experimental evidence. Most (82%) of these students revised their initial ideas about sodium chloride and 69% revised their initial ideas about sugar. Also, 80% of these students provided accurate molecular models of sodium chloride and 52% provided accurate molecular models of sugar, but only 46% showed accurate models for both sugar and salt. The reason why most students had problems modeling sugar but not sodium chloride was unclear. It is possible, however, that students were more familiar with the structure of sodium chloride than they were with sugar. It is also likely that these students simply lacked representational competence and were unable to generate accurate molecular models for both compounds.

Bruck *et al.* (2010) used manipulatives to test 141 college chemistry students' representational competence and particulate-level understanding of the solubility of ionic compounds. They reported that students who had instruction on how to use manipulative to model simple compounds developed a stronger conceptual understanding of solubility and did better on the posttest assignments than those in the control group. They also reported that both the treatment and the control group had problems in writing chemical equations and net ionic equations. Bruck *et al.* (2010), however, did not point out the reasons why these groups of students had problems writing simple balanced chemical equations and net ionic equations.

Yarroch (1985) asked 14 high school students to balance four simple chemical equations and then transform these balanced equations into particulate diagrams. These results showed that although all 14 students were able to correctly balance the chemical equations, only five students were able to generate particulate diagrams consistent with the balanced equations. The other nine students confused subscripts and coefficients and drew three hydrogen molecules ($3H_2$) as six linearly connected circles.

Nyachwaya *et al.* (2011) extended Yarroch's study by asking 110 college students in first semester general chemistry to balance three chemical equations then translate the balanced equations into particulate drawings. The results of the study showed that 63% of students had difficulty in translating the state symbols in the chemical equation to particulate drawings. Some students also confused subscripts and coefficients, interpreting two molecules of water ($2H_2O$) as two hydrogen molecules and two oxygen atoms. In another study, Sanger (2005) asked 156 college students to generate a balanced chemical equation from a particulate picture depicting a chemical reaction and then use their balanced equation to solve two stoichiometric problems. The results showed that 68 of the 156 students (44%) showed misunderstanding in the use of subscripts and coefficients when they converted the particulate picture to a balanced chemical equation. Al-Kunifed *et al.* (1993) asked 18 high school chemistry students to compute the number of atoms in chemical formulas and ions: $10H_2$, $2NaOH$, $5Cu(NO_3)_2$, $3AgNO_3$, $2CO_3^{2-}$, and $4NH_4^+$. The results showed that students had conceptual problems in understanding the relationships between subscripts and coefficients. The errors that the students committed included adding the numbers from the parenthesis subscripts, ignoring the subscripts and coefficients, multiplying subscripts and adding the result to the coefficient, adding the subscripts to the coefficient, ignoring the coefficient, and considering the ions' charge in the computation. Some of these results are corroborated by other studies. Lazonby *et al.* (1982) reported that students were unsure what each "2" meant in the formula $2Ag_2O$. Savoy (1988) also reported that students could not contrast potassium molecule (K_2) and two unbound potassium atoms (2K).

Taken as a whole, misconceptions in chemistry are common among both children and adults. Some of these misconceptions are resistant to instruction and are likely to remain even after applying conceptual change learning strategies in the classroom (Driver and Easley, 1978) while other misconceptions are easily dispelled by a single or a combination of instructional interventions such as animation, molecular modeling, analogies, and practical work. It is also true that if misconceptions are not addressed early, they can interfere with the learning process and frustrate students who may be interested in pursuing careers in science.

Students across all ages in elementary, high school and college experience confusion in understanding the process of dissolving. Some students described the process as melting and others a chemical transformation between the solute and the solvent. Yet, in the dissolving process no heat is applied and no new compounds are formed. It is simply that an ionic compound, which can be recovered by evaporation after it dissolves in water, is placed in a different chemical environment—water. However, the dissolving process involves complex chemical processes that occur in tandem, which confuses many students. Ebenezer and Erickson (1996) describes dissolving as the process in which the solvent must first hydrate the ionic salt and pull apart the individual ions that constitute the compound. This happens when the oxygen atom in water molecules is attracted to the positive part of the ionic salt and the hydrogen atoms of the water molecules are attracted to the negative part of the ionic salt. From this description, it appears that understanding the process of dissolving also has the potential to enhance students' understanding about the relationship between the symbolic and particulate descriptions of the dissolving process. For instance, when students are asked to write balanced equations of ionic compounds dissolving in water, they have to first imagine at the particulate level what the ions and water molecules are doing in solution then transfer that knowledge into written equations. This approach will also offer a means to assess students' understanding of subscripts and coefficients. For example, when students are asked to write an ionic equation for dissolved magnesium chloride ($MgCl_2$), students would have to consider whether the subscript (2) in the original compound would remain unchanged as a subscript or if it would become a coefficient. Moreover, when an ionic compound contains a polyatomic subscript, students would have to understand that polyatomic ions do not dissociate in water, and in compounds where the individual ions have subscripts, these subscripts change to coefficients when the compound dissolves in water. Students would also have to understand that when ions dissolve they do exist as charged species with the potential to conduct electricity. So the written equations should be balanced with respect to charges and atoms.

To improve students' understanding about the dissolving process, it is necessary for instructors to understand the misconceptions that students hold and the mistakes that they make in writing ionic equations of ionic compounds dissolving in water. Doing so will enable instructors to find better ways to address these misconceptions and improve students' conceptual understanding about the dissolving process.

Identifying students' misconceptions in writing balanced equations for ionic compounds dissolving in water is an open area that needs to be explored. Most of the research studies on misconceptions about the dissolving process have focused on students relating the macroscopic to the particulate level of representation. That may be an indication that chemical education researchers may need to evaluate the relationship between these students' understanding at the particulate and the symbolic levels. The first study of this dissertation focuses on identifying students' misconceptions in writing balanced equations for dissolving ionic compounds in water. The last two studies focus on using the misconceptions identified to develop multiple-choice questions at the symbolic and particulate levels to assess students' understanding of the dissolving process. The second study looks at how the use of animated and static visuals and the order in which students answer the symbolic and particulate questions affect their understanding of the dissolving process. The third study focuses on how the presences of monatomic and polyatomic subscripts affect students' understanding of the dissolving process.

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CHAPTER THREE

STUDENT MISCONCEPTIONS IN WRITING BALANCED EQUATIONS FOR DISSOLVING IONIC COMPOUNDS IN WATER

Abstract

The goal of this study was to identify student misconceptions and difficulties in writing symbolic-level balanced equations for dissolving ionic compounds in water. A sample of 105 college students were asked to provide balanced equations for dissolving four ionic compounds in water. Another 37 college students participated in semi-structured interviews where they provided balanced equations for dissolving the same four ionic compounds in water and were asked to explore their thought processes at the particulate level associated with writing these equations. Misconceptions identified from these data included (i) the notion that water reacts with the ionic salts through double displacement to form a metal oxide and an acid; (ii) the notion that ionic salts dissolve as neutral atoms or molecules in water; (iii) confusion regarding the proper use of subscripts and coefficients; and (iv) the notion that polyatomic ions will dissociate into smaller particles in water. This study also describes the possible sources of these misconceptions.

Introduction

Many concepts in chemistry can be very difficult for students to learn (Taber, 2002; Barke *et al.*, 2009), and several chemical education researchers have focused their efforts on identifying common student misconceptions in chemistry (Osborne and Cosgrove, 1983; Andersson, 1986; Stavy, 1990; Garnett and Treagust 1992a, b; Ebenezer and Gaskell, 1995; Sanger and Greenbowe, 1997; Boo, 1998; Furió *et al.*, 2000; Solomonidou and Stavridou, 2000; Ebenezer, 2001; Coll and Treagust, 2003; Taber, 2003; Cokelez and Dumon, 2005; Drechsler and Schmidt, 2005; Kelly and Jones, 2007; Costu, 2008; Papaphotis and Tsaparlis, 2008; Schmidt *et al.*, 2009; Cartrette and Mayo, 2011; Smith and Nakhleh, 2011). Identifying and describing students' conceptions regarding the process of dissolving compounds in water—both molecular compounds like sucrose and ionic compounds like table salt—is perhaps the most-studied area of misconceptions in the field of chemistry (Ebenezer and Erickson, 1996; Smith and Metz, 1996; Ebenezer, 2001; Ardac and Akaygun, 2004; Liu and Lesniak, 2006; Kelly and Jones, 2007; Tien *et al.*, 2007; Kelly and Jones, 2008; Barke *et al.*, 2009; Smith and Nakhleh, 2011). Several of these studies asked students to generate their own particulate drawings to explain the dissolution process (Smith and Metz, 1996; Ebenezer, 2001; Ardac and Akaygun, 2004; Kelly and Jones, 2007; Tien *et al.*, 2007; Kelly and Jones, 2008), while others provided particulate drawings to be analysed, often in the form of computer animations or hypermedia (Smith and Metz, 1996; Ebenezer, 2001; Kelly and Jones, 2007; Kelly and Jones, 2008).

Ebenezer and Erickson (1996) explored grade 11 chemistry students' conceptions about the solubility of three systems—sugar/water, salt/water, and water/alcohol/paint thinner. Several students confused the process of dissolving sugar or salt in water with melting. Other students believed that when sugar was added to water it reacted to form a new substance, and one student drew pictures showing sugar and tea molecules attached (bonded) together. These students also used density arguments to explain why paint thinner would not mix with alcohol and water. Some of these students also held the view that dissolved solute particles occupy small air spaces or pockets in water and that solute particles will dissolve only if they find enough space in the solvent. In 2001, Ebenezer (2001) analysed another cohort of fifteen 11th graders' conceptions about the process of dissolving sugar in water. Six of these students believed that sugar transformed from the solid state to the liquid state when it dissolves in water, four believed that sugar reacted with water, and three believed that sugar occupied empty spaces between the water molecules. However, when these same students were shown an animation of sugar dissolving in a hypermedia environment, four students revised their initial views of the dissolving process. Three students not only retained their views that sugar reacted with water, but they also insisted that their views were consistent with what they had seen in the animation. Only one of these students was able to draw particulate models close enough to that of the experts.

Kelly and Jones (2007) explored 18 college students' understanding of the process of dissolving sodium chloride in water using two different animations. One animation depicted the space-filling ions vibrating in the lattice and focused on the interactive forces during hydration; the other depicted sodium chloride in a lattice structure and showed the charges on the ions and still pictures of water molecules surrounding the hydrated ions. Before viewing the animations, students provided particulate drawings to illustrate their initial understanding of sodium chloride and water before, during, and after mixing. In these initial drawings, 15 students represented sodium chloride as neutral molecules and 8 drew water molecules as linear. Five students showed sodium chloride molecules interacting with water, and two of these students showed sodium chloride molecules forming bonds with water molecules. In a subsequent study, Kelly and Jones (2008) tested to see how viewing particulate animations of sodium chloride dissolving in water affected the same college general chemistry students' abilities to transfer their understanding from the previous week to explain the precipitation reaction of aqueous sodium chloride and silver nitrate. Although all 18 of these students corrected errors in their initial drawings after seeing particulate animations of sodium chloride dissolving in water, none showed the spheres of hydration around the sodium chloride and silver nitrate ions in their particulate drawings one week later. Six students showed sodium chloride as neutral molecules, and three students showed sodium chloride pairs with water molecules. In general, students had trouble transferring their improved conceptions from the particulate animations to the new precipitation reactions one week later.

Smith and Metz (1996) evaluated student-generated drawings for the precipitation reaction of aqueous nickel(II) chloride and aqueous sodium hydroxide, Liu and Lesniak (2006) studied grade 1-10 students' conceptions about the dissolution of baking soda in water, Tien *et al.* (2007) used the Model-Observe-Reflect-Explain (MORE) approach to evaluate college chemistry students' understanding of processes involved in dissolving sugar and salt in water, and Smith and Nakhleh (2011) focused on students' conceptions regarding the bonds that must be made and broken when ionic compounds melt and when they dissolve in water. All four studies found that students believed ionic compounds would dissolve in water as neutral molecules, and three of them showed evidence that students were confused regarding the difference between the processes of melting and dissolving and that they believed that the solute particles would form chemical bonds with the solvent (water) molecules (Liu and Lesniak, 2006; Tien *et al.*, 2007; Smith and Nakhleh, 2011).

Although several chemical education research studies have analysed students' conceptions of dissolving ionic and molecular compounds in water, none have looked at student difficulties when writing balanced equations for the dissolving process. The goal of this study is to identify college-level introductory chemistry students' misconceptions associated with writing balanced equations for the dissolution of ionic salts in water.

Part of the difficulty in discussing the process of dissolving ionic compounds in water is determining whether this represents a physical process or a chemical change. Ebenezer and Gaskell (1995) described the ambiguity very well:

"In the ordinary sense, solutions of sugar and salt in water are said to be the result of a physical change because the components can be separated by simple physical means such as evaporation. In another sense, however, salt dissolving in water can also be characterized as a chemical phenomenon. For example, the behavior of salt solution is different from the behavior of crystalline salt: unlike salt in the solid form, salt solution conducts electricity. Thus the concept of dissolving poses difficulty for students because of its dual behavior—a chemical process in some contexts and a physical one in others." (pp. 13-14).

Another way of framing this ambiguity is that dissolving an ionic compound in water can be classified as a physical process or a chemical change depending on how the ionic solid is viewed. If the ionic solid is viewed as an intact entity, then dissolving this compound into water results in a chemical change and creates new chemical species, the hydrated cations and anions. However, if the ionic solid is viewed as a collection of cations and anions, then dissolving does not create any new chemical species, it simply places the existing species in a new environment and is best described as a physical process.

In this study, students are asked to write balanced equations for dissolving ionic compounds in water. Those readers who view this as a physical process may question the use of the term *balanced equation*, which may imply that a chemical reaction is occurring. We recognize this difficulty and have attempted to minimize any confusion regarding the use of this term by refraining from the use of terms such as *balanced chemical equation*, *chemical reaction*, *reactant*, or *product* unless discussing examples where students actually believe a chemical reaction is occurring.

Theoretical perspective

Constructivist theory of learning posits that knowledge cannot be directly transferred from the instructor to students because students must actively construct their own knowledge that makes sense to them by integrating new ideas into their existing knowledge (Bodner, 1986; Bodner *et al.*, 2001). Unfortunately, many students learning chemistry hold on to their own personal views and inadequate interpretations of particulate phenomena that develop from their individual experiences, culture and classroom instruction (Duit and Treagust, 1995). When these views and interpretations differ from those widely accepted by chemists, they are referred to as misconceptions (Bodner, 1986). Often, misconceptions interfere with learning concepts in chemistry, and are known to occur among students capable of successfully solving quantitative problems in chemistry (Nurrenbern and Pickering, 1987; Pickering, 1990; Sawry, 1990).

The use of multiple representations (macroscopic, particulate, and symbolic) in chemistry instruction confuses many students (Johnstone, 1993; Gilbert and Treagust, 2009; Johnstone, 2010; Talanquer, 2011) and research has shown that students have difficulty moving from the macroscopic to the particulate level (Osborne and Cosgrove, 1983; Andersson, 1986; Ben-Zvi *et al.*, 1986; Gabel, 1993; Kelly *et al.*, 2008) and from the symbolic to the particulate level (Yarroch, 1985; Nurrenbern and Pickering, 1987; Pickering, 1990; Sawry, 1990; Gabel, 1993; Sanger, 2005; Kelly *et al.*, 2008). The ability to see the connections and move seamlessly between these levels is referred to as representational competence (Kozma and Russell, 1997; Madden *et al.*, 2011). More successful problem solvers are generally found to have stronger and richer representations than their less successful counterparts (Kozma and Russell, 1997; Bodner and Domin, 2000; Madden *et al.*, 2011). As a result, while chemistry instructors are able to move freely between these levels, beginning chemistry students often find this to be a challenge, and are likely to develop misconceptions during instruction (Gabel, 1993).

Methods

Free-response protocol

For the first part of this study, students (*N* = 105) enrolled in a first-semester introductory chemistry class who had previous instruction on solution chemistry (precipitations, acid-base reactions, oxidation-reduction reactions) were asked to write balanced equations for the dissolution of four ionic compounds in water. The ionic compounds were LiCl (a compound with no subscripts), $CaCO_3$ (a compound with a polyatomic subscript), $BaBr_2$ (a compound with a monatomic subscript), and K_2SO_4 (a compound with both types of subscripts). The student-generated equations were analyzed and categorized to determine common student errors made in writing these equations.

Interview protocol

In order to corroborate the student misconceptions and errors identified based on the written balanced equations, an additional 37 students were interviewed in groups of one or two using a semi-structured interview protocol (Borg and Gall, 1983); the interviews each lasted about 30 min and focused on students' particulate explanations of their self-generated (symbolic) balanced equations. Conceptual and propositional knowledge statements (Table 1) needed to fully understand the dissolving processes were derived by the researchers after reviewing several introductory college chemistry textbooks. These statements were reviewed by two college chemistry professors, and their comments were used to revise the list. The statements represent the scientifically accepted knowledge required for students to fully understand the dissolution process, and a framework for developing the interview protocol and the procedures for data analysis.

Table 1 Conceptual and propositional knowledge statements for the dissolution of ionic solids in water

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1. Ionic solids contain positively charged ions (cations) and negatively charged ions (anions). The ratio of cations to anions in the solid is determined by the charges of the two ions since the overall charge of the ionic solid must equal zero. Ionic solids are usually solids under normal laboratory conditions. The formula unit of an ionic solid contains the simplest (smallest) ratio needed to maintain neutrality. The cation is listed first and the anion is listed second. If more than one ion is needed in the formula unit, subscripts are used to denote the number of each ion present. If a subscript is needed for a polyatomic ion, parentheses must be placed around the formula of the polyatomic ion with the subscript appearing after the right parenthesis.
2. When an ionic compound dissolves in water, it changes from the solid state to an aqueous state. Ionic compounds do not dissolve in water as neutral ion-pairs. Instead, water-soluble ionic compounds are strong electrolytes in which the individual ions dissociate from one another and move independently throughout the solution.
3. Water does not chemically react with an ionic compound when it dissolves in water. Instead, water molecules hydrate the individual ions, positioning the partially negative oxygen atom in a water molecule toward the cations and a partially positive hydrogen atom in the water molecule toward the anions. Dissolving ionic compounds in water can be viewed as a physical process that can be reversed by evaporating the water.
4. The process of electrical conductivity requires charged particles that have the freedom to move from one electrode to the other. Solid ionic compounds have charged ions in them but these ions do not have the freedom to move from one electrode to the other, so the solid will not conduct electricity. Pure liquid water does not have an appreciable amount of charged particles in it to allow the conduction of electricity. Aqueous solutions of ionic compounds, on the other hand, do conduct electricity because the dissolved cations and anions have the freedom to move from one electrode to the other.

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5. Polyatomic ions represent clusters of two or more atoms that have a net electrical charge. Polyatomic ions are held together by strong covalent bonds. These ions tend to be stable in water and do not dissociate but instead remain intact when a solid ionic compound is dissolved in water.
6. When writing balanced equations for dissolving ionic compounds in water: (a) The ionic compound present before dissolving is in the solid state, designated as (s), and the individual ions present after dissolving are in the aqueous state, designated as (aq); (b) Although water is needed for the dissolution process, it is not a involved in a chemical reaction with the ionic solid and is left out of the equation; (c) The cations and anions present after dissolving are written separately to denote that these ions are no longer joined together in the solution; (d) Numbers placed after an atom or group of atoms (subscripts) are used to denote how many of each type of atom or group of atoms are present in a chemical species; (e) Numbers in front of a chemical formula (coefficients) are used to denote how many of these chemical species are present; (f) Polyatomic ions are left intact and any subscripts in the polyatomic ion are still written as subscripts; (g) Any subscripts placed in the formula unit of the ionic solid that are not part of polyatomic ions, used to denote how many of these ions are present in the formula unit, are now written as coefficients in front of the ion it modified.

The interviews started out with a chemical demonstration of the solubility and conductivity of solid lithium chloride in water. Participants were shown a sample of distilled water and solid LiCl, and the conductivity of each sample was measured. Then a small amount of LiCl was added to a sample of water and the participants were asked if it dissolved and how they knew. Then, the conductivity of the solution was tested. The participants were then asked to explain the conductivity data.

For the second part of the interview, participants were asked to write a balanced equation for the dissolution of LiCl in water, including states of matter, and were then asked to write similar equations for dissolving $CaCO_3$, $BaBr_2$, and K_2SO_4 in water. After writing each balanced equation, the students were asked to explain their thought processes regarding why they wrote the equations the way that they did. Follow-up questions were asked as needed including questions on charge balance, why water was reacting, why some subscripts did or did not become coefficients, why polyatomic ions did or did not dissociate in solution, *etc.* A brief summary of the interview protocol and some of the open-ended questions used in the interview process appear in Fig. 1.

Demonstration

After seeing a small amount of solid lithium chloride being added to a sample of distilled water:

1. How can you tell whether solid lithium chloride is dissolving?
2. Suppose you could zoom in really close inside the test tube, could you estimate the relative amount of lithium chloride and water?

After the conductivity tests of distilled water, solid lithium chloride, and the aqueous salt solution:

3. How does the salt solution conduct electricity? What part of the salt solution conducts electricity?

Balanced equations

Write the net ionic equation for what happens when these ionic compounds dissolve in water:

4. $LiCl(s) \rightarrow$
5. $CaCO_3(s) \rightarrow$
6. $BaBr_2(s) \rightarrow$
7. $K_2SO_4(s) \rightarrow$

Follow-up questions

The following questions were used as needed in the semi-structured interviews

8. What are the states of matter for the chemicals present before and after dissolving?
9. Why did you write these ions separate from each other?
10. Why did you change this number from a subscript to a coefficient?
11. Why didn't you change this number from a subscript to a coefficient?
12. What is the difference between F_2 and 2F?
13. Is the equation balanced?
14. Are charges balanced?
15. Why didn't you break the sulfate/carbonate ions apart?

Fig. 1 Interview protocol used for the semi-structured interviews regarding the dissolution process for the four ionic compounds in water.

Analysis of data

The balanced equations from the first group of students were tabulated for each ionic solid as a list of balanced equations along with the number of students writing each equation. These lists were analysed for errors, which were categorized into themes that represented common student misconceptions. The misconceptions identified from the written responses were used as a guide to analyse the semi-structured interviews. Each interview was digitally recorded, and the student-generated balanced equations were written on the question sheets used during the interview. The interviews were transcribed verbatim by the first author. The misconceptions identified by the free-response equations were either supported or refuted by referring to interview transcriptions. The digital recordings were analysed by two chemical education researchers; any initial disagreements were discussed and resolved by these researchers.

Results and discussion

The most common student-generated equations (provided by 5% or more of the student population) for each ionic solid are listed in Table 2.

Table 2 Student-generated balanced equations for ionic compounds dissolved in water for the free response and interview studies

	Number (per cent) of respondents		
Equation	Free-response	Interview	Equation errors
$LiCl(s) \rightarrow Li^+(aq) + Cl^-(aq)$	*44 (42)*	*9 (24)*	*None (correct)*
$LiCl(s) \rightarrow Li(aq) + Cl(aq)$	18 (17)	7 (19)	Charges missing
$2LiCl(s) + H_2O(l) \rightarrow Li_2O(aq) + 2HCl(aq)$	5 (5)	12 (32)	Water reacting
$LiCl(s) + H_2O(l) \rightarrow LiO(aq) + HCl(aq)$	7 (7)	0 (0)	Water reacting, Atoms not balanced
Other unique responses	31 (30)	9 (24)	Various
$CaCO_3(s) \rightarrow Ca^{2+}(aq) + CO_3^{2-}(aq)$	*21 (20)*	*11 (30)*	*None (correct)*
$CaCO_3(s) \rightarrow Ca(aq) + CO_3(aq)$	17 (16)	5 (14)	Charges missing
$CaCO_3(s) + H_2O(l) \rightarrow CaO(aq) + H_2CO_3(aq)$	7 (7)	14 (38)	Water reacting
$CaCO_3(s) \rightarrow CaCO_3(s)$	7 (7)	0 (0)	Solid does not dissolve
Other unique responses	53 (50)	7 (19)	Various
$BaBr_2(s) + H_2O(l) \rightarrow BaO(aq) + 2HBr(aq)$	10 (10)	12 (32)	Water reacting
$BaBr_2(s) \rightarrow Ba(aq) + Br_2(aq)$	11 (10)	5 (14)	Charges missing, Subscript error
$BaBr_2(s) \rightarrow Ba^{2+}(aq) + 2Br^-(aq)$	*11 (10)*	*5 (14)*	*None (correct)*
$BaBr_2(s) \rightarrow Ba^{2+}(aq) + Br_2^-(aq)$	10 (10)	4 (11)	Charges not balanced, Subscript error
$BaBr_2(s) \rightarrow BaBr_2(s)$	8 (8)	0 (0)	Solid does not dissolve
$BaBr_2(s) \rightarrow Ba(aq) + 2Br(aq)$	7 (7)	1 (4)	Charges missing
$BaBr_2(s) \rightarrow Ba^{2+}(aq) + Br^-(aq)$	7 (7)	0 (0)	Atoms not balanced, Charges not balanced
Other unique responses	41 (39)	11 (30)	Various
$K_2SO_4(s) + H_2O(l) \rightarrow K_2O(aq) + H_2SO_4(aq)$	8 (8)	13 (35)	Water reacting
$K_2SO_4(s) \rightarrow K_2(aq) + SO_4(aq)$	12 (11)	5 (14)	Charges missing, Subscript error
$K_2SO_4(s) \rightarrow 2K^+(aq) + SO_4^{2-}(aq)$	*8 (8)*	*8 (22)*	*None (correct)*
$K_2SO_4(s) \rightarrow K_2^+(aq) + SO_4^{2-}(aq)$	7 (7)	1 (3)	Subscript error, Charges not balanced
Other unique responses	70 (67)	10 (27)	Various

These responses include correct equations and incorrect equations involving several types of misconceptions described in greater detail below. Many of the student-generated equations had a combination of more than one error, resulting in quite a few unique (N = 1) responses. To get a better understanding of the prevalence of these mistakes, the number of students making each kind of error was tabulated for each ionic solid and these results appear in Table 3.

Table 3 Number (per cent) of students making common errors in student-generated equations

Error	LiCl		$CaCO_3$		$BaBr_2$		K_2SO_4	
	Free-response	Interview	Free-response	Interview	Free-response	Interview	Free-response	Interview
None	44 (42)	9 (24)	21 (20)	11 (30)	11 (10)	4 (11)	8 (8)	8 (22)
Water reacting	27 (26)	16 (43)	17 (16)	16 (43)	25 (24)	16 (43)	24 (23)	15 (41)
Charges missing	27 (26)	8 (22)	28 (27)	6 (16)	26 (25)	6 (16)	37 (35)	8 (22)
Subscript errors	0 (0)	2 (5)	5 (5)	2 (5)	40 (38)	16 (43)	44 (42)	10 (27)
Incorrect charges	8 (8)	2 (5)	26 (25)	2 (5)	25 (24)	7 (19)	32 (30)	3 (8)
Polyatomic ion dissociated	–	–	32 (30)	2 (5)	–	–	8 (8)	1 (3)
Atoms not balanced	17 (16)	2 (5)	27 (26)	0 (0)	28 (27)	0 (0)	32 (30)	2 (5)
Charge not balanced	11 (10)	2 (5)	22 (21)	1 (3)	24 (23)	5 (14)	31 (30)	3 (8)

Table 4 contains a list of student misconceptions identified from these equations and the subsequent interviews.

Table 4 List of misconceptions identified in this study

1. Ionic salts chemically react with water when dissolved *via* double displacement to form an acid and the metal oxide or hydroxide.
2. In double displacement reactions of the ionic salt and water, the hydrogen atoms from water combines with the cation of the salt and the oxygen atoms from water combines with the anion of the salt.
3. Ionic salts dissolve as a combination of neutral atoms or molecules in water.
4. Dissolved ions/ionic compounds have the same properties as their neutral elements.
5. There are no fixed rules for when a subscript or coefficient should be used, and subscripts and coefficients do not convey specific information to chemists.
6. When a subscript is added to a monatomic ion, it also changes the total charge of the ion.
7. Monatomic non-metal ions will bond together because their neutral elements exist as diatomic molecules; monatomic metal ions will not bond together because their neutral atoms do not exist as diatomic molecules.
8. Polyatomic ions dissociate into smaller components when dissolved in water.

Double displacement reactions involving water

Several students wrote balanced equations showing that ionic salts react with water through double displacement to form an acid and the metal oxide or hydroxide when they dissolve (Misconception 1). This response appeared in the top three responses in Table 2 for each ionic solid. It was the most common answer for the interview students (shown by over 40% of these students for each ionic solid), and was even more popular than the correct response. The following interview excerpt provides an example of this misconception:

Participant: (written) $2LiCl(s) + H_2O(l) \rightarrow Li_2O(aq) + 2HCl(aq)$.

Interviewer: From your equation is water reacting?

Participant: It should be a double displacement.

Interviewer: What about states of matter?

Participant: Aqueous.

Interviewer: How do you know it's aqueous?

Participant: You don't see a solid anymore.

Interviewer: Before you said there are ions in the mixture, and where are the ions in your written equation?

Participant: It's [a] net ionic [equation].

Interviewer: Though you wrote it in the molecular form, the charges in $Li_2O(aq)$ and $HCl(aq)$ will be?

Participant: Li^+, O^{2-}, H^+, Cl^-. (Misconception 1).

A few students wrote double displacement reactions in which the cation combined with the positively-charged hydrogen atoms from water and the anion combined with the negatively-charged oxygen atoms from water (Misconception 2). For example, four students wrote the equation: $LiCl(s) + H_2O(l) \rightarrow LiH_2(aq) + ClO(aq)$. To a chemist, this reaction appears to be an oxidation-reduction reaction but these students treated this reaction as a simple double displacement between Li, Cl, H_2, and O.

Dissociation into neutral atoms/molecules

Another common student mistake was to write balanced equations in which the ionic salts dissolve as neutral atoms or molecules instead of cations and anions (Misconception 3). This response also appeared in the top two responses in Table 2 for each ionic solid, and was routinely demonstrated by 16-35% of the students. When a pair of students who wrote lithium chloride dissolving as aqueous Li and Cl atoms were asked what in their written equation was causing the salt solution to conduct electricity, they stated it was the lithium atom because metals conduct electricity. The following interview excerpt illustrates the belief that dissolved ionic solids have the same properties as their neutral elements (Misconception 4):

> *Participant:* (written) $LiCl(s) \rightarrow Li(aq) + Cl(aq)$.
>
> *Interviewer:* Which of those [species] conducts electricity?
>
> *Participant:* Metal, lithium.
>
> *Interviewer:* How do you know the state of matter is aqueous?
>
> *Participant:* Because no solid [is present] and it's dissolved in water.
>
> (Misconception 4).

Subscript/coefficient errors

Several students wrote balanced equations showing confusion between the use of subscripts and coefficients. Less than 5% of students showed subscript/coefficient errors when the ionic solid contained no subscripts (LiCl), or when it only contained a subscript as part of a polyatomic ion ($CaCO_3$). When the ionic solid contained a subscript for monatomic ions ($BaBr_2$ and K_2SO_4), more of the student-generated equations (27-43%) contained subscript/coefficient errors, and most of these errors involved the monatomic ions (Br^- and K^+, respectively). Further probing in the interviews showed that many of these students did not know the scientific rules for using chemical subscripts and coefficients or what the difference between 2F and F_2 would be (Misconception 5).

> *Participant:* (written) $BaBr_2(s) + H_2O(l) \rightarrow BaO(aq) + H_2Br_2(aq)$.
>
> *Interviewer:* Why didn't you write 2HBr instead of H_2Br_2?
>
> *Participant:* 2HBr means 2 moles of HBr.
>
> *Interviewer:* What is the difference between 2F and F_2?
>
> *Participant:* F_2 means is balancing the charges in the formula. 2F means to balance the equation. (Misconception 5).

In writing monatomic ions with subscripts, it was common for students to write the "ion-pair" with the charge of a single ion (i.e., H_2^+, Br_2^-, K_2^+, *etc.*). It became clear that many of these students believed that the subscript placed at the bottom of the atom symbol not only modifies the total number of atoms present but also the total charge of the ion (Misconception 6). In other words, they believed that writing Br_2^- was the same as writing $(Br^-)_2$ which would be properly written as Br_2^{2-}.

One pair of students wrote equations showing that $BaBr_2$ dissolved in water to make the Br_2^- ion but that K_2SO_4 dissolved in water to make $2K^+$ ions. Subsequent questioning showed that they understood the difference between coefficients and subscripts. The students explained that ions of non-metal anions would bond together as a diatomic unit because their neutral elements do, but ions made of metals would not because their neutral elements do not (Misconception 7). This is an extension of Misconception 4 applied to monatomic ions.

> *Participant:* (written) $BaBr_2(s) \rightarrow Ba^{2+}(aq) + Br_2^-(aq)$; $K_2SO_4(s) \rightarrow 2K^+(aq) + SO_4^{2-}(aq)$.
>
> *Interviewer:* In $K_2SO_4(s)$, 2 is a subscript but you wrote $2K^+$, why is that?
>
> *Participant:* When they are diatomic, they can't exist by themselves.
>
> *Interviewer:* What is F_2?
>
> *Participant:* Stuck together.
>
> *Interviewer:* What is 2F?
>
> *Participant:* Separate.
>
> *Interviewer:* Why does Br bond together and K_2 doesn't?
>
> *Participant:* Elements like O_2, Br_2 are stuck together. They just can't exist alone. (Misconception 7).

Dissociating polyatomic ions

For the dissolution of $CaCO_3$ and K_2SO_4, some students wrote balanced equations showing the polyatomic ions dissociating into smaller particles (Misconception 8). This error was more common among the students in the free-response group, and was much more common for the carbonate ion than the sulfate ion. One reason why students may be more comfortable breaking up the carbonate ion is that chemistry instructors often show demonstrations of carbonate salts reacting (and breaking into CO_2 and "O^{2-}") in the presence of acids. Another reason may be that they recognize O_3 as ozone but do not recognize O_4 as a known substance.

> *Participant:* (written) $CaCO_3(s) \rightarrow Ca(s) + C(s) + O_3(g)$.
>
> *Interviewer:* You said O_3 is a gas and Ca and C are solids. How did you figure that out?
>
> *Participant:* Something that I know from class, but for Ca and C as solid, I am not sure. (Misconception 8).

Other errors

Several students wrote equations with incorrect charges for some of the ions (e.g., Li^{2+}, Cl^{2-}, Ca^{+}, CO_3^{-}, Ba^{+}, Br^{2-}, K^{-}, SO_4^{2+}, *etc.*). It is difficult to determine whether these represent incorrect conceptions or simply a lack of propositional knowledge regarding the common charges of these ions. Similarly, it is difficult to be sure that students writing correct charges have a mature understanding why these charges are the stable ones.

Several students also wrote equations that were not atom-balanced or charge-balanced (both ranging from 0-30% of the population for the four ionic solids). These errors were more common for the students in the free-response group than the interview group. Since the free-response group participated in this study when the topic of dissolving ionic compounds in water was first introduced in class but the second group of students were interviewed later in the semester, this could simply be a matter of familiarity and practice in writing balanced equations.

Conclusions

This study identified four major student misconceptions in writing balanced equations for ionic compounds dissolved in water. These misconceptions included the idea that ionic compounds react with water in a double displacement reaction when dissolved, the idea that ionic compounds dissociate into neutral atoms or molecules in water, a general confusion regarding the proper use of subscripts and coefficients, and the idea that polyatomic ions dissociate into smaller components when dissolved in water. It should be noted that these misconceptions could appear as a result of simple student mistakes, memory lapses on the part of the student (especially for those students predicting incorrect charges for the ions), or the fact that students and researchers may have assigned different meaning to terms used in discussing students' ideas (Klaassen and Lijnse, 1996).

Possible sources of student misconceptions

The misconception that water reacts with the dissolved ionic salts is not new. Ebenezer and Erickson (1996) found that many students considered dissolving to be a chemical reaction, in which sugar or sodium chloride react with water to form new compounds with entirely different physical and chemical properties. Tien *et al.* (2007) and Smith and Nakhleh (2011) reported that some college students gave responses suggesting that dissolved NaCl forms chemical bonds with water, but both groups failed to indicate if students thought that new compounds would form as a result. It is possible that our demonstration, which showed that solid lithium chloride and liquid water did not conduct electricity but the combination of chemicals did, could have convinced students that water was important to the process and therefore part of the reaction. In American textbooks, the concept of dissolving ionic compounds in water is immediately followed by the discussion of double displacement reactions including acid/base and precipitation reactions. This proximity could lead to misconceptions where students confuse double displacement acid/base or precipitation reactions with the process of dissolving ionic compounds in water.

The misconception that ionic compounds dissolve as neutral atoms/molecules in water is inconsistent with the conductivity demonstration performed as part of the interviews. Some of these students explained this discrepancy by saying that it is the metals in solution that are conducting electricity because (solid) metals always conduct electricity. This misconception that dissolved ions in water have the same properties as their neutral elements is common and dates back to 1883, in which members of the doctoral committee of Svante Arrhenius were reported to have discounted the idea that sodium chloride would dissociate into ions in water because these solutions had none of the properties of elemental sodium or chlorine (Jaffe, 1976; Chemical Heritage Foundation, 2010). Computer animations depicting ions and ionic compounds without labeled charges on the ions could also support this misconception (Tasker, 1998). Perhaps showing students the conductivity of ionic compounds that do not contain metals ions (like hydrochloric acid or ammonium nitrate) would help some of these students relinquish this misconception.

Students' confusion regarding the use of subscripts or coefficients has also been previously reported (Yarroch, 1985; Al-Kunifed, 1993; Sanger, 2005; Nyachwaya *et al.*, 2011). Some of these students did not understand the chemical conventions regarding subscripts or coefficients and did not understand the difference between the formulas 2F and F_2 or that the formulas Br_2^- and $(Br^-)_2$ are not the same. However, other students who did understand the rules for subscripts and coefficients still wrote formulas showing two cations or two anions bonded together (i.e., K_2^+ or Br_2^-), especially if they appeared that way in their neutral ionic salts (K_2SO_4 or $BaBr_2$). As a result, students exhibited more subscript/coefficient errors when the ionic compounds contained subscripts for monatomic ions (K_2SO_4 or $BaBr_2$) than when the ionic compounds did not (LiCl or $CaCO_3$).

The misconception that polyatomic ions dissociate into smaller components when dissolved in water most likely represents a lack of understanding of the nature of polyatomic ions. Although there are some notable exceptions (such as when carbonate ions are mixed with acids), polyatomic ions tend to stay together as a single object when dissolved in water and are often treated as a single entity by chemists. Nyachwaya *et al.*

(2011) showed particulate drawings from a student who drew "molecules" of $CaCO_3$ in which the Ca atom was in the middle with one C and the three O atoms bound to it, indicating that this student did not understand the structure of a polyatomic ion like carbonate. Smith and Metz (1996) showed similar student-generated particulate drawings with hydroxide groups broken into H and O atoms.

Although we identified several misconceptions in this study, there was another misconception that we had expected to see but did not. The dissolution of ionic compounds to form neutral ion pairs (i.e., solid LiCl dissolving in water as neutral LiCl molecules) has been well documented in the chemical education literature (Butts and Smith, 1987; Boo, 1998; Tasker, 1998; Liu and Lesniak, 2006; Kelly and Jones, 2007; Tien *et al.*, 2007; Kelly and Jones, 2008; Smith and Nakhleh, 2011; Nyachwaya *et al.*, 2011; Rosenthal and Sanger, 2011). Taber (Taber, 1994; Taber, 1997; Barke *et al.*, 2009) also noted that many students believed individual ion pairs exist in solid ionic salts, even though the cations and anions in the solid were surrounded by several ions of the opposite charge. However, only one student out of the 142 students in both studies demonstrated this misconception in his or her balanced equations. We are not sure why this common misconception was not more popular among our students.

This study was performed using students in first-semester introductory chemistry courses where the concept of dissolving ionic compounds in water is first introduced. We had originally interviewed 20 students in a second-semester introductory chemistry course (after they had studied equilibrium solubility of ionic compounds in water including K_{sp} calculations) to corroborate or refute the misconceptions identified in the first part of this study. However, all of these students were able to write the correct equations for the solubility of the four compounds used in this study. It is encouraging to see that after studying the solubility of ionic compounds in two different chemistry courses, these students demonstrated a solid understanding of writing balanced equations for the dissolution process.

Future studies

This study has identified several misconceptions exhibited by students when writing balanced equations for dissolving ionic compounds in water. These results may be useful to instructors, textbook authors, or instructional designers trying to develop strategies to improve students' conceptual understanding about the dissolving process. Research involving instruction that incorporates the conceptual change approach (Posner *et al.*, 1982), in which the instructor elicits and then actively confronts student misconceptions, may help some students relinquish some of the misconceptions identified in this study.

Most research involving the use of computer animations of chemical reactions at the particulate level have focused on instructional interventions to improve students' conceptual understanding of these chemical processes (Williamson and Abraham, 1995; Sanger *et al.* 2000; Kelly and Jones, 2008; Gregorius, 2010a, b). Few have used these animations a part of the assessment process (Sanger *et al.*, 2007; Rosenthal and Sanger, 2011). Nyachwaya *et al.* (2011) compared students' abilities to balance chemical equations at the symbolic level to their abilities to create particulate drawings of these chemical reactions, and found that students were adept at balancing chemical equations but could not translate these formulas into the particulate level. The authors of the present study have created particulate animations depicting the dissolving process of four ionic compounds in the form of multiple-choice questions with four distractors based on the misconceptions identified in this study (the correct process, one showing a reaction with water, one showing neutral ion pairs/molecules, and one involving a confusion of subscripts and coefficients). Students in a future research study will be asked to answer questions for the same four ionic compounds dissolving in water, posed at the particulate and symbolic levels. This study will allow the authors to determine whether students' choices from the symbolic equations and the particulate animations are consistent, which may imply a more robust conception (whether right or wrong). It may also allow the researchers to further probe whether students understand the chemical conventions used for subscripts and coefficients in the symbolic-level balanced equations at the particulate level.

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CHAPTER FOUR

INVESTIGATING STUDENTS' UNDERSTANDING OF THE DISSOLVING PROCESS

Abstract

In a previous study, the authors identified several student misconceptions regarding the process of dissolving ionic compounds in water. The present study used multiple-choice questions whose distractors were derived from these misconceptions to assess students' understanding of the dissolving process at the symbolic and particulate levels. The symbolic-level questions were based on balanced equations, and the particulate-level questions used multiple-choice questions involving dynamic animations or static pictures. This paper analyzes students' responses to these questions to look for associations among four variables—Answer (the correct answer and three misconceptions), Representation (symbolic or particulate question), Visualization (static or animated pictures), and Representation Order (symbolic questions before or after the particulate questions). The results indicate that the correct answer and the acid-base misconception were the more popular than the ion-pair or subscript error misconceptions, the ion-pair misconception was more popular for the particulate questions than the symbolic questions, and that participants were more likely to select the correct answer when viewing static particulate questions compared to animated particulate questions, especially if the particulate questions are seen first. These results suggest that the animated motion of dissolving these compounds in water may be distracting for students.

Introduction

Students often find the process by which ionic compounds dissolve in water abstract and difficult to understand (Butts and Smith, 1987; Smith and Metz, 1996; Barke *et al.,* 2009; Liu and Lesniak, 2006; Naah and Sanger, 2012). Because of this difficulty, several chemical education researchers have focused on developing effective instructional interventions to assess students' understanding of the dissolving process (Ebenezer, 2001; Kabapinar, 2004; Kelly and Jones, 2007; Smith and Nakhleh, 2011). Several of these interventions have asked students to observe solid sodium chloride or table sugar (sucrose) dissolve in water, and then generate particulate diagrams to explain the dissolving process (Ebenezer, 2001; Ardac and Akygun, 2004; Tien *et al.,* 2007; Kelly and Jones, 2007; Kelly and Jones, 2008), whiles others used paper and pencil diagnostic questions (Kabapinar 2004) or semi-structured interviews to ask students to predict and explain how the mixture of sodium chloride and water would appear at the particulate level (Ebenezer and Erickson, 1996; Smith and Nakhleh, 2011). Common student misconceptions and errors identified from these studies included confusing the dissolving process with melting (Ebenezer and Erickson, 1996; Ebenezer, 2001; Liu and Lesniak, 2006; Tien *et al.,* 2007; Smith and Nakhleh, 2011), the dissolved compound reacting or bonding with water molecules (Ebenezer and Erickson 1996; Ebenezer 2001; Liu and Lesniak 2006; Tien *et al.,* 2007; Kelly and Jones 2007; Smith and Nakhleh 2011; Naah and Sanger 2012), and ionic solids dissolving as neutral formula units or ion-pairs (Butts and Smith, 1987; Smith and Metz, 1996; Liu and Lesniak, 2006; Tien *et al.,* 2007; Kelly and Jones, 2007; Kelly and Jones, 2008; Smith and Nakhleh, 2011).

Naah and Sanger (2012) used a free-response questionnaire and semi-structured interviews to identify student misconceptions when writing balanced equations for dissolving ionic compounds water. The most common misconception identified in this study was that water reacts with ionic compounds through double displacement to form a metal oxide and an acid. Another common mistake made by students and was confusing when to use a subscript and when to use a coefficient in their written equations related to monatomic and polyatomic ions. Although only one participant out of 142 in this study wrote equations showing ionic solids dissolving as neutral formula units or ion-pairs, this misconception has been identified by several chemical education researchers and is considered to be prevalent among chemistry students (Butts and Smith, 1987; Taber, 1994; Taber, 1997; Boo, 1998; Liu and Lesniak, 2006; Kelly and Jones, 2007; Tien *et al.*, 2007; Kelly and Jones, 2008; Nyachwaya *et al.*, 2011; Smith and Nakhleh, 2011; Rosenthal and Sanger, 2012).

In the present study, the authors were interested to see whether students' answers to multiple-choice questions (based on the correct conception and the three misconceptions mentioned above) for dissolving ionic compounds in water would be different if the questions were posed as symbolic-level balanced equations or as particulate-level drawings. The particulate-level multiple-choice questions were created as dynamic animations; however, sometimes animated visuals improve student learning and sometimes they are detrimental to learning (Sanger 2009). Finally, the authors were also interested to see whether students' responses changed if they answered the symbolic-level questions first and then the particulate-level questions or vice versa. The research question for the present study is:

Are there any significant associations between students' answers to these questions, the representational level of the question (symbolic or particulate), the type of visualization used for the particulate questions (static or animated pictures), and the order in which the symbolic and particulate questions are asked (symbolic questions before or after particulate questions)?

Theoretical perspectives

Chemists often describe and explain chemical reactions using three distinct but related chemical representations—the macroscopic, particulate, and symbolic levels (Johnstone, 1993; Gilbert and Treagust, 2009; Johnstone, 2010; Talanquer, 2011). In an experiment where they compared experts' and novices' abilities to move seamlessly among multiple representations including video segments, graphs, animations, and chemical equations, Kozma and Russell (1997) described this ability as a measure of the learner's *representational competence.* The idea of representational competence has been used extensively in chemical education research, including studies using the macroscopic, particulate, and symbolic representations (Kelly *et al.,* 2004; Chandrasegaran *et al.,* 2007; Chittleborough and Treagust, 2007; Gilbert and Treagust, 2009; Sande, 2010; Hilton and Nichols, 2011) and those using other non-chemistry specific representations including graphical, mathematical, verbal/linguistic, and visuo/spatial modes (Kozma and Russell, 1997; Bodner and Domin, 2000; Wilder and Brinkerhoff, 2007; Kraft *et al.,* 2010; Strickland *et al.,* 2010; Madden *et al.,* 2011; Stieff *et al.,* 2011). Comparing students' responses to symbolic- and particulate-level questions for dissolving ionic compounds in water will allow us to probe students' representational competence. Students choosing answers that are not self-consistent and do not depict the same chemical or physical processes for the symbolic and particulate questions would have a less-developed representational competence than those choosing answers that are self-consistent between the two representations.

The instructional effectiveness of animated versus static visuals is described by Mayer's Cognitive Theory of Multimedia Learning (Mayer 2001), which makes three fundamental assumptions about learning with multimedia. The first assumption is that learners use two separate channels for processing information—one of these channels is referred as the auditory or verbal channel, and the other is referred as the visual or pictorial channel (Paivio, 1986; Baddeley, 1986; Baddeley, 1999). As a result, combining both visual and auditory/verbal information during instruction can be an effective way of increasing the quality of information students process in working memory. The second assumption is that each of these channels has a limited capacity in the amount of information processed at any given time (Baddeley, 1986; Baddeley, 1999; Mayer, 2001). When the demands of learning exceed the learner's capacity, cognitive overload occurs (Sweller, 2008; Sweller, 2010). This limitation relates to Mayer's coherence principle (Moreno and Mayer, 2000; Mayer, 2001), which explains that learning from multimedia is more effective when extraneous materials are excluded. The third assumption is that learning is an active process through which learners construct knowledge by selectively processing relevant incoming information and integrating it to existing knowledge to form a coherent structure (Mayer and Moreno, 2002). Since the present study is comparing students' responses to particulate questions using static or animated pictures, the results will determine (based on Mayer's coherence principle) whether the animated motions in these questions are integral to the learning process or distract students from important information necessary for learning.

A few studies have looked at how the order of presenting information affects student learning (Velázquez-Marcano *et al.,* 2004; Tellinghuisen and Sulikowsi, 2008; Blakely, 2011). Velázquez-Marcano *et al.,* (2004) asked students to predict the behavior of gas particles in sealed flasks when the stopcock separating two flasks was opened for three different experiments. For each experiment, they compared students' predictions before any instructional intervention, then once again after seeing each of two different multimedia depicting the events occurring after the stopcock was opened. Half of the participants viewed a video demonstration of these events at the macroscopic level and then viewed a computer animation of these events at the particulate level; the other half of the participants viewed the particulate-level animation first and the macroscopic-level video second. The results of this study showed that the number of correct responses increased after each instructional intervention, regardless of which type of multimedia lesson was used and in which order they were shown. While the Velázquez-Marcano *et al.,* study measured students' responses to macroscopic- and particulate-level instructional interventions, the present study compares students' responses to symbolic- and particulate-level questions. The present study is also interested in determining whether changing the order in which the symbolic- and particulate-level questions are asked will have an effect on the participants' responses.

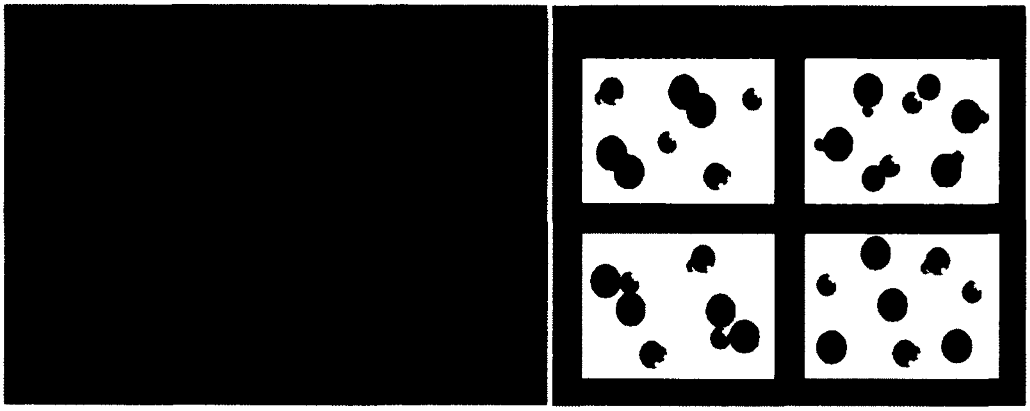
Methods

Subjects

This participants in the present study consisted of a sample of 98 college students enrolled in first-semester introductory general chemistry who had previous instruction in solution chemistry (balancing equations, precipitation reactions, acid-base reactions, oxidation-reduction reactions, etc.). The study took place in a chemistry laboratory session, and participants were randomly assigned to one of four groups. Participants in each group were asked to answer eight multiple-choice questions that best depict what happens when four ionic compounds dissolve in water.

Experimental design

The four ionic compounds used in the multiple-choice questions were: NaBr (a compound with no subscripts), KNO_3 (a compound with a polyatomic subscript), $MgCl_2$ (a compound with a monatomic subscript), and Ag_2SO_4 (a compound with both monatomic and polyatomic subscripts). The participants were asked to answer two multiple-choice questions for each ionic compound; they answered the questions for NaBr first, then the questions for KNO_3, then the questions for $MgCl_2$, and finally the questions for Ag_2SO_4. One of these questions focused on symbolic-level balanced chemical equations for these compounds dissolving in water; the other question used particulate-level pictures depicting the dissolving process. For each multiple-choice question, the four choices used as distactors in the symbolic-level equation questions—the correct process, one in which the ionic salt reacts with water to make a metal oxide and an acid, one where the ionic salt dissolves as neutral ion pairs/molecules, and one which shows a confusion regarding the use of subscripts and coefficients—came from a series of misconceptions identified in a previous study (Naah and Sanger, 2012). To compare students' understanding of the dissolving process at the symbolic and particulate levels, we developed computer animated multiple-choice questions for each compound depicting the same four choices that appeared in the symbolic-level questions. A screen shot of the symbolic- and particulate-level questions for magnesium chloride appear in Fig. 1. Each distractor in the particulate-level questions contained two water molecules because one of the distractors requires that water molecules be present to react with the ionic compound. The correct response appears as choice D in both questions; the response where water reacts with the ionic compound appears as choice C in Fig. 1a and choice B in Fig. 1b; the ion-pair response appears as choice A in Fig. 1a and choice C in Fig. 1b; and the subscript error response appears as choice B in Fig. 1a and choice A in Fig. 1b.



(a) (b)

Fig. 1 The symbolic-level (a) and the particulate-level (b) questions for dissolving solid magnesium chloride in water

The four experimental groups differed from each other by the order in which the participants saw the symbolic- and particulate-level questions and whether the particulate-level questions involved dynamic computer animation or static pictures. The static pictures were taken as screen shots from the dynamic computer animations. For the static-picture questions, one screen showed the ionic compound in its solid lattice before it dissolves and the other showed the four choices for how the ionic compound would look after it dissolves. One group saw the balanced equations first and the dynamic animations second (BA), another group saw the balanced equations first and the static pictures second (BP), a third group saw the dynamic animations first and the balanced equations second (AB), and the last group saw molecular the static pictures first and the balanced equations second (PB). Once the participants had answered a multiple-choice question and moved on to the next question, they were no longer allowed to see the previous question(s); however, participants viewing the animated questions were allowed to repeat each animation as many times as they wanted until they answered those questions and moved on to the next question. Each participant took about 3-5 minutes to complete the eight multiple-choice questions, from when program was opened to when it was closed, and these times were recorded and compared.

Data analysis—student responses

Students' responses to the eight multiple-choice questions were categorized according to four independent variables. The first variable was the type of chemical representation appearing in the question—the balanced equation questions were categorized as symbolic questions and the picture questions were categorized as particulate questions. The second variable was the type of visualization used in the question—this variable denotes whether the participants viewed dynamic animated pictures or static pictures. The third variable was representation order, and denotes whether the participants viewed the symbolic balanced equations before the particulate questions (S/P) or after the particulate questions (P/S). The last variable represented the answer chosen by the participant for each question—the correct response, the acid-base reaction, the formation of ion pairs, or the response showing a subscript error. Once the students' responses were categorized by the four independent variables, the number (frequency) of student responses appearing in the same category was tallied (Table 1) and analyzed by loglinear analysis using the statistical program SYSTAT.

Table 1 Frequency data for the students' responses based on the four independent variable in the present study

Representation	Visualization	Representation Order	Answer			
			Correct	Acid-Base	Ion-Pair	Subscript
Symbolic	Animated	S/P	30	54	2	6
		P/S	16	55	3	18
	Static	S/P	29	54	5	12
		P/S	39	48	6	11
Particulate	Animated	S/P	30	36	17	9
		P/S	29	34	22	11
	Static	S/P	30	26	30	14
		P/S	47	17	27	13

Loglinear Analysis, which is an extension of Multiway Frequency Analysis, is a statistical tool used to discover relationships (associations) among three or more categorical variables (Tabachnick and Fidell, 1996). When a relationship exists between a single categorical variable it is referred as a one-way association, when a relationship exists between two categorical variables it is referred as a two-way association, etc. Significant associations are often determined by the computed difference between the observed and expected frequency in a cell; the larger this difference the more likely the variables linked to this cell are involved in a statistically significant association. (Cramer, 2003; Foster *et al.,* 2006).

Tabachnick and Fidell (1996) described four practical issues that affect the power of loglinear results, and each of these issues have been satisfied in the present study. First, all of the categories must be mutually exclusive, so that each question appears in only one cell. Second, there should be at least five times as many student responses as cells in the study (in the present study, there are an average of 24.4 questions per cell). Third, when cases are rare and *N* is less than five in any cell, the marginal frequencies may not be evenly distributed. To test for this issue, the expected cell frequencies for all two-way associations should be examined to assure that all are greater than zero, and no more than 20% are less than five (in the present study, all cell frequencies were greater than five for each two-way association). Fourth, when performing unsaturated tests, there may be substantial differences between observed and expected frequencies that make it impossible for the proposed model to adequately fit the data. This is not an issue in the present study since we performed saturated tests. The results for the saturated loglinear analysis appear in Table 2.

Table 2 Loglinear analysis of the four independent variables in the present study

Association	*df*	χ^2	*p*
Representation, REP	1	14.16	0.000*
Visualization, VIS	1	4.51	0.034*
Representation Order, RPOR	1	0.73	0.393
Answer, ANS	3	192.23	0.000*
REP × VIS	1	1.10	0.294
REP × RPOR	1	0.35	0.555
REP × ANS	3	97.25	0.000*
VIS × RPOR	1	0.50	0.480
VIS × ANS	3	17.09	0.001*
RPOR × ANS	3	3.66	0.300
REP × VIS × RPOR	1	0.00	0.952
REP × VIS × ANS	3	1.87	0.510
REP × RPOR × ANS	3	3.83	0.280
VIS × RPOR × ANS	3	11.50	0.009*
REP × VIS × RPOR × ANS	3	1.86	0.603

* Significant at the $p < 0.05$ level

Data Analysis—Time-on-Task

The amount of time each participant spent answering the eight multiple-choice questions in the present study was measured using a digital stopwatch, from when the participant opened the program to when it was closed. A two-way analysis of variance (ANOVA) was conducted with the time each participant spent answering the questions as the dependent variable and visualization (static pictures or dynamic animations) and the representation order (symbolic balanced equations first and particulate pictures second or the pictures first and equations second) as the independent variables. The results of the ANOVA analysis appear in Table 3.

Table 3 Analysis of Variance results for time-on-task based on visualization type and representation order

Source	*df*	SS	MS	*F*	*p*
Visualization, VIS	1	33338.537	33338.54	4.668	0.033*
Representation Order, RPOR	1	30.136	30.136	0.004	0.948
VIS × RPOR	1	8140.706	8140.706	1.14	0.288
Error	92	657099.895	7142.39		

*Significant at the $p < 0.05$ level

Discussion

The results of the loglinear analysis (Table 2) showed three significant one-way associations (Representation, Visualization, and Answer), two significant two-way associations (Representation × Answer and Visualization × Answer), and one significant three-way association (Visualization × Representation Order × Answer). The four-way association in the present study was not significant.

One-way associations

Representation (REP) and Visualization (VIS) Associations

Although the REP and VIS associations were found to be significant, they are an artifact of the data collection methods and should not be viewed as meaningful associations. The REP variable consists of either symbolic (balanced equation) or particulate (visual) questions. Each participant was supposed to answer one symbolic and one particulate question for each of four ionic compounds; therefore, the number of symbolic responses should equal the number of particulate responses. One participant, however, did not answer the symbolic questions, so percentage of symbolic responses (49.7%) was slightly lower than the percentage of particulate responses (50.3%), $\chi^2(1) = 14.16, p < 0.000$.

For the VIS association, we found that more participants viewed the static pictures (52%) than the dynamic animations (48%), $\chi^2(1) = 4.51, p = 0.034$. The participants in the present study were randomly assigned to one of four groups—two of the groups viewed static pictures (BP and PB) and two of the groups viewed dynamic animations (BA and AB). The difference in the number of participants viewing static versus animated pictures is due to the fact that more participants were randomly assigned to the two groups viewing static pictures than to the two groups viewing animated pictures.

Answer (ANS) Association

The ANS variable represents the students' choices of the four answers to each multiple-choice question. The percentage of participants choosing the correct response (32%), the acid-base reaction with water (41%), the formation of ion pairs (14%), and the choice showing subscript errors (12%) is plotted in Fig. 2.

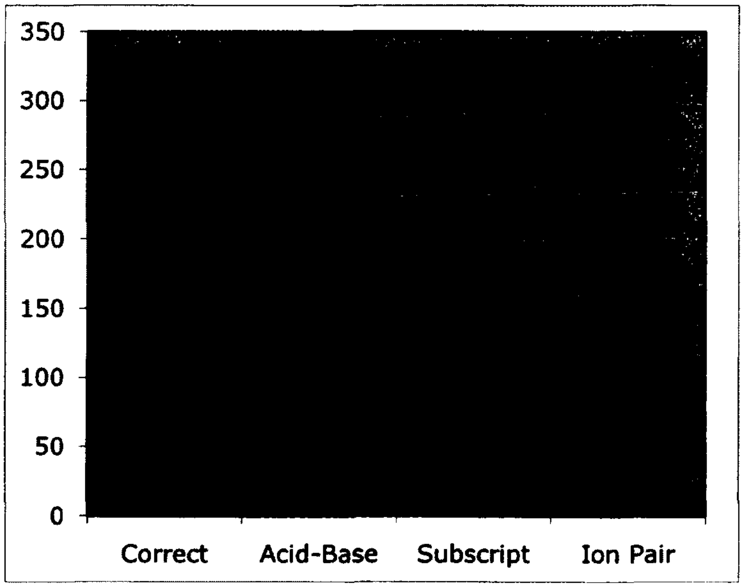


Fig. 2 Distribution of responses for the ANS association: More participants chose the 'Correct' and 'Acid-Base' choices and fewer participants chose the 'Subscript' and 'Ion Pair' choices

The one-way association for this variable ($\chi^2(3) = 192.23, p < 0.000$) shows that participants were more likely to choose the correct response and the acid-base response than they were to choose the ion-pair response or the subscript response. The fact that the acid-base was a more popular choice among participants than the ion-pair or subscript choices is consistent with misconceptions data reported by the authors using a different sample of students (Naah and Sanger 2012). However, several other researchers have noted that the ion-pair misconception is very popular among their subjects (Butts and Smith, 1987; Taber, 1994; Taber,1997; Boo,1998; Liu and Lesniak, 2006; Kelly and Jones, 2007; Tien *et al.,* 2007; Kelly and Jones, 2008; Nyachwaya *et al.,* 2011; Smith and Nakhleh, 2011; Rosenthal and Sanger, 2012).

Two-way associations

Representation - Answer (REP × ANS) Association

The REP × ANS association ($\chi^2(3) = 97.25, p < 0.000$) shows that the subjects chose different answers based on whether they were answering the symbolic questions involving balanced equations or the particulate questions involving pictures (Fig. 3).

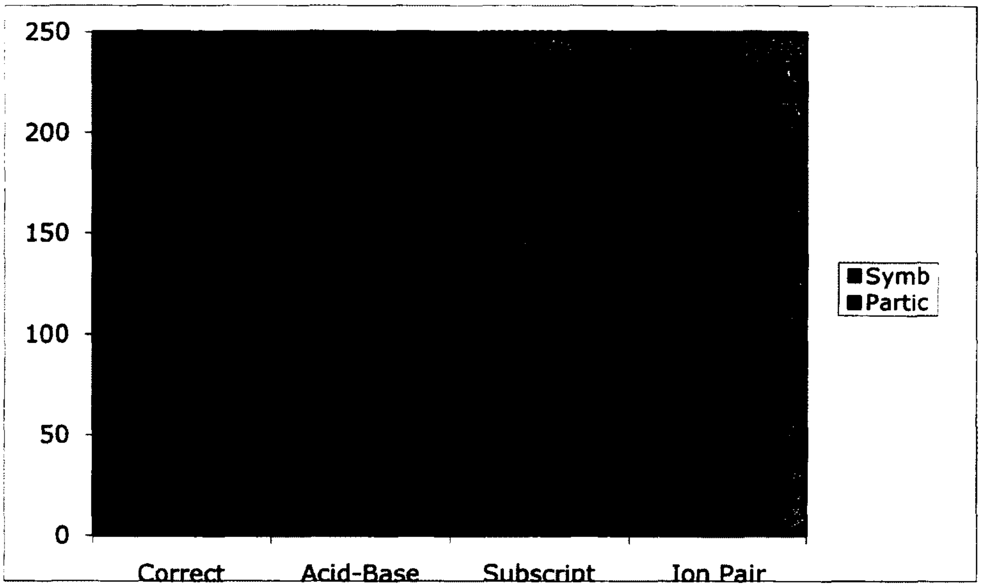


Fig. 3 Distribution of responses for the REP × ANS association: The 'Acid-Base' choice was more popular for the symbolic questions than for the particulate questions, while the 'Ion Pair' choice was more popular for the particulate questions than for the symbolic questions

The residuals from this association suggest that participants answering the symbolic questions were more likely to choose the acid-base answer and less likely to choose the ion-pair answer, while participants answering the particulate question were more likely to choose the ion-pair answer and less likely to choose the acid-base answer. The reason why this association exists is unclear. It is possible that the way the visual pictures for the distractors were drawn has made the acid-base reaction a less attractive choice and the ion-pair response a more attractive choice for the participants. The fact that the ion-pair answer was less attractive for the participants might explain the somewhat unexpected results found in a recent study. Naah and Sanger (2012) asked students to provide symbolic balanced chemical equations for dissolving several ionic compounds in water. In the present study, very few students wrote balanced equations showing ion pairs, even though this is a common misconception reported in the literature (Butts and Smith, 1987; Taber, 1994; Taber, 1997; Boo, 1998; Liu and Lesniak, 2006; Kelly and Jones, 2007; Tien *et al.,* 2007; Kelly and Jones, 2008; Nyachwaya *et al.,* 2011; Smith and Nakhleh, 2011; Rosenthal and Sanger, 2012). However, all of these studies identified this ion-pair misconception based on interviews with students involving particulate-level drawings or discussions.

Visualization - Answer (VIS × ANS) Association

The two-way association for VIS × ANS ($\chi^2(3) = 17.09, p = 0.001$) was statistically significant; the residuals showed that participants viewing the dynamic animations were more likely to choose the acid-base choice than the participants viewing the static pictures (Fig. 4). Apparently, the motion depicted in the animations made the acid-base answer more attractive to students compared to the static pictures. Although the difference in number of correct responses for the participants viewing the dynamic animations and static pictures is larger than the difference for the acid-base choice, the LOGIN calculations in SYSTAT did not find this difference statistically significant. This is mostly likely due to the way LOGLIN calculations are done—when the two-way associations were calculated, the program had already partialed out the effect of the three- and four-way associations. Since the three-way association of Equation order × Visualization × Answer already found a significant difference in the number of correct answers from participants based on whether they viewed the static pictures or dynamic animations and whether they viewed the symbolic questions before or after the particulate questions, the difference in the number of correct answers in the VIS × ANS association had already been taken into account. However, we believe that this difference has practical significance and tells us that participants who viewed the static pictures were more likely to answer these questions correctly than those participants viewing the dynamic animations.

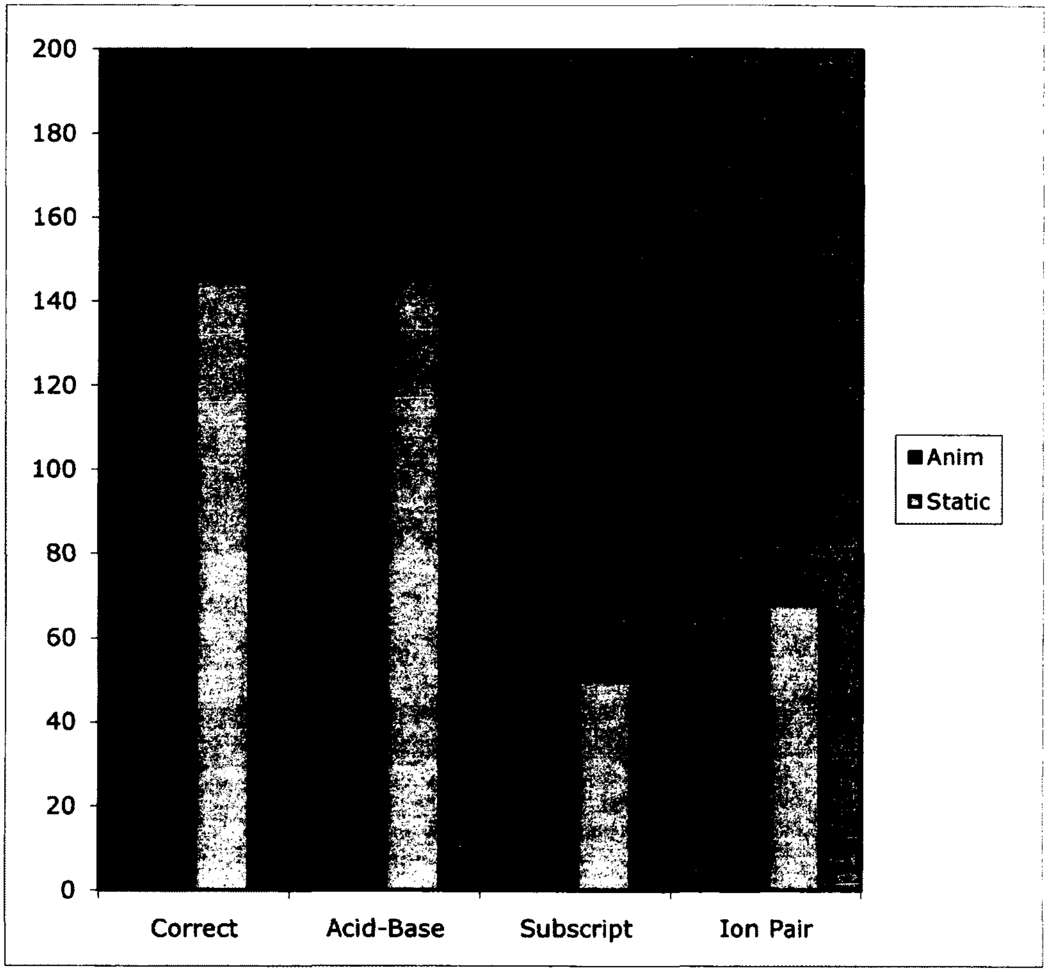


Fig. 4 Distribution of responses for the VIS × ANS association: The 'Acid-Base' choice was more popular for the animated questions than for the static picture questions. Although the 'Correct' and 'Ion Pair' choices appear to be more popular for the static picture questions than for the animated questions, this difference is not statistically significant

Three-way association: Visualization × Representation Order × Answer

The order in which participants saw the symbolic equations and the particulate drawings, coupled with whether they saw dynamic animations or static pictures, had an effect on students' answers to these questions, $\chi^2(3) = 11.50, p = 0.009$. The residuals showed that those participants viewing the symbolic equations first and dynamic animations second (BA group) and those viewing the static pictures first and the symbolic equations second (PB group) were more likely to select the correct answer while participants viewing the symbolic equations first and static pictures second (BP group) and those viewing the dynamic animations first and the symbolic equations second (AB group) were less likely to choose the correct answer. The bar charts for the correct answer responses in Fig. 5 show that when participants viewed the balanced equations first and the particulate representations second (BA and BP groups), they were equally likely to pick the correct response; however, when participants viewed the particulate representations first (AB and PB groups), participants viewing the dynamic animations were much less likely to pick the correct response compared to participants viewing the static pictures.

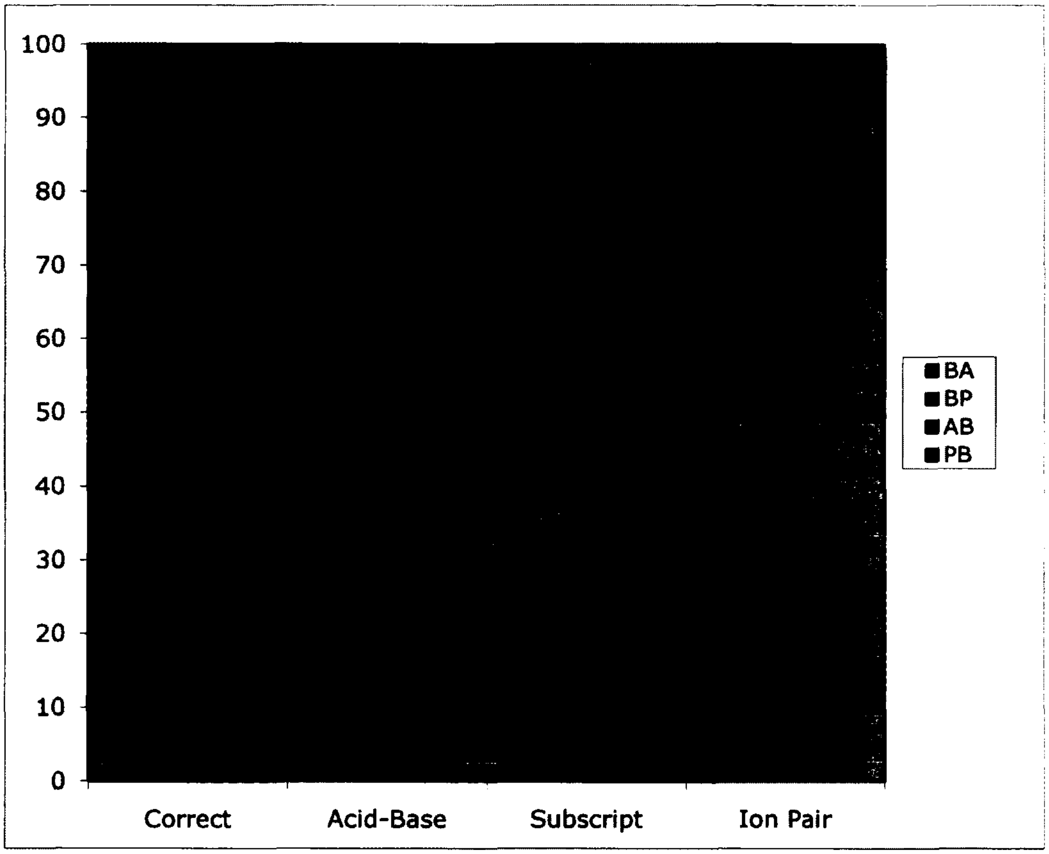


Fig. 5 Distribution of responses for the VIS × RPOR × ANS association: When answering the balanced equations first (BA and BP), there was no difference in the number of participants choosing the 'Correct' choice; however, when answering the particulate representation first, the 'Correct' choice was less popular for the animations (AB) than for the static pictures (PB)

One explanation for this difference is that for participants who viewed the dynamic animations first, the motion in these animations may have proved more distractive compared to the participants who viewed the same pictures without the animated motions. For participants who viewed and answered the symbolic equations first, the type of visualization used in the second question did not seem to have an impact on their responses. Mayer's coherence principle of multimedia learning states that the addition of interesting but irrelevant words, pictures, and sounds to a multimedia lesson can result in diminished student learning (Mayer *et al.,* 1996; Harp and Mayer, 1998; Moreno and Mayer, 2000; Mayer, 2001; Mayer *et al.,* 2001). Although Mayer's principle does not explicitly mention the fact that animated motions may also be distracting, this result is consistent with the spirit of the coherence principle which is ultimately based on cognitive load theory. Cognitive load theory states that learners are limited in the amount of information they can process at any given time, and that information presented that is irrelevant to learning may hinder learning (Baddeley, 1986; Baddeley 1999; Carlson *et al.,* 2004; Sweller, 2008; Sweller, 2010). In this case, the cognitive load the animated motions put on the limited resources of the students' working memory may have caused them to pay less attention to the chemical concept depicted in the animation.

Time-on-task data

The ANOVA results (Table 3) comparing the time participants spent answering the eight questions, based on the visualization type and the representation order, showed a significant difference in the amount of time participants spent answering the dynamic animation and static picture questions: $F(1) = 4.666, p = 0.033$. The average time spent answering all eight questions was 239 seconds for the dynamic animations groups and 276 seconds for the static picture groups. Assuming that the increase in time was spent on the four particulate questions and not the identical symbolic questions, the increase of 37 seconds for the static pictures translates into about 9 seconds more on each of the four particulate questions. Based on the loglinear analysis, it appears that this additional 9 seconds that participants spent on-task trying to understand the static pictures resulted in them being more likely to pick the correct answer.

Conclusions and implications

Of the three student misconceptions regarding the dissolving of ionic compounds in water—acid-base reactions with water, the formation of ion-pairs, and issues with coefficient/subscript errors—that were previously identified by Naah and Sanger (2012), the present study found that the acid-base reaction was the most common misconception and was even more popular than the correct answer. The present study also found that the acid-base response was a more popular choice for the symbolic balanced equations than for the particulate pictures, and that it was slightly more popular for the dynamic animated questions than for the static picture questions. More research is needed to determine if these trends are generalizable to other populations, and to explain why the acid-base choice is more attractive for the symbolic and animated questions.

Although the formation of ion-pairs is a popular misconception that has been reported and corroborated by several chemical education researchers (Butts and Smith, 1987; Taber, 1994; Taber, 1997; Boo, 1998; Liu and Lesniak, 2006; Kelly and Jones, 2007; Tien *et al.*, 2007; Kelly and Jones, 2008; Nyachwaya *et al.*, 2011; Smith and Nakhleh, 2011; Rosenthal and Sanger, 2012), it was a less commonly held misconception in the present study compared to the acid-base reaction. The ion-pair misconception was found to be more popular for the particulate questions than for the symbolic questions, and this result seems consistent with fact that most of the literature has reported this misconception based on students' responses to particulate questions (Butts and Smith, 1987; Taber, 1994; Taber, 1997; Boo, 1998; Liu and Lesniak, 2006; Kelly and Jones, 2007; Tien *et al.*, 2007; Kelly and Jones, 2008; Nyachwaya *et al.*, 2011; Smith and Nakhleh, 2011; Rosenthal and Sanger, 2012).

It is unclear whether the three misconceptions described in the present study represent robust conceptions that are firmly held and consistently demonstrated by students or if they represent random errors or guesses by the students. We are currently working on a research study to evaluate the robustness of these three misconceptions. The present study did find that the acid-base choice was more popular among participants for the symbolic balanced equations while the ion-pair choice was more popular for the particulate pictures. Students choosing different answers for symbolic and particulate questions may not only lack a robust conception regarding the dissolving of ionic compounds in water, but may not have the representational competence needed to see the inconsistencies of their answers at the symbolic and particulate levels (Kozma and Russell, 1997; Bodner and Domin, 2000; Madden *et al.*, 2011).

Participants were more likely to choose the correct answer when viewing the static pictures compared to the dynamic animations, especially if particulate pictures (static or animated) were seen first. Based on the results of the present study, it appears that the best teaching option is PB (static pictures first, then balanced equations). Results of computer animation research in chemistry instruction shows that computer animations are generally effective in helping students improve their conceptual understanding of chemical processes at the particulate level (Williamson and Abraham, 1995; Kozma *et al.,* 1997; Burke *et al.,* 1998; Sanger *et al.,* 2000; Sanger *et al.,* 2001; Kelly *et al.,* 2004; Ardac and Akaygun, 2005; Kelly and Jones, 2007; Sanger *et al.,* 2007; Gregorius *et al.,* 2010a; Gregorius *et al.,* 2010b) but can be distractive if the lesson does not involve visualization, motion, or trajectory (Reiber, 1989; Sanger and Greenbowe, 2000). Since balanced equations can be viewed as a "before and after" snapshot of a chemical reaction that is concerned only with the initial reactants and the final products, and not the mechanism of how the reaction got there, it makes sense that animations of the process could be distracting to students.

The superiority of static pictures over dynamic animations in the present study has implications for instructors and for animation designers: Animated motions in depictions of chemical reactions do not necessarily lead to better learning. The motion in these animations may distract students from focusing on the important or relevant chemical concepts that the animation is intending to convey. As a result, instructors should carefully consider the instructional effectiveness of any animation before selecting it for classroom use. More research is needed to determine those chemistry topics where computer animations of chemical processes at the particulate level lead to improved student learning and those topics where these animations can actually interfere with or diminish student learning.

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CHAPTER FIVE

THE EFFECT OF SUBSCRIPTS AND CHEMICAL REPRESENTATION ON STUDENTS' UNDERSTANDING OF DISSOLVING IONIC COMPOUNDS IN WATER

Abstract

This study used several multiple-choice questions at the symbolic- and particulate-levels to assess students' understanding of the process of dissolving of ionic compounds in water. The distractors for the multiple-choice questions came from the misconceptions identified in a previous study. The symbolic-level multiple-choice questions were based on balanced equations of the ionic compounds dissolving in water while the particulate-level multiple-choice questions used particulate drawings of ionic compounds dissolving in water. Students' responses to these questions were compared for the symbolic- and particulate-level questions for four different ionic compounds either containing or lacking monatomic and polyatomic subscripts. These comparisons showed that the correct response and the acid-base response were more popular than the ion-pair and subscript responses; the acid-base response was more popular for the symbolic questions (especially if there were no monatomic subscripts in the compound); the ion-pair response was more popular for the particulate questions (especially if there were no polyatomic subscripts in the compound); the correct response was more popular if there were no monatomic subscripts in the compound; and the subscript response was more

popular when there were no polyatomic subscripts in the compound (especially for the symbolic questions).

Introduction

Students often have difficulty understanding chemistry concepts, which can result in these students developing misconceptions in chemistry (Nakhleh, 1992, Taber, 2002; Barke *et al.,* 2009). Chemistry misconceptions are commonplace in the minds of students and are independent of international boundaries, as evidenced by the abundance of research studies across the world identifying student misconceptions in chemistry (Osborne and Cosgrove, 1983; Andersson, 1986; Peterson and Treagust, 1989; Stavy, 1990; Garnett and Treagust, 1992; Taber, 1994; Ebenezer and Gaskell, 1995; Sanger and Greenbowe, 1997; Boo, 1998; Furió *et al.,* 2000, Solomonidou and Stavridou, 2000; Ebenezer, 2001; Galley, 2004; Cokelez and Dumon, 2005, Drechsler and Schmidt, 2005; Papaphotis and Tsaparlis, 2008; Schmidt *et al.,* 2009; Mayer, 2011). One of the most studied areas of student misconceptions in chemistry involves students' understanding of the process of dissolving ionic and molecular compounds in water (Butts and Smith, 1987; Ebenezer and Erickson, 1996; Smith and Metz, 1996; Ebenezer, 2001; Ardac and Akaygun, 2004; Liu and Lesniak, 2006; Tien *et al.,* 2007; Kelly and Jones, 2007; Furió-Más *et al.,* 2007; Kelly and Jones, 2008; Barke *et al.,* 2009; Smith and Nakhleh, 2011; Naah and Sanger, 2012). Based on these studies, several common student misconceptions and errors for dissolving ionic compounds have emerged. Although most of these studies have focused on student misconceptions identified using student-generated particulate drawings, the study by Naah and Sanger (2012) is unique in that it looked at student misconceptions based on student-generated symbolic-level balanced equations for dissolving four different ionic compounds in water.

The most misconception/error made by the students in Naah and Sanger's (2012) study (appearing in 27% of all responses) was depicting a chemical reaction between the ionic compounds and water. These reactions typically involved a double displacement (metathesis) reaction in which the cation of the ionic compound joins with the oxygen atom in water to form a metal oxide and the anion joins with the hydrogen atoms in water to form an acid—for example, $K_2O(aq)$ and $H_2SO_4(aq)$ being made from the reaction of $K_2SO_4(s)$ and water. Double displacement reactions between water and an ionic compound dissolving in water have been previously reported (Tien *et al.*, 2007; Kelly and Jones, 2007), but these errors were made by a small fraction of the population under investigation (about 6-7% of all students). While other studies (Ebenezer, 2001; Liu and Lesniak, 2006; Tien *et al.,* 2007; Kelly and Jones, 2007; Smith and Nakhleh, 2011) have reported student comments suggesting that the dissolving compounds chemically interact with water molecules, most of these statements have been rather vague. For example, Ebenezer (2001) reported several student quotes of the reaction of water and salt (NaCl) "molecules" in which the students used phrases like *joined with*, *combining together*, *attract to*, and *attach themselves*. In general, the use of these generic phrases in describing "chemical reactions" between the ionic compounds and water (which may be more indicative of intermolecular/ionic forces) is more common than metathesis reactions (Kelly and Jones, 2007; Tien *et al.*, 2007).

The misconception that ionic compounds dissolve in water as neutral molecules or ion-pairs is probably the most common and prevalent misconception found in the chemical education literature (Butts and Smith, 1987; Smith and Metz, 1996; Ardac and Akaygun, 2004; Liu and Lesniak, 2006; Kelly and Jones, 2007; Tien *et al.*, 2007; Kelly and Jones, 2008; Smith and Nakhleh, 2011; Nyachwaya *et al.,* 2011). This misconception appears when students are asked to specifically describe how ionic compounds dissolve in water (Butts and Smith, 1987; Liu and Lesniak, 2006; Tien *et al.,* 2007; Kelly and Jones, 2007; Smith and Nakhleh, 2011) but also appears when students are asked to describe chemical reactions involving aqueous solutions of ionic compounds (Ardac and Akaygun, 2004; Kelly and Jones, 2008; Smith and Nakhleh, 2011; Nyachwaya *et al.,* 2011). This misconception also appears in student-generated particulate drawings (Butts and Smith, 1987; Smith and Metz, 1996; Ardac and Akaygun, 2004; Liu and Lesniak, 2006; Kelly and Jones, 2007; Tien *et al.*, 2007; Kelly and Jones, 2008; Nyachwaya *et al.*, 2011) and in verbal descriptions of these solutions (Butts and Smith, 1987; Liu and Lesniak, 2006; Tien *et al.*, 2007; Kelly and Jones, 2007; Kelly and Jones, 2008; Smith and Nakhleh, 2011). Several researchers (Butts and Smith, 1987; Taber, 1994;Taber, 1997; Boo, 1998) have reported that many students describe the structure of solid NaCl as containing a single ion-pair/molecule of NaCl (held together by a strong covalent bond) surrounded by and attracted to other NaCl "molecules" by weaker intermolecular forces/ionic bonds. The prevalence and stability of this misconception can be seen by the results of two studies by Kelly and Jones (2007). In the first study 15 of the 18 students (83%) initially created particulate drawings of sodium chloride containing NaCl ion-pairs/molecules. After instruction using computer animations of the dissolving process, only 3 of the 18 students (17%) drew pictures with NaCl ion-pairs. The second study asked the same students to construct particulate drawings of an aqueous NaCl solution one week later, and 50% of these students drew NaCl ion-pairs/molecules. Given that this is a very common and prevalent misconception, it is interesting that only one of the 142 students in Naah and Sanger's study (2012) wrote balanced equations showing neutral ion-pairs/molecules.

In general, chemistry students have difficulty interpreting the difference between subscripts and coefficients and struggle to understand the proper use of each of them. The misconceptions/errors associated with the use and interpretation of subscripts and coefficients (Lazonby, 1982; Savoy, 1988; Smith and Metz, 1996; Furió-Más *et al.,* 2007; Smith and Nakhleh, 2011; Nyachwaya *et al.*, 2011; Naah and Sanger, 2012) come from two different types of subscripts: Monatomic subscripts and polyatomic subscripts. Monoatomic subscripts represent subscripts in ionic compounds that modify a monatomic ion (e.g., the '3' in $AlCl_3$); when ionic compounds dissolve in water, the subscripts for monatomic ions should become coefficients (Al^{3+} + $3Cl^-$). This change from subscript to coefficient denotes the fact that these monatomic ions do not remain attached to each other when the compound dissolves in water. Although we refer to subscripts that denote how many ions are present in an ionic compound as 'monatomic subscripts' in this paper, these subscripts can also modify polyatomic ions like the '2' in $Mg(OH)_2$. A few studies (Smith and Metz, 1996; Nyachwaya *et al.,* 2011) have included examples of student-generated particulate drawings showing confusion between the use of monoatomic subscripts and coefficients. Smith and Metz (1996) provided student drawings showing $NiCl_2(aq)$ as '$Ni + Cl_2$', $Ni(OH)_2(s)$ as '$Ni + (OH)_2$' or '$Ni(OH_2)_2$' (one Ni atom with two H_2O molecules attached), $2NaOH(aq)$ as 'Na_2OH' (two Na and one H atom attached to an O atom), and $2NaCl(aq)$ as 'Na_2Cl' (two Na atoms attached to one Cl atom).

Nyachwaya *et al.*, (2011) provided similar student drawings showing $CaCl_2(aq)$ as '$Ca + Cl_2$' and $CaCO_3(s)$ as '$Ca(CO)_3$' (three CO molecules attached to one Ca atom). Student confusion between the use of subscripts and coefficients has also been reported based on students' verbal explanations and interpretations of symbolic formulas and balanced equations (Lazonby, 1982; Savoy, 1988; Furió-Más et al., (2007); Naah and Sanger, 2012). For example, Furió-Más *et al.*, (2007) reported that one student believed that $H_2SO_4(aq)$ ionizes to produce '$H_2^+ + SO_4^-$'. Naah and Sanger (2012) saw similar formulas like 'H_2^+', 'Br_2^- or Br_2^{2-}', and 'K_2^{2+}' from student-generated equations involving monatomic ions dissolved in water, and found that 39% of student responses involving ionic compounds with monatomic subscripts ($BaBr_2$ and K_2SO_4) had subscript-coefficient errors while only 3% of student responses involving ionic compounds without monatomic subscripts (LiCl and $CaCO_3$) showed these errors. Several researchers have also reported that some students did not know the difference between F_2 and 2F, (Naah and Sanger, 2012), 2K and K_2, (Lazonby, 1982) or the '2's in the formula $2Ag_2O$ (Savoy, 1988).

Polyatomic subscripts represent subscripts embedded within a polyatomic ion that denote how many atoms are present in the polyatomic ion (e.g., the '4' in $CuSO_4$); when ionic compounds dissolve in water, the subscripts for polyatomic ions should remain subscripts ($Cu^{2+} + SO_4^{2-}$) since the polyatomic ion remains intact in aqueous solutions. Several studies (Smith and Metz, 1996; Smith and Nakhleh, 2011; Naah and Sanger, 2012; Nyachwaya *et al.*, 2011) provide examples of students breaking polyatomic ions apart in aqueous solutions. A particulate drawing from one student in Smith and Metz's

(1996) study showed hydroxide ions dissociated in NaOH(aq) (drawn as 'H-Na-O') and $Ni(OH)_2(s)$ (drawn with two separate O atoms and two separate H atoms bonded to a single Ni atom). A similar student drawing for $CaCO_3(s)$ in Nyachwaya *et al.*, (2011) showed one C atom and three O atoms surrounding a single Ca atom; another student in this study wrote $CaCO_3(s)$ as 'Ca^{2+}', 'C^{4+}', and 'O^{2-}' ions dissolved in water. Sanger and Naah, 2012 reported that 15% of the student-generated equations for ionic compounds containing polyatomic ions included answers where the polyatomic ions were dissociated; and Smith and Nakhleh (2011) reported that one student believed that the bonds between all atoms in chalk ($CaCO_3$) would break when it dissolved in oil.

Theoretical framework

Chemists describe chemical phenomena using three different but related chemical representations (macroscopic, particulate and symbolic representations) (Johnstone, 1993; Gilbert and Treagust, 2009; Johnstone, 2010; Telanquer, 2011). The macroscopic representation describes chemical phenomena experienced by the five senses; the particulate representation describes how chemists use models to qualitatively explain chemical phenomena based on atoms, molecules, and ions; and the symbolic representation, which uses chemical symbols to represent atoms and chemical equations, describes how chemists quantitatively explain chemical phenomena using symbols and numbers (Gilbert and Treagust, 2009). The ability of learners to transform one form of representation to the other is described as *representational competence*, and Kozma and Russell (1997) used video segments, graphs, animations, and chemical equations to show that chemical experts had better representational competence in translating from one chemical representation to another compared to novices. The present study is concerned with students' ability to move between the symbolic representation (balanced equations of ionic compounds dissolving in water) and the particulate representation (pictures including the behavior of ions and molecules during the dissolving process), and whether their responses at these two levels are representationally consistent. Other chemical education research studies have shown that while students can solve mathematical (symbolic) chemistry problems, these students often have difficulty answering particulate-level conceptual questions on the same topic (Nurrenbern and Pickering, 1987; Sawrey, 1990; Pickering, 1990; Nakhleh, 1993).

Several researchers have also shown that students have difficulty converting between symbolic-level balanced chemical equations and particulate-level drawings of these reactions (Yarroch, 1985; Al-Kunifed *et al.,* 1993; Smith and Metz, 1996; Sanger, 2005; Nyachwaya *et al.*, 2011). Most of these studies (Yarroch, 1985; Al-Kunifed *et al.,* 1993; Smith and Metz, 1996; Nyachwaya *et al.,* 2011) provided symbolic-level balanced equations and asked students to draw pictures or explain these reactions at the particulate level. On the other hand, Sanger (2005) provided students with a particulate drawing of a chemical reaction and asked students to generate a symbolic-level balanced chemical equation. Of the 156 students in that study, 44% committed subscript-coefficient errors when converting the particulate picture to a balanced chemical equation (e.g., writing '$(CS_2)_3$' to describe three separate CS_2 molecules in the picture). The present study provides students with four possible symbolic-level balanced equations and the equivalent particulate-level pictures of ionic compounds dissolving in water to determine whether students' answers will change based on the representational level of the question. Another goal of this study is to determine whether the presence of monatomic and polyatomic subscripts in the ionic compounds will affect students' answers.

Research Questions

Based on the literature, we initially identified three research questions. The first two questions come from the research (Smith and Metz, 1996; Furió-Más, 2007; Naah and Sanger, 2012; Nyachwaya *et al.,* 2011) showing that students often make subscript-coefficient errors when converting monatomic subscripts in solid ionic compounds into ion coefficients when the compound dissolves in water. The third question comes from the fact that ion-pair responses appear to be a very popular and prevalent misconception based on research studies using particulate-level drawings or explanations (Butts and Smith, 1987; Smith and Metz, 1996; Ardac and Akaygun, 2004; Liu and Lesniak, 2006; Tien *et al.,* 2007, Kelly and Jones, 2007; Kelly and Jones, 2008; Smith and Nakhleh, 2011; Nyachwaya *et al.*, 2011) but were not commonly seen in the one study using symbolic-level balanced equations (Naah and Sanger, 2012). The fourth question comes from the fact that the statistical analysis we are using in this study measures all possible associations of the four variables in this study.

1. Are students more likely to choose the correct answer when the ionic compounds contain no monatomic subscripts compared to compounds with monatomic subscripts?

2. Are students more likely to make a subscript-coefficient error when the ionic compounds contain monatomic subscripts compared to compounds with no monatomic subscripts?
3. Are students more likely to make an ion-pair error when answering the particulate-level questions compared to the symbolic-level questions?
4. Are there any additional associations between students' answers to the multiple-choice questions, the representational level of the question (symbolic or particulate), and the absence or presence of monatomic subscripts and polyatomic subscripts?

Methods

Subjects

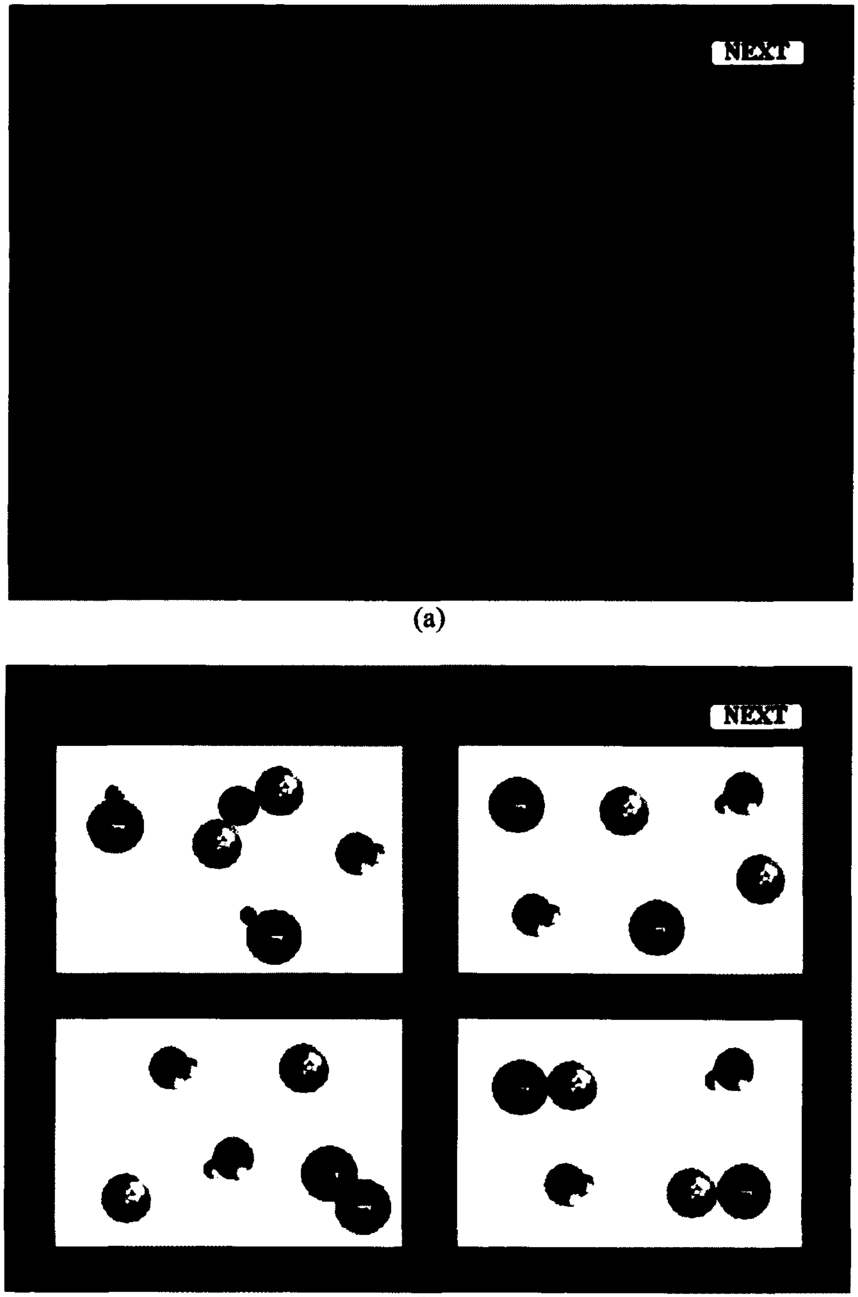
The participants in this study consisted of 98 college students attending a comprehensive southern university. These students were enrolled in a first-semester introductory general chemistry course and had previous instruction in solution chemistry (including writing and balancing equations, ionic and net ionic equations, precipitation reactions, acid-base reactions, and oxidation-reduction reactions). The data for this experiment were collected during a three-hour general chemistry laboratory session.

Experimental design

The subjects were asked to answer eight multiple-choice questions describing what happens when four different ionic compounds dissolve in water. The first ionic compound in the multiple-choice questions was NaBr (a compound with no subscripts), the second was KNO_3 (a compound containing a polyatomic subscript only), the third was $MgCl_2$ (a compound containing a monatomic subscript only), and the fourth was Ag_2SO_4 (a compound with both monatomic and polyatomic subscripts).

For each ionic compound, participants answered two multiple-choice questions: One of these questions contained symbolic-level balanced equations for the ionic compound dissolving in water; the other question contained particulate-level drawings that depicted the dissolving process for the ionic compound. Each symbolic- and particulate-level multiple-choice question had four choices — the correct answer and three distractors. One of the distractors showed the ionic compound reacting with water to form a metal oxide and an acid, another distractor showed the ionic compound dissolving as neutral ion pairs/molecules, and the final distractor showed the ionic compound reacting so that monatomic ions would cluster together or polyatomic ions would fall apart (consistent with students' answers showing a confusion regarding the use of subscripts and coefficients). These distractors were based on student misconceptions identified by the authors in an earlier study (Naah and Sanger, 2012).

The symbolic- and particulate-level multiple-choice questions were created using Macromedia Director 8.5; a screen shot of the symbolic- and particulate-level questions for sodium bromide appear in Figure 1. Choice D in the symbolic question (Figure 1a) and choice B in the particulate question (Figure 1b) depict the correct response. Choice B in the symbolic question and choice A in the particulate question depict the ionic compound reacting with water, while choice C in the symbolic question and choice D in the particulate question depict the ionic compound forming ion pairs. Choice A in the symbolic question (and choice C in the particulate question) depict a common misconception in which the student confuses the use of subscripts and coefficients in symbolic balanced equations, writing $(Br^-)_2$ instead of 2 Br^-. The computerized instrument did not allow students to navigate among the eight multiple-choice questions; they were only allowed to view one question at a time and once they answered the question the program allowed them to move on to the next question. Each student took from 3-5 minutes to complete the eight multiple-choice questions.



(a)

(b)

Fig. 1 Screen shots for the symbolic- (a) and particulate-level (b) questions for dissolving solid sodium bromide in water.

Data Analysis

The students' answers to the eight multiple-choice questions were categorized based on four independent variables. The first variable was the chemical representation used in the question—the balanced equation questions (Figure 1a) used the symbolic representation while the questions with drawings (Figure 1b) used the particulate representation. The second variable was whether the ionic compound contains a monatomic subscript—NaBr and KNO_3 do not, but $MgCl_2$ and Ag_2SO_4 do. The third variable was whether the ionic compound contains a polyatomic subscript—NaBr and $MgCl_2$ do not, but KNO_3 and Ag_2SO_4 do. The last variable was the participants' answer to each question—the correct response, the acid-base reaction, the formation of ion pairs, or the response showing a subscript-coefficient error.

Table 1 Frequency data for the students' responses based on the four independent variables

			Answer			
Representation	Monatomic Subscript	Polyatomic Subscript	Correct	Acid-Base	Ion-Pair	Coefficient Error
symbolic	absent	absent	25	51	1	20
		present	34	53	6	4
	present	absent	25	53	3	16
		present	30	54	6	7
particulate	absent	absent	41	23	26	8
		present	44	20	20	14
	present	absent	18	37	29	14
		present	33	33	21	11

The number (frequency) of students' responses with the same values for the four independent variables was tallied. These data, which appear in Table 1, were statistically analyzed via loglinear analysis using SYSTAT 10.2 (Engelman, 2002). The results for the loglinear analysis appear in Table 2. Loglinear Analysis (an extension of Multiway Frequency Analysis) is used to determine relationships (associations) among three or more categorical variables (Tabachnick and Fidell, 1996; Sanger, 2008). When a relationship exists within a single variable it is referred as a one-way association, when a relationship exists between two variables it is referred as a two-way association, and when a relationship exists among three or four variables it is referred to as a three- or four-way association, respectively. As with chi-square tests of independence, significant associations are determined by computing the difference between the observed and expected frequencies in a cell; the larger this difference, the more likely it is that the variables linked to this cell are involved in a statistically significant association (Cramer, 2003; Foster *et al.,* 2006).

Table 2 Loglinear analysis for the four independent variables

Association	***df***	***χ2***	***p***
Representation, REP	1	15.90	0.000[a]
Monatomic Subscript, MAS	1	0.95	0.330
Polyatomic Subscript, PAS	1	0.18	0.671
Student Answer, ANS	3	202.55	0.000[a]
REP × MAS	1	0.34	0.562
REP × PAS	1	0.06	0.805
REP × ANS	3	99.44	0.000[a]
MAS × PAS	1	0.18	0.667
MAS × ANS	3	11.57	0.009[a]
PAS × ANS	3	12.48	0.006[a]
REP × MAS × PAS	1	0.01	0.928
REP × MAS × ANS	3	7.85	0.049[a]
REP × PAS × ANS	3	16.48	0.001[a]
MAS × PAS × ANS	3	1.34	0.719
REP × MAS × PAS × ANS	3	5.04	0.169

[a] Significant at the $p < 0.05$ level

Tabachnick and Fidell (1996) described four practical issues affecting the power of loglinear analyses. (1) All of the categories must be mutually exclusive, so that each response appears in only one cell. (2) There should be at least five times as many responses as cells in the study. (3) When cases are rare ($N < 5$ in any cell), the marginal frequencies may not be evenly distributed. This is not a problem if the expected cell frequencies for all two-way associations are greater than zero, and no more than 20% are less than five. (4) When performing unsaturated tests, there may be substantial differences between observed and expected frequencies making it impossible for the proposed model to adequately fit the data. All of these criteria have been met by this study (all independent variables are mutually exclusive, there are an average of 24.4 responses per cell, all expected frequencies in the two-way associations are greater than five, and this study uses a saturated model).

Results and discussion

The output from the loglinear analysis listed in Table 2 shows two significant one-way associations (Student Answer and Representation), three significant two-way associations (Representation × Student Answer, Monatomic Subscript × Student Answer, and Polyatomic Subscript × Student Answer) and two significant three-way associations (Representation × Monatomic Subscript × Student Answer and Representation × Polyatomic Subscript × Student Answer). The four-way association was not found to be significant.

One-Way Associations

The one-way association for the Representation variable suggests that students' answers were not equally distributed across the symbolic and particulate questions ($\chi^2(1) = 15.90, p < 0.001$). Each student was asked to answer four symbolic questions and four particulate questions, one for each ionic compound, so the number of responses in these two categories should be identical. The reason why these two numbers are different is because one student answered all four particulate questions but did not answer any of the symbolic questions. Therefore, although the percentage of symbolic-level answers (49.7%) was found to be significantly lower than the percentage of particulate-level answers (50.3%), this difference does not appear to be particularly useful in explaining students' responses to these questions.

The one-way association for the Student Answer variable ($\chi^2(3) = 202.55, p < 0.001$), suggests that the students' answers were not equally distributed among the four choices of the multiple choice questions. Overall, 32% of the participants chose the correct response, 41% chose the response showing an acid-base reaction with water, 14% chose the ion-pair response, and 12% chose the response reflecting a subscript-coefficient error. These data are depicted in a bar chart in Fig. 2.

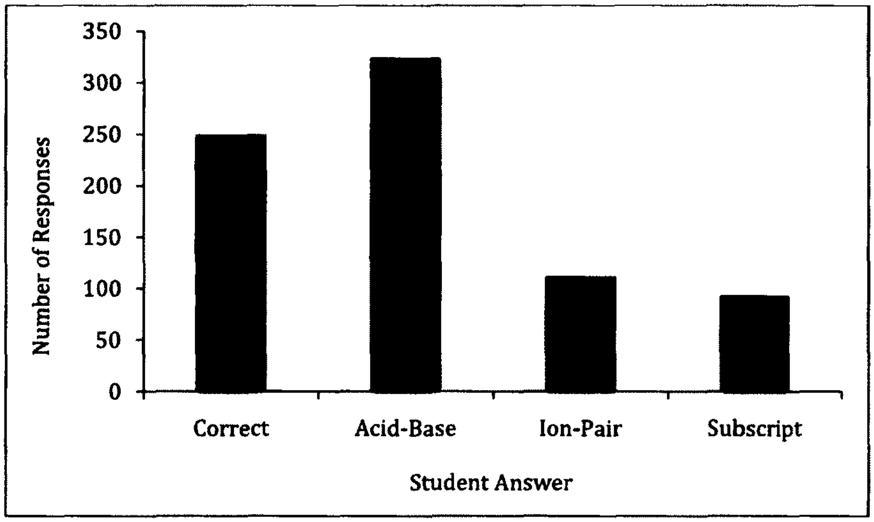


Figure 2. Distribution of students' answers for the eight questions. More students chose the 'Correct' and 'Acid-Base' responses and fewer students chose the 'Ion-Pair' and 'Subscript' responses.

Based on the one-way association for the Student Answer variable, students were more likely to choose the correct or acid-base responses than they were to choose the ion-pair or subscript responses. The popularity of the acid-base response among students over the ion-pair or the subscript responses is consistent with the misconceptions results previously reported by Naah and Sanger (2012). One possible explanation for why the acid-base response was the most popular answer is that most chemistry textbooks, including the one used by the students in this study (More *et al.*, 2010) and many chemistry instructors teach students about writing balanced equations for acid-base reactions in the same chapter, and usually right after, discussing the dissolution of ionic compounds in water and the precipitation of ionic compounds from aqueous solutions. It is possible that discussing these two topics so closely together leads to student confusion/conflation of these two ideas. Although this study showed that students were less likely to confuse subscripts and coefficients or believe in ion-pairs when choosing their answers, several other researchers have reported that confusion between the use of subscripts and coefficients (Lazonby *et al.*, 1983; Yarroch, 1985; Savoy, 1988; Al-Kunifed *et al.*, 1993; Sanger, 2005; Nyachwaya *et al.*, 2011; Naah and Sanger, 2012) or comments suggesting that ionic "molecules" or ion-pairs exist in aqueous solutions (Butts and Smith, 1987; Taber, 1994; Taber, 1997; Liu and Lesniak , 2006 ; Tien *et al.*, 2007; Kelly and Jones, 2007; Kelly and Jones, 2008; Nyachwaya *et al.*, 2011; Smith and Nakhleh, 2011) are popular among the participants in their studies. One reason for the difference in students' responses could be that most of these studies used free-response questions to identify student errors regarding the use of subscripts and coefficients (Yarroch, 1985; Al-Kunifed *et al.*, 1993; Sanger, 2005; Nyachwaya *et al.*, 2011) and the presence of ion pairs (Taber, 1994; Butts and Smith, 1987; Liu and Lesniak, 2006; Tien *et al.*, 2007; Kelly and Jones, 2007; Kelly and Jones, 2008; Nyachwaya *et al.* 2011; Smith and Nakhleh 2011) while the present study used multiple-choice questions to assess students' conceptions regarding the dissolving process.

Two-Way Associations

The two-way Representation-Student Answer association ($\chi^2(3) = 99.44, p < 0.001$) identifies a variation in students' answers depending on whether they were answering the symbolic-level questions (balanced equations) or the particulate-level questions (pictures depicting molecules and ions). Figure 3 contain a bar chart of these data. The calculated residuals from this association suggest that the acid-base response was a more popular choice for the symbolic-level questions than for the particulate-level questions, while the ion-pair response was a more popular choice for the particulate-level questions than for the symbolic-level questions.

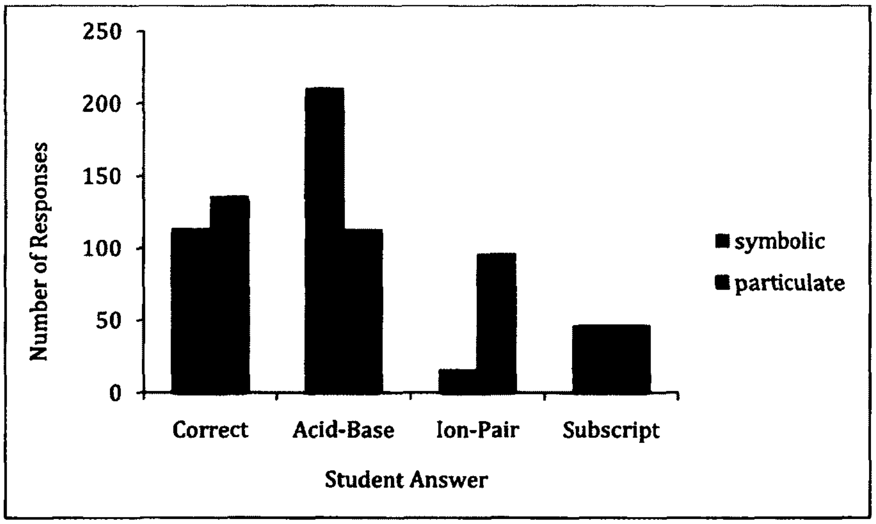


Fig. 3 Distribution of students' answers for the symbolic- and particulate-level questions. For the symbolic-level questions (blue), the 'Acid-base' response was more popular and the 'Ion-Pair' response was less popular compared to the particulate-level questions (r

The popularity of the acid-base response for the symbolic balanced equations over the particulate pictures is also consistent with the hypothesis that students confuse dissolution and acid-base reactions because they are taught these two topics consecutively. Most chemistry textbooks focus on teaching students to write symbolic-level balanced chemical equations for dissolution and acid-base reactions over constructing or evaluating particulate drawings of these processes. So, students are more likely to confuse these concepts (and chose the acid-base response for the dissolving process) when answering the symbolic-level questions in this study. The popularity of the ion-pair response for the particulate-level questions over the symbolic-level questions can perhaps shed light on the fact that although the one-way Student Answer association described above found that the ion-pair response was not a popular choice among students in this study, the existing chemical education literature is filled with examples of student responses consistent with this error (Butts and Smith, 1987; Taber, 1994; Taber, 1997; Liu and Lesniak, 2006; Tien *et al.*, 2007; Kelly and Jones, 2007; Kelly and Jones, 2008; Nyachwaya *et al.* 2011; Smith and Nakhleh, 2011). In each of those literature studies, their students' conceptions were probed at the particulate-level. Looking at the distribution of student responses to the particulate-level questions in Figure 3 (the red bars) shows that the ion-pair response represents a significant proportion of the students' responses to the particulate-level questions in this study as well. However, the ion-pair response appears to be very unpopular for symbolic-level questions (the blue bars), which is consistent with the fact that Naah and Sanger (2012) only one student out of 142 write symbolic-level balanced equations that included ion-pairs. This association suggests that students *are* more likely to make an ion-pair error when answering the particulate-level questions compared to the symbolic-level questions (Research Question 3).

The Monatomic Subscript-Student Answer association ($\chi^2(3) = 11.57, p = 0.009$) suggests that students selected different answers based on whether the question contained a monatomic subscript or not. The residuals showed that students were more likely to select the correct answer when the ionic compound had no monatomic subscript (NaBr and KNO_3) than if it had a monatomic subscript ($MgCl_2$ and Ag_2SO_4); (Fig. 4) contains a bar chart depicting these results.

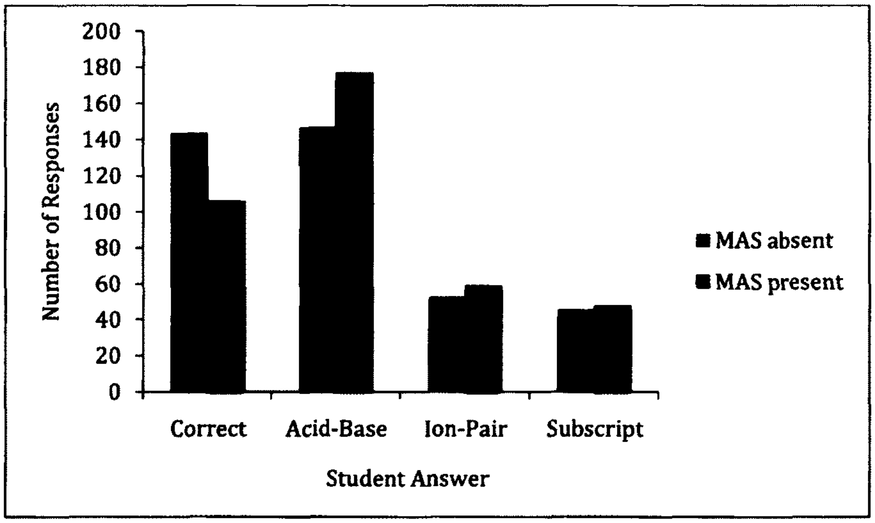


Fig. 4 Distribution of students' answers for questions with and without monatomic subscripts. The 'Correct' response was more popular when the ionic compound did not contain a monatomic subscript and less popular when the ionic compound did have a monatomic subscript.

Any subscripts appearing in ionic compounds without monatomic subscripts would be part of polyatomic ions that remain intact during the dissolving process. So, any subscripts in these compounds would remain subscripts when the compound has dissolved. However, if the ionic compound had monatomic subscripts, then students need to recognize that these subscripts will become coefficients once the ionic compound has dissolved. Therefore, it is reasonable that students would have more difficulty choosing the correct answer for ionic compounds containing monatomic subscripts. Student difficulty in dealing with the appropriate use of subscripts and coefficients has been widely reported in the chemical education literature (Lazonby, 1982; Yarroch, 1985; Savoy, 1988; Al-Kunifed *et al.,* 1993; Sanger, 2005; Nyachawa *et al.,* 2011; Naah and Sanger, 2012). This association is consistent with the study done by Naah and Sanger (2012) which reported that students generating their own balanced equations for ionic compounds dissolving in water were more likely to write equations showing confusion regarding the use of subscripts or coefficients for ionic compounds containing monatomic subscripts ($BaBr_2$ and K_2SO_4) compared to ionic compounds without monatomic subscripts (LiCl and $CaCO_3$) and is in agreement with Research Question 1. However, this association did *not* show that students were more likely to make a subscript-coefficient error when the ionic compounds contain monatomic subscripts compared to compounds with no monatomic subscripts (Research Question 2).

The Polyatomic Subscript-Student Answer association ($\chi^2(3) = 12.48, p = 0.006$) shows that students selected different answers based on whether the question contained a polyatomic subscript or not. Based on the residuals from this association, it appears that students were more likely to select the subscript response when the ionic compound had no polyatomic subscript (NaBr and $MgCl_2$) than when the ionic compound did contain a polyatomic subscript (KNO_3 and Ag_2SO_4). A plot of these data appears in Figure 5.

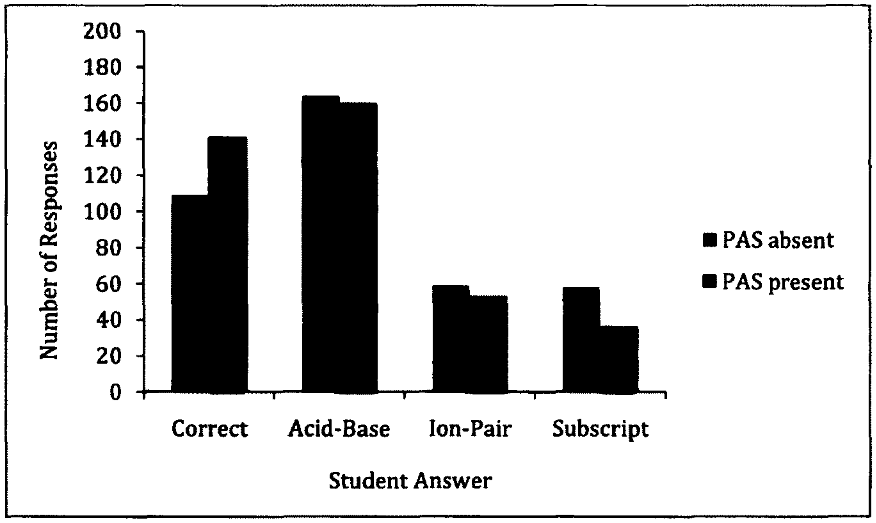


Fig. 5 Distribution of students' answers for questions with and without polyatomic subscripts. The 'Subscript' response was more popular when the ionic compound did not contain a polyatomic subscript and less popular when the ionic compound did have a polyatomic subscript.

For the ionic compounds without polyatomic subscripts, the subscript response contained the bromide ions in NaBr and the chloride ions in $MgCl_2$ forming diatomic halogen ions, $(X^-)_2$(aq). For the ionic compounds with polyatomic subscripts, the subscript response contained the silver ions in Ag_2SO_4 forming the $(Ag^+)_2$(aq) ion and the nitrate ions in KNO_3 falling apart into N^-(aq) and O_3(aq) for KNO_3. The number of students choosing the subscript response was 28 for NaBr, 30 for $MgCl_2$, 18 for KNO_3, and 18 for Ag_2SO_4. The reason why the number of subscript responses for KNO_3 was lower than that for NaBr or $MgCl_2$ could be because students recognized nitrate as a polyatomic ion and were less likely to choose an answer depicting the dissociation of a polyatomic ion. When students were asked to generate balanced equations for dissolving solid K_2SO_4 in water in a previous study (Naah and Sanger, 2012) only 6% of these students wrote equations depicting the sulfate ion dissociating into smaller parts compared to 38% writing equations showing subscript/coefficient errors involving the monatomic potassium ion. The reason why the number of subscript responses for Ag_2SO_4 was lower than that for NaBr or $MgCl_2$ could also be explained by a student quote reported in that previous study (Naah and Sanger, 2012). This student wrote balanced equations that showed solid $BaBr_2$ forming Ba^{2+}(aq) and Br_2^-(aq) ions but showed solid K_2SO_4 forming $2K^+$(aq) and SO_4^{2-} (aq) ions. When asked to explain why the bromide ions were stuck together but the potassium ions were separate, the student responded that "Elements like O_2, Br_2 are stuck together. They just can't exist alone." This response shows that this student was confusing the behaviors and properties of neutral atoms with those of ions of the same element. The significant association shows that students in this study were also more likely to choose responses containing diatomic ions of chloride and bromide than of silver, perhaps because elemental chorine and bromine are diatomic but elemental silver is not. Although this misconception was identified by Naah and Sanger based on a single student quote, this study appears to corroborate this misconception and may suggest that this misconception is more common and might be held by more than a single student.

Three-Way Associations

The Representation-Monatomic Subscript-Student Answer association ($\chi^2(3)$ = 7.85, $p = 0.049$) suggests that student responses were different for the symbolic- and particulate-level questions depending on whether the ionic compounds in these questions had monatomic subscripts or not. These data are depicted in a bar chart in Fig. 6.

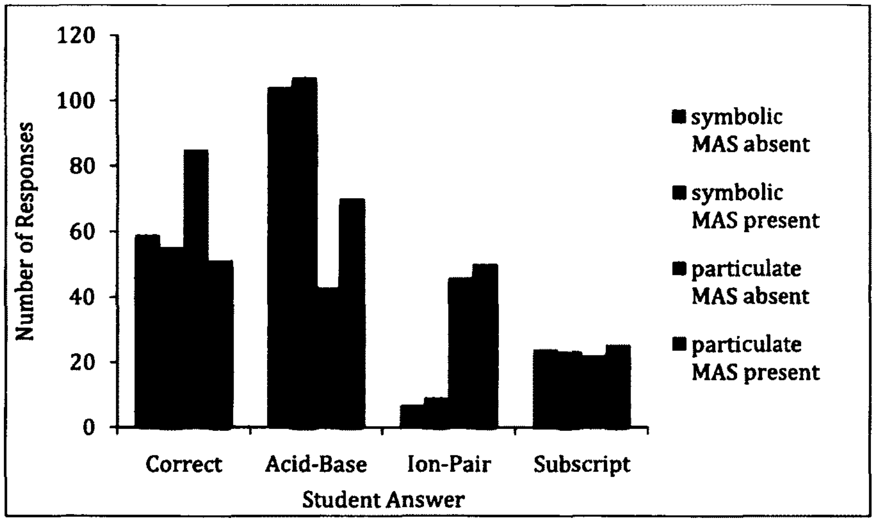


Fig. 6 Distribution of students' answers for the symbolic- and particulate-level questions with and without monatomic subscripts. The 'Acid-Base' response was more popular for the symbolic/MAS absent (light blue) and particulate/MAS present (dark red) cases and less popular for the symbolic/MAS present (dark blue) and particulate/MAS absent (light red) cases.

The residuals from this association showed that the acid-base response was more popular for the symbolic-level questions with no monatomic subscripts and for the particulate-level questions with monatomic subscripts present, while the acid-base response was less popular for the symbolic-level questions with monatomic subscripts present and for the particulate-level questions with no monatomic subscripts. According to Tabachnick and Fidell (1996), three- and higher-way associations can be difficult to explain or understand. Since the two-way Representation-Student Answer association (Figure 3) showed an association based on students' responses involving the acid-base response, it might be easiest to relate the analysis of this three-way association to that two-way association. From two-way association data, 65% of all acid-base responses were made by students answering symbolic-level questions, while 35% of all acid-base responses were made to particulate-level questions. These percentages are 71%/29% for the symbolic/particulate-level questions involving ionic compounds without monatomic subscripts (NaBr and KNO_3) and 60%/40% for the symbolic/particulate-level questions involving ionic compounds with monatomic subscripts ($MgCl_2$ and Ag_2SO_4). Although the acid-base response is about twice as popular for students when answering the symbolic-level questions compared to the particulate-level questions, this disparity is more pronounced for the questions involving ionic compounds without monatomic subscripts.

The Representation-Polyatomic Subscript-Student Answer association ($\chi^2(3) = 16.48, p = 0.001$) suggests that student responses were different for the symbolic- and particulate-level questions depending on whether the ionic compounds in these questions had polyatomic subscripts or not (Fig. 7).

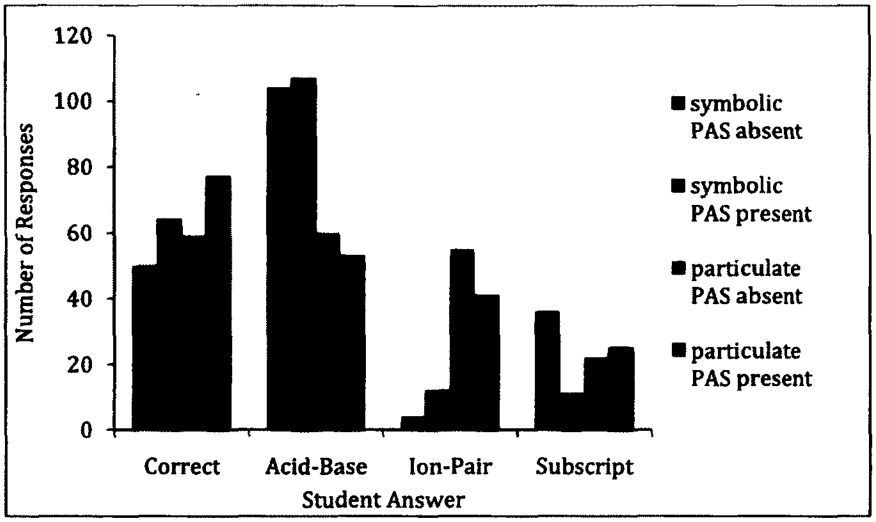


Fig. 7 Distribution of students' answers for the symbolic- and particulate-level questions with and without polyatomic subscripts. The 'Ion-Pair' response was more popular for the symbolic/PAS present (dark blue) and particulate/PAS absent (light red) cases and less popular for the symbolic/PAS absent (light blue) and particulate/PAS present (dark red) cases. The 'Subscript' response was more popular for the symbolic/PAS absent (light blue) and particulate/PAS present (dark red) cases and less popular for the symbolic/PAS present (dark blue) and particulate/PAS absent (light red) cases.

The residuals from this association showed that the ion-pair response was more popular for the symbolic-level questions with polyatomic subscripts present and for the particulate-level questions with no polyatomic subscripts, while the ion-pair response was less popular for the symbolic-level questions with no polyatomic subscripts and for the particulate-level questions with polyatomic subscripts present. The residuals also showed that the subscript response was more popular for the symbolic-level questions with no polyatomic subscripts and for the particulate-level questions with polyatomic subscripts present, while the subscript response was less popular for the symbolic-level questions with polyatomic subscripts present and for the particulate-level questions with no polyatomic subscripts. For consistency, the significant residuals from this three-way association will be compared to the significant residuals from the two-way associations discussed previously.

For the ion-pair responses, this three-way association can be compared to the two-way Representation-Student Answer association (Fig. 3). The data from this two-way association showed that 14% of all ion-pair responses were made by students answering symbolic-level questions, while 86% of all ion-pair responses were made to particulate-level questions. These percentages are 7%/93% for the symbolic/particulate-level questions involving ionic compounds without polyatomic subscripts (NaBr and $MgCl_2$) and 23%/77% for the symbolic/particulate-level questions involving ionic compounds with polyatomic subscripts (KNO_3 and Ag_2SO_4). Although the ion-pair response is about six times as popular for students when answering the particulate-level questions compared to the symbolic-level questions, this disparity is greater for the questions involving ionic compounds without polyatomic subscripts.

For the subscript responses, this three-way association can be compared to the two-way Polyatomic Subscript-Student Answer association (Fig. 5). The data from this two-way association showed that 62% of all subscript responses were made by students involving ionic compounds without polyatomic subscripts (NaBr and $MgCl_2$), while 38% of all subscript responses were made to questions involving ionic compounds with polyatomic subscripts (KNO_3 and Ag_2SO_4). For the symbolic-level questions, these percentages are 77%/23% for the ionic compounds without/with polyatomic subscripts; for the particulate-level questions, these percentages are 47%/53% for the ionic compounds without/with polyatomic subscripts. Although the subscript response is more popular for the ionic compounds without polyatomic subscripts overall, this disparity is greater for the symbolic-level questions; for the particulate-level questions, the subscript response seems to be equally popular for the ionic compounds with and without polyatomic subscripts. The preference of choosing $(Cl^-)_2(aq)$ and $(Br^-)_2(aq)$ as valid responses over $(Ag^+)_2(aq)$ or $N^-(aq) + O_3(aq)$ was originally identified from students' self-generated symbolic-level balanced equations (Naah and Sanger, 2012). It appears that this particular misconception is not as prevalent among students answering particulate-level questions. It could be that the symbolic formulas prompted students to think about the neutral diatomic Cl_2, Br_2, or Ag_2 molecules (and the stability and likelihood of the first two over the third one) more strongly than the particulate pictures did.

Conclusions

All of the meaningful associations identified in this study involved differences in the distribution of students' answers to the questions used in this study. While the correct response was more popular than the ion-pair or coefficient-subscript responses, it was not as popular as the acid-base response. One reason why students might be confusing dissolution reactions with acid-base reactions is that these concepts are often presented in textbooks and instructor lectures one right after the other. This proximity may cause students to run these two ideas together in their minds as they are studying this material. This study also found that students were more likely to choose the correct answer for ionic compounds lacking monatomic subscripts (like NaBr and KNO_3) compared to ionic compounds containing monatomic subscripts (like $MgCl_2$ and Ag_2SO_4). In compounds with monatomic subscripts, the subscript in the compound must become a coefficient in the balanced equations. Several chemical education researchers (Lazonby, 1982; Yarroch, 1985; Al-Kunifed *et al.,* 1993; Sanger, 2005; Nyachawa *et al.,* 2011; Naah and Sanger, 2012) have shown that students have difficulty properly distinguishing between the proper use of subscripts and coefficients, what each of them tells us, and how they differ from each other.

The acid-base response was the most popular response among students, and students were more likely to choose the acid-base response when answering the symbolic-level than the particulate-level questions. It is certainly possible that the way we chose to depict the acid-base responses in the particulate-level questions may have made these reactions appear less likely or valid to the students in this study. However, we are hypothesizing that the reason for the difference in the distribution of acid-base responses between the symbolic- and particulate-level questions is due to the popularity of the acid-base response for the symbolic-level questions. Most textbooks (and presumably many chemistry instructors) tend to focus on the symbolic-level balanced equations when teaching students about the dissolving process, precipitation reactions, and acid-base reactions over similar particulate-level pictures. As a result, the balanced equations present in the symbolic-level questions of this study may be triggering the "acid-base balanced equation" algorithm/schemata in many of these students, making this response more popular than the other responses. Presumably, the drawings in the particulate-level questions look different enough to these students that they are not triggering this algorithm. More research is needed to determine whether this hypothesis is valid and supported by additional data, and perhaps to explain why the preference of the acid-base response for the symbolic-level questions over the particulate-level questions is more pronounced when the ionic compounds contain no monatomic subscripts.

Although the ion-pair response was less popular than the correct response or the acid-base response, it did appear to be a more popular response to the particulate-level questions than the symbolic-level questions and this difference was greater for ionic compounds without polyatomic subscripts. The increased popularity of the ion-pair response for the particulate-level questions can help explain why so many researchers (Boo, 1987; Butts and Smith, 1987; Taber, 1994; Taber, 1997; Liu and Lesniak, 2006; Tien *et al.,* 2007; Kelly and Jones, 2007; Kelly and Jones, 2008; Smith and Nakhleh, 2011) had identified ion pairs as a common and prevalent student misconception based on particulate-level explanations, but Naah and Sanger (2012) found so few students writing symbolic-level balanced equations showing ion pairs. More research is needed to determine whether the way the ion pairs were depicted in the particulate-level questions in this study made this response more attractive or whether the ion-pair response was simply less popular for the symbolic-level balanced equation questions. It is possible that the ion-pair response was less popular for the symbolic-level questions because textbooks and instructors point out that ionic compounds do not remain intact when dissolved in water when they introduce the concepts of overall equations (sometimes incorrectly called “molecular” equations), complete ionic equations, and net ionic equations. For example, the reaction ($NaBr(s) \rightarrow NaBr(aq)$ represents the overall equation, but would be written as $NaBr(s) \rightarrow Na^+(aq) + Br^-(aq)$ for the complete ionic and net ionic equations).

The response that showed the ionic compounds reacting in ways that would result in the incorrect use of subscripts and coefficients was less popular than the correct response or the acid-base response. However, the subscript response was more popular for ionic compounds without polyatomic subscripts (NaBr and $MgCl_2$) compared to ionic compounds with polyatomic subscripts (KNO_3 and Ag_2SO_4), and this difference was more pronounced for symbolic-level questions compared to the particulate-level questions. In part, these results suggest that most students recognized that polyatomic ions will not further dissociate in water, which is consistent with the free-response data provided by Naah and Sanger’s (2012) participants. The fact that students were less likely to chose a response showing the dissociation of a polyatomic ion for the symbolic-level questions (compared to the particulate-level questions) is not surprising since students are encouraged to memorize the (symbolic) chemical formula for these ions when they are introduced. These results also showed that students were more likely to choose ion dimers of $(Cl^-)_2$ and $(Br^-)_2$ ions compared to $(Ag^+)_2$ ions. These results corroborate an interview quote from a single student in a previous study (Naah and Sanger, 2012) in which the student stated that solid $BaBr_2$ would form Br^-_2 ions when dissolved in water but solid K_2SO_4 would form $2K^+$ ions when dissolved because elemental bromine forms dimers but elemental potassium does not. The fact that the preference of chloride or bromide dimers over the silver dimer was stronger for the symbolic-level questions (compared to the particulate-level questions) could be explained by the fact that the symbolic-level formulas triggered students schemata regarding the relative likelihood of neutral Cl_2, Br_2, and Ag_2 molecules (since many textbooks and/or instructors provide a list of symbolic formulas of stable diatomic elements) while the drawings in the particulate-level questions did not. Additional research studies would be helpful in determining if other students preferring chloride or bromine ion dimers over silver ion dimers are using the stability of diatomic elements to justify their answers.

Based on the results of this study, we were able to corroborate our hypotheses that students were more likely to choose the correct answer when the ionic compounds contain no monatomic subscripts compared to compounds with monatomic subscripts (Research Question 1) and that students were more likely to make an ion-pair error when answering the particulate-level questions compared to the symbolic-level questions (Research Question 3). However, these results did not corroborate our hypotheses that students were more likely to make a subscript-coefficient error when the ionic compounds contain monatomic subscripts compared to compounds with no monatomic subscripts (Research Question 2).

This study was able to identify several other significant associations related to students' answer to a series of multiple-choice questions concerning the dissolution of ionic compounds in water at the symbolic- and particulate-levels, and many of these associations supported and corroborated misconceptions previously identified by interviews and student-generated balanced equations using different samples of students enrolled in the same class at the same university during different semesters (Naah and Sanger, 2012). Additional research should be performed using the same or a similar research instrument with students from different populations (at different universities or high schools from different regions of the United States or abroad) to determine whether the same associations are significant with these other populations. Associations that are significant across several populations are more likely to represent common student errors or misconceptions that are not unique to a single group of students. These studies should also include student interviews in which students' opinions or explanations can be used along with the statistical comparisons to support these identified misconceptions via triangulation. We are currently working on another manuscript in which we are trying to determine whether the three incorrect responses used as distractors in this study (acid-base reactions, ion-pair formation, and subscript-coefficient errors) represent robust student conceptions or were chosen as a result of random guessing.

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CHAPTER SIX

SYNTHESIS AND CHARACTERIZATION OF FUNCTIONALIZED MESOPOROUS CARBON ACID CATALYST FOR BIODIESEL PRODUCTION

Introduction

Biodiesel, which consist of fatty acid methylesters or fatty acid ethylesters, are often made from seed oils and renewable biomass using sodium hydroxide (NaOH) or potassium hydroxide (KOH) catalysts. These catalysts, which are referred as homogenous catalysts, also cause emulsion and soap to form in the biodiesel, adding an extra cost in the production process. This extra cost often involves significant amount of washing to remove residual NaOH, soap, and emulsion from the final product. Because of the extra cost involved in purifying biodiesel, heterogeneous catalysts are becoming an attractive alternative to conventional homogeneous catalysts. Unlike homogeneous catalysts, heterogeneous catalysts do not form soap and emulsion in the reaction mixture; they also can be recovered and reused after the reaction is complete. Most of the solid-supported heterogeneous catalysts reported in literature are based on basic metal oxides such as KNO_3/Al_2O_3 (Vyas *et al.,* 2009), CaO (Kawashima *et al.,* 2009), KOH/Al_2O_3 and KOH/NaY(Noiroj *et al.,* 2009), Mg/La mixed oxides (Babu *et al.,* 2008), NaOH/alumina (Arzamendi *et al.,* 2007) and MgO/silica (Li and Rudolph, 2008). The only known solid acid catalysts for transesterification reaction are the sulfonated amorphous carbon and sulfated zirconia (Okamura *et al.,* 2006, Fu *et al.,* 2008).

The present study explores a new method for preparing an acidic mesoporous carbon catalyst suitable for the transesterification reaction involved in biodiesel synthesis. Besides avoiding the need to wash the biodiesel to remove residual NaOH and soap, acidic solid catalysts can also tolerate free fatty acids and moisture present in waste cooking oil (Arzamendi *et al.,* 2007, Barakos *et al.,* 2008). The biodiesel produced from solid acid catalysts not only avoids an extra step of neutralization but also its less corrosive to engine parts. Recently, Okamura *et al.,* (2006) showed that sulfonated amorphous carbon prepared from partial carbonization of glucose compared to sulfuric acid was effective in catalyzing the hydration reaction of 2,3-dimethyl-2-butene to generate 2,3 dimethyl-2-butanol. As a result mesoporous carbon may hold promise as a catalyst in the synthesis of fatty acid esters of various carbon chain lengths. The goal of the present study is to synthesize and characterize sulfonated mesoporous carbon for the transesterification reaction involving vegetable oil and ethanol.

Experimental methods

Materials

The chemicals used for preparing mesoporous carbon—Pluronic F-127, phloroglucinol, and formaldehyde—were purchased from Sigma-Aldrich (St. Louis, MO). The vegetable oil, fuming sulfuric acid (30% free SO_3 basis), and hydrochloric acid (36.5-38 %) were purchased from Thermo Fisher Scientific (Waltham, MA). The copper grids for supporting the mesoporous carbon samples were obtained from Ted Pella (Redding, CA).

Instrumentation

A tube furnace (Thermolyne Model 5930), a graphite furnace (Thermal Technology Model 1000-2560-FP2), and the Eppendorf 5840 centrifuge were used for the carbon synthesis. Thermogravimetric analysis (TGA) was performed on TA Instrument Q50 TGA over the temperature range of 25 °C to 600 °C. The N_2 sorption analysis of the carbon samples was measured with Micrometrics Gemini analyzer. The specific surface area was calculated using the Brunauer-Emmett-Teller (BET) method from the nitrogen adsorption data in the relative range (P/Po) of 0.06-0.30. The total pore volume was determined from the amount of N_2 uptake at P/Po =0.95. The Hitachi HD-2000N scanning transmission electron microscope (STEM) was operated at the voltage of 200 kV.

Synthesis of mesoporous carbon-127 (MPC-127)

The rationale behind the synthesis procedures of MPC-127 was reported in previous publications (Liang et al., 2008, Liang *et al.,* 2006) and summarized in the following procedure.

Pluronic F127 (50.4 g), phloroglucinol (25.2 g), and HCl (10 g) were mixed in 1300 mL of distilled water and the reaction mixture refluxed at about 400 °C and stirred vigorously until the solution appeared yellow and homogenous. Formaldehyde (26 g) was added to the yellowish solution and the reaction mixture refluxed for an additional two hours. The solution was vacuum filtered to give a yellowish solid material. This solid material was dried at 120 °C for three hours and later carbonized in a tube furnace at 850 °C for 12 hours under a constant flow of N_2.

Sulfonation of MPC-127

MPC-127 (0.189 g) was added to 3.0 mL of fuming sulfuric in a round bottom flask fitted with a condenser. The mixture was purged with nitrogen and refluxed at 150 °C for 16 hours under continuous stirring. The solution, which appeared dark, was transferred into a centrifuge tube and centrifuged at 7500 rpm for 10 minutes. The supernatant was decanted and washed several times until the water (80 °C) from the washed sulfonated MPC-127 tested neutral (pH 7). The final product, sulfonated MPC-127, was dried at 80 °C for 12 hours.

Results and discussion

We were able to synthesize MPC-127 from Pluronic F127 (a block co-polymer of polyethylene oxide and polypropylene oxide (PEO-PPO-PEO)), and phloroglucinol because of the ability of these chemicals to self-assembly to form an ordered framework. The hydrogen bonding in the framework stabilizes the assembly through the hydroxyl groups of phloroglucinol and the oxygen in the polymer chain of Pluronic F127. Polymerization of the phloroglucinol units with formaldehyde, and subsequent carbonization at a temperature of 850 °C generated the mesoporous carbon structure. The one-pot synthesis reaction of the highly ordered mesoporous carbon appears in Fig. 1.

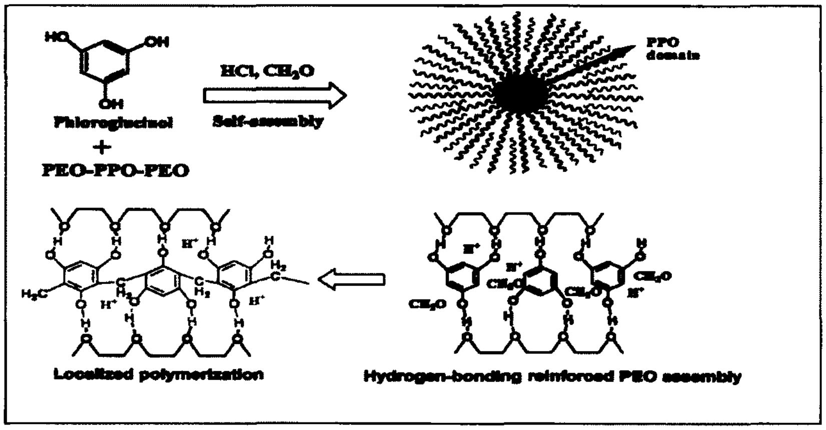

Fig. 1. One-pot synthesis of highly ordered MPC-127

The acidic conditions used in the current synthesis coupled with the use of phloroglucinol caused formaldehyde and phloroglucinol to polymerize faster than previous synthesis that used resorcinol and formaldehyde. This faster reaction led to a more highly ordered mesoporous carbon framework (Liang and Dai, 2006). Besides the varying reactivity of the phenolic precursors, the acid concentration also affected the properties of the mesoporous carbon. The more highly acidic synthetic conditions promoted facile self-assembly through coulombic interaction and hence a greater degree of structural order and thermal stability.

The carbonization of the self-assembled polymer beads produced mesoporous carbon particles (MPC-127) of fairly similar sizes. The porous structure of MPC-127 was observed to be fairly uniform. Because the sulfonic acid groups inhibited the electronic conductivity of the carbon surface, the SEM image of the sulfonated MPC-127 (which appears in Fig. 2) showed a lower image contrast compared to the original MPC-127. Elemental analysis of the functionalized MPC-127 (which appears in Fig. 3) showed the presence of sulfur, oxygen and carbon, confirming that the sulfonic acid functional group was successfully introduced into the carbon matrix. Because the sample was supported on copper grids, small signals of copper were also observed in the elemental analysis.

Fig. 2 Scanning electron micrograph of the MPC-127 mesoporous carbon structure

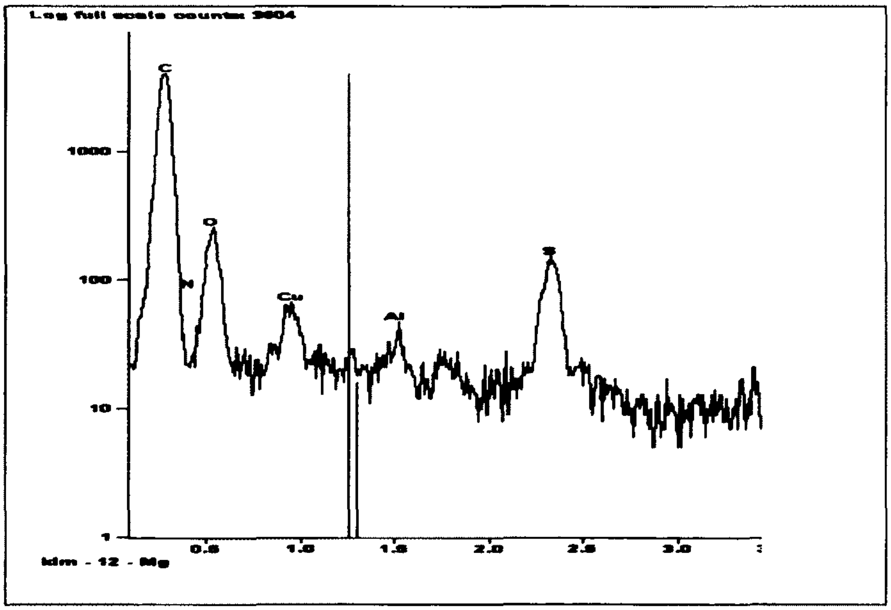

Fig. 3 Energy-dispersive X-ray microanalysis of functionalized MPC-127

The nitrogen sorption isotherm of MPC-127 shows a steep plot indicating a well-ordered mesostructure that is consistent with previous studies.[10-12] The MPC-127 mesoporous carbon samples produced from various batches have a BET surface area and pore size of 354.2±9.46 m^2/g and 5.88±0.21 nm. The measured value of the pore volume for MPC-127 is 0.50 cm^3/g. Comparison of the thermogravimetric data seems to suggest that the sulfonation process was more effective in fuming sulfuric acid compared to regular sulfuric acid.

The sulfonated MPC-127 showed moderate catalytic activity in converting vegetable oil to ethyl esters. Preliminary results showed that the reaction was incomplete after six hours, generating intermediate by-products of monoglycerides and diglycerides in the reaction mixture. Future research will focus on improving the stability of the sulfonic groups on MPC-127, and comparing the catalytic efficiency of sulfonated MPC-127, NaOH, and sulfuric acid in the transesterification reaction.

Conclusions

The results showed that the sulfonated mesoporous carbon catalyst prepared from phloroglucinol and Pluronic F127 yielded an acidic catalyst with a high surface area and narrow pore size distribution of about 5.9 nm. The hydrogen bonding between phloroglucinol and Pluronic F127 facilitated its self-assembly to form the highly ordered mesoporous carbon structure. The highly acidic reaction conditions also increased the polymerization rate of phenolic resins and induced coulombic interactions in the self-assembly of the surfactant-polymer nanocomposites to produce the mesoporous carbon structure. Preliminary evaluation of MPC-127 catalyst for transesterification of vegetable oil to biodiesel showed that the catalyst was capable of yielding ethyl esters but the reaction was incomplete because large amounts of vegetable oil, monoglycerides, and diglycerides remained in the reaction mixture.

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CHAPTER SEVEN

CONCLUSIONS

The first study of the dissertation identified several students' misconceptions in writing balanced equations for dissolving ionic compounds in water. The most popular misconception was that water chemically reacts with an ionic compound through double displacement to form a metal oxide and an acid. Another popular misconception was that ionic compounds dissolved as neutral atoms or molecules. Another common error was that students confused subscripts and coefficients, showing they were unsure which one to use when they wrote the balanced equations for the dissolved ionic compounds. When the ionic compound contained no subscripts ($LiCl$) or when it contained a subscript of a polyatomic ion ($CaCO_3$), less than 5% of students' equations showed subscript/coefficient errors. However, when the ionic compound contained subscript for monatomic ions ($BaBr_2$ and K_2SO_4), several students in the range of (27-43%) wrote equations that contained subscript/coefficient errors.

In the second study of the dissertation, the three misconceptions were used as distractors in multiple-choice questions developed at the symbolic and particulate levels to assess students' understanding of the dissolving process. The symbolic level questions used balanced equations and the particulate level questions used animated and static pictures of ionic compounds dissolving in water. The results showed that the acid-base misconception was the most popular, followed by the correct answer, then the ion pair, and least popular was the subscript misconception. The ion-pair misconception was more popular for the particulate questions than the symbolic questions, and the acid-base misconception more popular for symbolic questions than the particulate questions. Students, however, were slightly more likely to select the correct answer when viewing static particulate questions compared to when viewing animated particulate questions.

The final study of the dissertation used the same test instrument of multiple-choice questions at the symbolic and particulate-levels to assess students' understanding of two types of subscripts when ionic compounds dissolved in water. The results showed that the subscript misconception was more popular for symbolic questions (balanced equations) compared to particulate questions (animated). The correct answer was less popular for particulate and symbolic questions when the question contained a monatomic subscript.

The results of these studies have several implications for chemistry instructors, textbook authors, and instructional designers. The misconceptions identified in the first study may help these practitioners develop instructional strategies to improve students' conceptual understanding about the dissolving process. The conceptual change instructional approach (Posner *et al.,* 1982) could also help some students relinquish some of these misconceptions. The second study showed that the static visuals were a little better than the animations, so it appears that the motion in the animations may be a distraction to students. Animation designers should therefore consider the effect of motion on students' working memory capacities when creating animations of ionic compounds dissolving in water at the particulate level to improve students understanding of the dissolving process. On the other hand, instructors should consider the likely instructional effectiveness of an animation before using it in the classroom.

Students in this study also found monatomic subscripts more confusing and difficult to understand compared to polyatomic subscripts; therefore instructors should use interventions that include visualization and modeling to help students see the difference at the particulate level, particularly when treating solution chemistry involving ionic compounds dissolved in water. Instructors should also assess students' knowledge at the symbolic and particulate levels to ensure that students are consistent in their answers. Assessing students using both levels will determine whether students have a solid understanding of the chemical concepts taught and whether students are capable of transforming symbolic equations to particulate diagrams and vice versa. Students who can successfully transform symbolic equations to particulate diagrams may be developing representational competence, while students who cannot may lack representational competence (Kozma *et al.,* 1997).

Although 240 students participated in the study, it is still difficult to make generalizations about the trends discovered in students' understanding of the dissolving process. More research is needed to see if these trends are common to other student populations. Since participants in the second and third studies were assessed based on the common misconceptions identified in the first study, it is difficult to discuss the presence and extent of the less popular misconceptions in these samples of students. Moreover, it is unclear why the acid-base answer was more popular for symbolic questions and the ion-pair more popular for particulate questions.

In future studies students should be asked to explain the reasons behind their choice of answers for each multiple-choice question. Since previous studies have reported that animation or particulate pictures sometimes can cause new misconceptions to develop in students (Sanger and Greenbowe, 2000; Sanger *et al.,* 2001; Kelly and Jones, 2007), asking students to explain their choices will allow researchers to understand the extent to which students' choices are affected by the information presented by the symbolic or particulate representations of the task at hand. It may also help researchers to understand why the acid-base answer is more common for symbolic questions and the ion-pair answer more common for particulate questions. At present, a manuscript is being prepared to determine whether the correct answer and the popular errors— acid-base, ion-pair, and coefficient/subscript errors— that student chose are robust conceptions or are simply caused by random errors and lapses in students' memory.

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